PTF12os and iPTF13bvn
Two stripped-envelope supernovae discovered by the Palomar Transient Factory

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Abstract

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by Christoffer Fremling

This thesis is based on research made by the intermediate Palomar Transient Factory [(i)PTF], and it is particularly closely tied to the still ongoing research on the stripped-envelope (SE) supernova (SN), iPTF13bvn (Type Ib), that occurred in the nearby galaxy NGC 5806. This SN was initially thought to have been the explosion of a very massive Wolf-Rayet star, but we have shown that this is very likely not the case. We suggest instead that the most likely scenario is that iPTF13bvn originated from a binary system where the envelope was stripped off from the SN progenitor by tidal forces from a companion star (Paper I), in a similar way as for the very well studied Type IIb SN 2011dh. We have also investigated another SE SN, PTF12os (Type IIb), that occurred in the same galaxy as iPTF13bvn, with the conclusion that PTF12os and iPTF13bvn are very similar amongst themselves, and that both of them are also remarkably similar to SN 2011dh, in terms of all of the available observations (light-curves, spectra; Paper II). In Paper II a grid of hydrodynamical models were used to constrain the explosion parameters of iPTF13bvn, PTF12os and SN 2011dh; finding $^{56}$Ni masses in the range $0.063 - 0.075 \, M_\odot$, ejecta masses in the range $1.85 - 1.91 \, M_\odot$, and kinetic energies in the range $0.54 - 0.94 \times 10^{51} \, \text{erg}$. Using the $^{56}$Ni-masses derived from our hydrodynamical modeling in combination with nebular models and late-time spectroscopy we were able to constrain the Zero-Age Main Sequence (ZAMS) mass to $\sim 12 \, M_\odot$ for iPTF13bvn and $\lesssim 15 \, M_\odot$ for PTF12os. In current stellar evolution models, stars with these masses on the ZAMS cannot lose their hydrogen envelopes and become SE SNe without binary interactions. As a by-product of this research, a fully automatic reference image subtraction photometry pipeline was also developed for the Palomar 60-inch telescope (P60; Paper II). The imaging data collected by the P60 is reduced on-the-fly by this pipeline and the resulting photometry is automatically uploaded to the web-based iPTF SN follow-up database interface hosted at CalTech.
List of Papers

The papers included in this licentiate thesis will be referred to as Paper I and Paper II. Short summaries of Papers I and II are given in Chapt. 5.


While Papers I and II are the basis of this thesis, I have also, during my PhD studies, worked on and contributed to many other projects that have lead to publications by other leading authors. These will be listed below, and I am a co-author on all of the listed papers. However, in the list below I give the first three authors only. Many of the papers below also contain analysis based on photometry produced by my automatic pipeline for host-subtraction (FPipe), presented in Paper II and Chapt. 4. These are marked with [FPipe] at the end of the entries.

**Papers not included in this thesis:**


Statement

Contribution to Paper I. The author of this thesis (CF) used photometric and spectroscopic data collected by the iPTF collaboration, along with archival HST images, to perform the analysis presented in the paper. Spectra were reduced by collaborators within the iPTF. The host-subtracted photometry presented in the paper was reduced using the pipeline developed by CF (FPipe; see Chapt. 4). CF designed all figures, and wrote the entirety of the text in the paper. The hydrodynamical model fitting results presented in the paper were computed by M. Ergon. Changes were incorporated after discussing the first draft with the coauthors.

Contribution to Paper II. The author of this thesis (CF) analyzed and presented results based on photometric and spectroscopic data collected by the iPTF collaboration. HST archival images were analyzed by CF and M. Fraser. CF performed the astrometric progenitor identification presented in the paper, and M. Fraser performed the HST photometry and image subtractions. F. Taddia performed the metallicity measurements based on long-slit spectroscopy presented in the paper. Some of the metallicity measurements were based on spectra obtained via a service-mode proposal at the Nordic Optical Telescope by CF (Proposal ID 48-408, PI C. Fremling). All previously unpublished spectra of PTF12os and iPTF13bvn were reduced by collaborators within the (i)PTF collaborations. The host-subtracted photometry presented in the paper was reduced using the pipeline developed by CF (FPipe; which is also presented and described in the paper). CF produced all figures from the relevant data, except Fig. 4 (provided by M. Fraser) and Fig. 1 (which is composed by CF from the original color image created by ESA/NASA/Andre van der Hoeven). CF wrote the entirety of the text in the paper, except for Sect. 5.1, which contains significant contributions from M. Fraser, and Sect. 3 which contains contributions from F. Taddia. The hydrodynamical model fitting results presented in the paper were computed by M. Ergon. Changes and additions were incorporated after discussing the first draft with the coauthors.

Figures in this thesis. The figures in this thesis were created (using GIMP, Pages, MATLAB and DS9) by CF (Figures 1.3, 1.4, 1.6, 1.7, 4.1), either from scratch or based on PTF and iPTF data. Figures 2.10, 2.15, 2.18, 2.19, 2.20, 2.22, 2.26, 2.29, 2.30, 2.33, 2.35, 2.36, 2.37 have been created in the same way by CF, but these are adaptations of figures previously published in Papers I and II. Fig. 2.12 was created by M. Fraser for Paper II. Fig. 1.2 was created by M. Fraser for Paper II. Fig. 1.9 was created by A. Nyholm specifically for this thesis. Figures 1.5, 1.8, 2.1, 2.2, 2.3, 2.4, 2.5, 2.6, 2.7, 2.8, 2.9, 2.11, 2.13, 2.14, 2.16, 2.17, 2.21, 2.23, 2.24, 2.25, 2.27, 2.28, 2.31, 2.32, 2.34 are reproduced from other sources (ESO, or other published papers), sometimes with minor additions, as described in their captions.

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1.1 Supernovae

Exploding stars, or supernovae (SNe), belong to the most energetic astronomical phenomena observed in our galaxy – and beyond. In a SN explosion, an incredible amount of kinetic energy is released, typically on the order of $10^{51}$ erg. SNe are important cosmic laboratories, as they are the origin of some of the most energetic cosmic rays. Some SNe even produce gamma-ray bursts (GRBs, e.g. Galama et al., 1998; Woosley & Bloom, 2006), possibly in connection with the formation of a black-hole at the center of the exploding star. SNe from massive stars also make up an important component in the evolution of galaxies, as they are responsible for the chemical enrichment of the interstellar medium (ISM). Heavy elements that were produced in the fusion reactions during the lifetime of the star (and also synthesized in the explosions themselves) are dispersed into the ISM as a result of the explosions. The explosion of a $17\, M_\odot$ star will enrich the ISM with $1.3\, M_\odot$ of oxygen (Woosley & Heger, 2007). Heat and momentum is also deposited into the surrounding ISM as a result of the SN blast waves, driving the evolution of the gas in the galaxy.

There are two fundamentally different groups of supernovae, thermonuclear SNe and core-collapse (CC) SNe. In a thermonuclear SN, it is believed that a white dwarf reaches the Chandrasekhar limit ($> 1.4\, M_\odot$, Nomoto, 1982), due to mass transfer from a companion star. Beyond the Chandrasekhar limit a white dwarf becomes unstable and a thermonuclear runaway process is triggered, resulting in a supernova. This process leads to SNe that have approximately the same luminosity at their peak, and they can subsequently be used for distance measurements, and cosmology. Type Ia SNe have been used to show that the universe is expanding and that the expansion rate is accelerating (Riess et al., 1998; Perlmutter et al., 1999).

In CC SNe, which are the focus of this thesis, a massive star ($> 8 \to 12\, M_\odot$; Poelarends et al., 2008) collapses on itself when the fusion processes in the center of the star can no longer be sustained, due to the star running out of elements in the center that can lead to an energy release when fused together. When this occurs, the core of the star predominantly consists of densely compressed iron. It is this compact iron core that collapses under gravity on itself. During the core-collapse, an extremely dense proto-neutron star is formed at the center. The outer mantle of the iron core bounces off the proto-neutron star and creates a strong outward-bound shock. However, the energy injected by this shock into the outer envelope of the star is not enough to create a supernova explosion by itself (Woosley & Weaver, 1986). It is an important fact that the detailed processes involved in how the collapse translates the gravitational potential energy contained in the collapsing iron core into a successful supernova explosion are still not known. However, at the extreme conditions (temperature, density) present during collapse of the iron core, a large amount of neutrinos are created, with a luminosity of up to $3 \times 10^{51}$ erg. It has been suggested that if a small fraction of this energy is trapped in the outer parts of the star, the shock produced during the bounce could become strong enough (Janka et al., 2007). Simulations involving complex trapping
mechanisms for the massive amount of neutrinos that are released during the collapse have since resulted in successful supernova explosions, but only for a few specific stellar masses \(11.2 \, M_\odot\), \(13 \, M_\odot\) and \(15 \, M_\odot\), see e.g. Hanke et al., 2012 for a review). A significant observation in support of the neutrinos playing an important role was the detection of neutrinos from SN 1987A (Hirata et al., 1987).

Among CC SNe there are also two main subclasses, which are separated by the presence or lack of a hydrogen envelope around the star at the time of the explosion (Filippenko, 1997). This thesis is particularly focused on SNe that have been stripped of their hydrogen envelopes, or so called stripped envelope (SE) supernovae. Note that SE SNe are rare, making up only around 6\% of SNe discovered in a typical magnitude-limited SN search (Li et al., 2011). Two such SNe have been studied in detail (PTF12os and iPTF13bvn), both discovered by the (intermediate) Palomar Transient Factory [(i)PTF] collaboration. A particular focus is put on how the progenitor stars to these peculiar SNe might have been stripped of their hydrogen envelopes.

1.2 The intermediate Palomar Transient Factory

The (i)PTF (Law et al., 2009; Rau et al., 2009) is an international endeavor with participants from all over the world, with the Oskar Klein Center (Stockholm University) in Sweden, the Weizmann Institute of Science in Israel, and California Institute of Technology (CalTech) in the USA playing leading roles in the SN research effort of the collaboration. The iPTF is focused on Transient Science – the study of energetic and quickly evolving astronomical phenomena (transients), such as massive stellar eruptions and supernovae – both within the Milky Way and beyond. Of particular interest is to detect new transients when they are as young as possible, preferably during the same night as they occurred – or exploded – in the case of SNe.

The main instrument of the (i)PTF is the automated Palomar Samuel Oschin 48-inch telescope (P48), and both PTF and iPTF have been untargeted SN searches\(^1\). The P48 is a wide-field telescope that utilizes a mosaic CCD camera. The field-of-view (FOV) is approximately 8 deg\(^2\). In comparison, the apparent size of the full moon on the night sky is roughly 0.2 deg\(^2\). With such a large FOV, the telescope is able to image a large part of the northern sky, several times each night. These science images can then be compared to reference images obtained of the same sections of the sky during previous visits\(^2\) (see Fig. 1.1, for an example of a discovery by the iPTF). Any new objects not present in the reference images are flagged as possible new transients, e.g. potential SN candidates or stellar eruptions. However, the subtraction process is far from trivial. For example, bright stars, asteroids, variable stars and active galactic nuclei (AGN) in the center of bright galaxies tend to result in strong signals or residuals in the subtractions, and these can easily give rise to false detections. A typical residual that may occur in the center of a bright galaxy is seen at the top of the right panel of Fig. 1.1, such a residual could easily give rise to a false detection. A large amount (\(> 10000\)) of candidates are flagged on a typical night of observations, some of which are real transients, and others not.

To deal with the large amount of candidates, the discovery of new transients within the iPTF is done via a very sophisticated and automated computer-learning neural network back-end, which first compares telescope images from one night to the next - to detect potential transient candidates, and then attempts to filter out false detections (see Cao et al., 2016b and Masci et al., 2016, for technical descriptions of the current detection pipelines). However, even with this sophisticated machinery, some human intervention

\(^1\)In an untargeted search, the telescope is not pointed preferentially at any specific type of galaxy in order to find SNe, unlike for a targeted search where for example a specific set of galaxies might have been chosen to be observed.

\(^2\)Typically, 60 second exposures are used for the science observations, which result in average detection limits of 21.5 mag, using an R-band photometric filter.
1.2. THE INTERMEDIATE PALOMAR TRANSIENT FACTORY

![Discovery Image of iPTF13bvn](image)

Figure 1.1: The discovery image of iPTF13bvn resulting from the iPTF reference subtraction pipelines and machine-learning algorithms. The left panel shows the discovery image, the middle panel shows the reference image used and the right panel shows the subtraction of the reference from the discovery image. The position of iPTF13bvn is indicated by the green cross.

is still needed. Inspection of the best ($\sim 100 - 200$) candidates found each night is done by eye, and a selected few are assigned for follow-up at available telescopes by the person acting as the daily scanner. In Stockholm, a significant part of the manual scanning effort is performed, and this has led to the discovery of many exciting SNe, in addition to the two which are the basis of this thesis. On average, while working as a PhD student, I have performed the iPTF scanning duties for one day every second week. During the lifetime of the (i)PTF (2009 to present), 2852 SNe have been discovered\textsuperscript{3}. Note that a significant byproduct of the (i)PTF surveys, is the large amount of science data collected during the long lifespan of the projects. As an example, the galaxy (NGC 5806) shown in Fig. 1.1 and Fig. 1.2, has been imaged in excess of 1000 times by the P48, during a span of 7 years. This makes it possible to do statistical studies of the flux measured at the position of many SNe, during a very long timespan, both before and after the SN explosions, which could give us new information about the behavior of SN progenitor systems.

Considerable effort is also put in by the participants of the iPTF collaboration to obtain follow-up data on the best (closest and youngest) discoveries with appropriate observations from both ground- and space-based telescopes. The Nordic Optical Telescope (NOT) at La Palma, The Keck telescopes on Hawaii, the Very Large Telescope (VLT) in Chile, the Gemini telescopes on Hawaii and in Chile, and the space-based \textit{Swift} ultra-violet (UV) telescope, among others, are extensively used. As a part of my PhD work, I have been actively triggering Gemini and VLT, and I have also performed on-the-fly spectroscopic reductions of the data collected by these telescopes in order to rapidly classify potentially interesting SNe\textsuperscript{4}. I have worked with \textit{Swift} Target-of-Opportunity requests for UV follow-up photometry, I have submitted a NOT proposal to map the metallicity of NGC 5806, and I have worked with iPTF spectroscopic follow-up observations by remote-observing with Keck I and Keck II.

\textsuperscript{3}This number for the total SNe discovered by the iPTF is from 2016 Oct. 15.

\textsuperscript{4}I have worked on GMOS data from Gemini North and X-Shooter data from VLT.
Figure 1.2: NGC 5806 imaged by the HST in multiple filters during 2004 when SN 2004dg was discovered in the galaxy. Regions with strong star-formation are shown in red (Hα emission, derived from data obtained with the narrow-band WFC filter F658N). The locations of PTF12os, PTF13bvn, SN 2004dg, and SN Hunt 248 are marked by white boxes. Red circles mark the locations where we have measured the metallicity in Paper II. North is up and east is to the left in the figure. Credits for the original image: ESA/NASA/Andre van der Hoeven.
1.3 Supernovae iPTF13bvn and PTF12os

The discovery of iPTF13bvn (Fig. 1.1), was made extremely early by the iPTF. There was no sign of any transient at the same position in the previous images obtained less than a day prior to the discovery image. This implies that the SN likely exploded within 1 day of discovery (around 0.6 d, estimated by Cao et al., 2013). It was also found that there was an object exactly at the position of iPTF13bvn in Hubble Space Telescope (HST) images of the host galaxy (NGC 5806, see Fig. 1.2) taken several years prior to the explosion. This object was thought to be the star that later exploded as the SN. The extremely early detection in combination with a likely progenitor observation spurred a considerable amount of interest in this SN by the community. The first paper was published very rapidly by Cao et al., 2013 based on early observations, which hinted at the progenitor star being a very massive star with a mass of up to 30 M⊙. Such a star will be a Wolf-Rayet star (see Sect. 2.2), that lost its hydrogen envelope due to strong stellar winds. Following the same line of thought, Groh et al. (2013a) published a suitable model for the SN progenitor, based on their stellar evolution models.

However, as iPTF13bvn evolved, we realized that it behaved rather typically for a SE SN, with a peak LC duration (see Sect. 2.5) of approximately 30 d. For a 30 M⊙ progenitor, a much broader LC peak would be expected. This finding motivated the investigation going into Paper I, where we use the full LCs of iPTF13bvn to show that the SN likely had a lower-mass progenitor with a mass < 17 M⊙. Such a low mass implies that the SN was likely part of a binary system (see Sect. 2.2.2).

The PTF also previously discovered another SN in the same host as iPTF13bvn (see Fig. 1.2). This SN, PTF12os, is another SE SN. Thus we were presented with two very rare and exotic events in a nearby host, which allowed a very detailed observational comparison-study to be done. This was the motivation for the science done in Paper II, where we also compare iPTF13bvn and PTF12os to SN 2011dh, a SE SN with exceptional observational coverage (Ergon et al., 2014, Ergon et al., 2015).

1.4 Supernova observations

Typically after a young SN is discovered by the iPTF, both imaging and visual long-slit spectroscopy data are collected, using charge-coupled-device (CCD) image sensors. Observations in the visual regime are usually obtained by ground-based telescopes, such as the NOT, Gemini, or Keck. For the imaging observations, broad-band filters (e.g. UBVRI or ugriz) that cover the visual wavelengths are used. In a filtered imaging observation, all of the light contained within the wavelength range where there is a significant amount of transmission in the chosen filter is collected onto the CCD image (see the left panel of Fig. 1.3 for an example image taken with an i-band filter). This means that the total flux within the filter can be accurately measured. However, at the same time any information about small-scale variations in the observed flux from the SN within this wavelength range is lost (see Fig. 1.4 for an illustration).

Figures 1.1, 1.2 and 1.3 also illustrate an important problem that arises when obtaining photometry of SNe. In the left panel of Fig. 1.1, it is clearly seen that at the position of the SN, in the spiral arm of the galaxy, the light from the galaxy is quite significant. Thus, in order to obtain the total flux within the imaging filter from only the SN itself, the contribution from the host galaxy must be removed. This process involves sophisticated image processing techniques, but in principle a reference image without

Note that within the context of SE CC SN progenitors, a low mass star usually implies a star with a mass < 15 − 17 M⊙, which in most other contexts would still be a very massive star. For SE SNe, a massive star progenitor would be a star with a mass exceeding 25 − 30 M⊙. This convention comes from stellar evolution modeling: in current models, low-mass progenitors cannot lose their hydrogen envelopes and become SE SNe, without binary interactions. SE SN progenitors are discussed in detail in Sect. 2.2.
light from the SN is subtracted from the image of the SN. The reference could be an image taken prior to the SN explosion, or a long time after the SN has faded. For the research presented in Paper I and Paper II in this thesis, an automatic pipeline for the removal of the host-contamination has been developed. Some of the most important intricacies involved in the process and the pipeline itself is described in Chapt. 4. The pipeline is also presented and described in Paper II.

While detailed information on the wavelength dependency of the flux from a SN is lost in imaging observations, multi-band imaging and the subsequent host-subtracted photometry that can be obtained from the data, can still give a rough estimate of the spectral energy distribution (SED) of the SN emission (see Fig. 1.4) at the time of the observations. This information can be used to constrain important properties of the SN explosion, such as the radius and temperature (see Sect. 2.5). Furthermore, since imaging requires relatively short exposure times (compared to spectroscopic observations) photometry of SNe can be obtained at a high cadence of up to several images per night in multiple broad-band filters, tracking the evolution of the SN flux over time, or the SN light-curve (LC; see Fig. 1.5 for some examples in the $B$ band).

To obtain more detailed information about the structure and composition of a SN and its ejecta, more detailed information about the SN flux as a function of wavelength is needed, i.e. spectroscopic observations are required. Spectral observations most importantly give information about which elements are present in the SN ejecta, and at what velocities they were ejected. The position of a line is directly dependent on which emitting ion is present, and the width of the associated spectral emission/absorption feature is a relatively direct measure of the velocity (see e.g. Fig. 1.6 for a few example spectra). Typically
Figure 1.4: An early spectroscopic observation of a SN (iPTF13bvn), overlaid by typical photometric filters (green, red and pink lines) used for supernova follow-up. A black-body SED with a temperature of 8000 K is also shown (dashed gray line).

long-slit spectroscopy at low resolution is collected for SNe, but in some cases high or medium resolution spectra can also be very useful (e.g. for constraining the extinction following for example Poznanski et al., 2012, or to measure the velocity of narrow emission lines).

For low-resolution long-slit spectroscopy of SNe, typically a slit with a width of 1″ or 1.5″ is used to disperse the SN light across the CCD. In a typical telescope instrumentation setup, the result is a relatively linear trace at some position of the science image. An example from the EFOSC instrument at the NTT is shown in the right panel of Fig. 1.3. This type of 2-dimensional data, can be processed (by extracting the signal along the SN trace and removing the background and sky lines) into a one-dimensional spectrum measuring the observed SN flux as a function of wavelength. Spectroscopic observations require significantly longer exposure times compared to filtered imaging (typically 1 hour of observation time, compared to a couple of minutes per filter for imaging, at the NOT). Thus, spectra have to be obtained much more selectively compared to photometric observations. At early times, a higher cadence can be warranted if the SED of the SN is evolving rapidly, but at later times, especially after a few months past the explosion, much lower cadences are the norm.

In the case of iPTF13bvn (Papers I and II) we have obtained 14 spectra during the first 15 days, 6 spectra during the following 15 days (see the purple line in Fig. 1.6 for an example spectrum taken during this phase), and 8 spectra between 36 to 85 days. One spectrum was obtained at 250 days past the explosion (red line in Fig. 1.6), and three spectra were obtained approximately 1 year after the SN explosion. This is an example of an exceptionally well observed SN. Typically, within iPTF, the spectral coverage is significantly more sparse.

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*This image processing step is typically done in a software package for image manipulation, such as IRAF (Tody, 1986, 1993) or MATLAB.*
Finally, in some cases, especially for nearby or very young SNe, UV observations will also be obtained to supplement the visual information. These must be obtained using space-based telescopes (e.g., Swift, or HST), since UV emission is completely absorbed by the atmosphere of the earth. Furthermore, nearby or very young SNe are required to get meaningful observations in the UV, since the observed flux, which is typically due to shock-breakout cooling, declines very rapidly in this regime (see Sect. 2.5 for details). In the case of PTF12os and iPTF13bvn, UV photometry from Swift was obtained for both objects at early times.

1.5 Supernova classification and supernova types

Supernovae can be classified into many classes and subclasses based on their observed spectral features and LC behaviors. This classification process has been well described by Filippenko (1997). As a visual aid, we have illustrated the main classes and the typically used classification scheme\(^7\) in Fig. 1.7.

Following Fig. 1.7, from the top down, we can see that SNe that show signatures of hydrogen in their spectra are classified as Type II SNe, and SNe that do not, are classified as Type I. Continuing along the Type I track in the figure – supernovae that show strong silicon features, but no helium, are classified as Type Ia. Type Ia SNe are the result of thermonuclear explosions of accreting white dwarfs (see Sect. 1.1), and the spectral signatures from these are quite distinct from all other classes, making Type Ia SNe possibly the most uniform class (compare the spectrum at the top of Fig. 1.8 to the others in the figure).

SNe of Type Ia have been found to occur in all types of galaxies, i.e. they can happen in both young and old stellar populations, including in elliptical galaxies that predominantly consist of very old stars. This means that the progenitor stars of Type Ia SNe cannot be very massive, since the lifetimes of massive stars are too short to still be present in such galaxies. This observational fact also agrees well with accreting

\(^7\)Note that some of the minor SN subclasses, e.g. Ia-pec, and Ibn, have been omitted in this figure.
white dwarfs being the progenitors of Type Ia SNe, in addition to the rest of the main observational properties (spectral signatures and light curve behavior, Filippenko, 1997).

All SN types except Type Ia SNe, are believed to be the result of the core-collapse of massive stars. Type II, Ib and Ic SNe have never been observed in an elliptical galaxy, a strong piece of evidence for the core-collapse scenario (Filippenko, 1997). Among Type II SNe – Type IIP, Type IIL, and Type IIIn SNe show the strongest signatures of hydrogen in their spectra, and are believed to originate from red supergiant stars (IIP, IIL, IIIn) or LBV stars (IIIn), all surrounded by thick hydrogen envelopes at the time of the explosions (see e.g. Smartt, 2009 and Smith, 2014). The distinction between IIP and IIL is traditionally based on the light-curve behavior, with IIPs having approximately the same brightness for the first 100 days following the LC peak, while IILs decline in a linear fashion after their peaks (see Fig. 1.5). Spectroscopically, Type IIP SNe tend to show somewhat deeper P-Cygni features compared to Type IIL SNe (Patat et al., 1994). However, this difference is not large, and most Type IIP and Type IIL spectra look approximately like spectrum (b) in Fig. 1.8 or the bottom spectrum in Fig. 1.9, at early times. Type IIIn SNe appear to be a separate class, as their spectra show narrow spectral features, not seen in other Type II SNe. These narrow features are thought to be the result of interactions between the SN blast wave and a dense circumstellar medium (CSM). Another feature of these interaction dominated spectra are a lack of strong P-Cygni profiles (see Fig. 1.9).
In this thesis the focus is on stripped-envelope SNe, e.g. SNe of Type IIb, Ib and Ic, which are shown in the center of Fig. 1.7. These are classified as follows. Type Ib SNe completely lack signatures of hydrogen, but show strong signatures of helium in their spectra. Type Ic SNe completely lack both hydrogen and helium in their spectra. Furthermore, Type IIb SNe, which are thought to be a transitional class, show clear signatures of hydrogen in their early spectra. However, these signatures gradually disappear, over the course of 30-90 d past the explosions, and after that the spectra become virtually indistinguishable from Type Ib SNe. These differences are illustrated in Fig. 1.6, where the gray line at the top of the figure shows a Type IIb (SN 2011dh), the following purple line shows a Type Ib (iPTF13bvn), and the following a Type Ic (iPTF15dtg). Finally at the bottom of the figure we show a late-time spectrum of iPTF13bvn. All three subclasses display spectra that closely resemble this kind of spectrum at late times, and become dominated by oxygen and calcium features when the inner parts of the SN ejecta become visible.

There is also an important subclass of Type Ic SNe, that has been designated broad-line (BL); Type Ic-BL SNe. These SNe are similar to Type Ic SNe but release significantly (> 10 times) more kinetic energy in their explosions, resulting in much higher expansion velocities of their ejecta, leading to broader features in their spectra. Some Type Ic-BL have also been observed to be connected with long-duration GRBs (e.g. SN 1998bw, Galama et al., 1998).

Possibly the simplest explanation for these observational differences among the SE SNe subclasses, is...
that different amounts of the helium/hydrogen envelopes have been stripped off the star prior to the SN explosions. In this picture, Type Ic SNe are the most stripped and IIb the least (the mechanisms responsible for the stripping is further discussed in Chapt. 2). Note that there are no clear differences observed in the LCs of Type IIb, Ib and Ic SNe (e.g. Lyman et al., 2016). Note also that no SN has been observed to transition from weak hydrogen signatures to a fully stripped helium-free spectrum, i.e. all Type IIb SNe turn into Type Ib SNe, and none have thus far turned into Type Ic SNe.
Figure 1.9: Early spectrum taken 10 d past the explosion of a Type IIn SN (SN 1998S, Leonard et al., 2000, top red line), late-time spectrum (400 d past the explosion) of a Type IIn SN (SN 2010jl, Zhang et al., 2012, middle black line) and spectrum taken 45 d past the explosion of a Type IIP SN (SN 1999em, Leonard et al., 2002, bottom blue line). Note the lack of P-Cygni absorption features on the blue side of Hα in the two Type IIn spectra and the strong P-Cygni feature in the Type IIP spectrum. Image credits: Anders Nyholm.
2.1 Connecting theory and observations

One of the main questions essential for understanding SE SNe (the Type IIb, Ib and Ic subclasses) is to explain how the progenitors (the stars that give rise to the SNe) lose their hydrogen (and helium in the case of Type Ic SNe) envelopes prior to the SN explosions. Traditionally it was thought that since some SE SNe show hydrogen signatures in their spectra (Type IIb) and some do not (Type Ib, Ic), the two groups should come from different kinds of progenitors or stripping mechanisms (see e.g. Filippenko, 1997). The two main contenders in this simple picture are binary mass transfer (e.g. Iben & Tutukov, 1985; Yoon et al., 2010; Claeyts et al., 2011; Yoon, 2015) in binary systems, and strong line-driven winds from isolated massive stars (e.g. Conti, 1976; Smith, 2014; Owocki, 2014). See also Langer (2012) for a review on pre-supernova evolution of both massive single and binary stars.

Mass transfer in binary systems comes with a natural mechanism to explain the partial stripping observed in Type IIb SNe. When the envelope of the star that is losing mass (the donor star, and SN progenitor) decreases in extent below the Roche limit, the mass-transfer ceases, and partial stripping or a Type IIb SN progenitor, is the natural result. The Roche limit (or radius), is the radius where the envelope of a star starts to disintegrate due to the tidal forces from the gravitational field of another star becoming higher than the gravitational field from the star itself. However, one should note that by adjusting the binary configuration (i.e. the rotational period which is tied to the distance between the stars for a stable system), it is also possible to produce fully stripped Type Ib and Ic SNe from binary progenitors (Yoon et al., 2010; Yoon, 2015). See Sect. 2.2.2 for further discussion on binary evolution.

For an isolated massive star to expel its entire hydrogen envelope prior to when the core-collapse sets in, very strong line-driven winds are needed. This class of stars is called Wolf-Rayet (WR) stars (Maeder, 1981; Dessart et al., 2011), and the line-driven wind that is responsible for expelling the remaining hydrogen envelope after the red supergiant (RSG) phase is called the WR wind. In current models, in order to achieve strong enough winds to expel most or all of the hydrogen envelope, typically a very high mass is needed (~ 30 M☉, Dessart et al., 2011) for the progenitor on the Zero-Age Main Sequence (ZAMS, the hydrogen burning phase). Otherwise the star will end up as a hydrogen rich Type II SN. In a massive single-star mass-loss scenario there is no natural cut-off mechanism for the wind after the RSG phase, and typically Type Ib or Ic SNe are produced in stellar evolution models. It is still possible to construct models that give rise to Type IIb SNe with as little hydrogen in the envelopes as is observed (e.g. < 0.1 M☉ for SN 2011dh; Ergon et al., 2014), but these require a significant amount of fine-tuning of the initial mass, rotation and metallicity (Dessart et al., 2011; Groh et al., 2013b). Massive star evolution is further discussed in Sect. 2.2.1.

The definitive solution to disentangle between binaries and single-star systems as the progenitors of SE SNe would be to directly observe the progenitor systems both before the SN, and after the SN has faded, to detect or show the lack of a possible binary companion. This kind of investigation is very rarely
possible, since it requires a very nearby galaxy (typically closer than 30 Mpc, and the existence of HST observations prior to the occurrence of the SN). However, in some cases this has been doable, e.g. for the Type IIb SN 1993J and SN 2011dh, where the binary companions may have been directly observed. It was initially thought that the progenitor system of iPTF13bvn, one of the objects studied in detail in this thesis, was a Wolf-Rayet star. However, this has been shown to be inconsistent with the rest of the observables of this SN (see the following sections, and Papers I and II), and pre- and post-SN images from the HST have been used to show that a binary system is more plausible. However, it is still too early to detect the binary companion for this SN as well (another attempt will be made in the next HST cycle, spring 2017). Progenitor detections of SE SNe are further discussed in Sect. 2.3.

When it is not possible to directly observe the progenitor systems, constraints on the progenitors must be obtained by other means. One possibility is to investigate their host environments. The metallicity of the host environment controls the strength of the line-driven winds from isolated massive stars, if they were born from the same gas that is probed. It could be that low-metallicity environments give rise to the partially stripped Type IIb SNe, while higher metallicity environments produce Type Ib or Ic SNe. If this were the case, there should be an observable trend for Type IIb SNe happening more commonly in environments of low metallicity, and some evidence for this behavior exists. The metallicity at the positions of the Type IIb PTF12os and Type Ib iPTF13bvn has been measured in Paper II. Via stellar evolution models of star-forming regions, line-diagnostics can also be used to estimate the age of the gas at the position of a SN. This provides another constraint on the mass of the progenitor stars, when compared with the time-until explosion of massive star evolutionary models. Details and a general discussion on the host environments of SE SNe can be found in Sect. 2.4.

Another possibility is to look at the observed lightcurves. The broadness of a radioactively powered LC (as is the case for SE SNe) is related to the ejecta mass (and expansion velocity), and the peak luminosity seen in the LC is related to the radioactive nickel mass. The light curves (see Sect. 2.5) in combination with spectral information about the ejecta structure and dynamics (see Sect. 2.6) can be further used in comparisons with hydrodynamical models of the SNe, which can offer quantitative constraints on the energy, nickel mass and envelope mass (discussed in Sect. 2.7). From evolutionary models (Sect. 2.2), the predicted ejecta masses are typically higher for single massive star progenitors, and lower for binary systems.

Another avenue of research is to look at late-time spectra obtained when the ejecta is transparent and we can see the emission from the center of the SN. This can provide independent constraints on the ZAMS mass when combined with nebular models (see Sect. 2.6.1).

In the case of iPTF13bvn and PTF12os, we have used all of the above-mentioned methods in unison to show that massive single-star progenitor models are not consistent with the observed properties of the SNe (Paper I and Paper II). Binary systems seem much more plausible as the progenitors (see Chapt. 3 for further discussion). In the following sections we will go into some more detail for each of the avenues of research typically explored for SE SNe briefly discussed above (progenitor searches, host metallicity, light-curves and spectra), with a focus on the research that has been done on iPTF13bvn and PTF12os (Papers I and II).

2.2 Stripped envelope SN progenitors, stellar evolution and mass loss

On one hand, if SE SNe originate from very massive stars (\(> 20 \, M_{\odot} \)), the envelopes of the stars can be stripped by two main mechanisms. One being uniform mass loss from line-driven winds and the other due to rotation. Both of these effects are likely in effect simultaneously, and their strength is strongly
correlated with the initial mass of the stars, so that a larger initial mass tends to lead to stronger stripping (i.e. a Type Ic instead of a Type IIb/Ib SN). Which effect that dominates will depend on the amount of metals present in the star and the rotational velocity (see e.g. Heger et al., 2000; Groh et al., 2013; Georgy et al., 2012, 2013 for some examples of stellar evolution modeling). The total mass lost during the lifetime of the stars might also be increased by powerful stellar pulsations or eruptions leading to shorter periods of extremely high mass loss (see Smith, 2014 for a review). It is even possible that the most massive (> 40 M⊙) WR stars have all undergone an eruptive luminous blue variable (LBV) phase prior to the WR phase, and this is also typically assumed when constructing evolutionary models (Stothers & Chin, 1996, but see also Langer, 2012). The natural end result of the evolution for a very massive star is in any case an envelope stripped Wolf-Rayet star (Maeder, 1981), which is basically a bare helium- (Type Ib) or carbon-oxygen-core (Type Ic). On the other hand, if stars in binary systems are the progenitors of SE SNe, mass transfer due to tidal forces should be the dominant factor for the envelope stripping. In this case stars giving rise to the bare stellar cores and SE SNe can have significantly lower masses (while still being > 8 M⊙ in order to collapse). Note that these two scenarios are fundamentally different from a stellar-evolution perspective, but can still achieve very similar end results.

A useful tool for illustrating the evolution of stars is the Hertzsprung-Russell (HR) diagram (Fig. 2.1). In a HR diagram the stellar luminosity is plotted against the temperature (or spectral type, or color), such that hot stars reside to the left in the diagram and luminous stars reside at the top of the diagram. An important feature that will emerge when plotting a large number of randomly selected stars in such a diagram is the Zero-age Main Sequence, which can be seen as a diagonal concentration of stars ranging from luminous and hot stars to faint and cool stars. ZAMS stars are fusing hydrogen into helium in their cores, and most stars spend the majority of their lifetimes on the ZAMS, with their luminosity being directly correlated to the stellar mass, with more massive stars being more luminous. Another interesting feature seen when plotting stars on a HR diagram is that there appears to be an upper limit to the possible luminosity of a star that is temperature dependent. No observed stars seem to reside above this limit (Humphreys & Davidson, 1979), also known as the Eddington limit. At the Eddington limit the radiation pressure of the star is in a delicate balance with the gravitational force in the envelope of the star, making it highly unstable. If the luminosity increases, the envelope will become unbound, resulting in a giant mass ejection (a period from a few days to a few years of extremely high mass loss). Stars that are observed to be close to this limit and undergo dramatic periodic increases in their mass loss are called luminous blue variables (LBVs, see e.g. Stothers & Chin, 1996).

Below we briefly describe the different stages in the life of a star that could give rise to Type Ibc or IIb SE SNe, first for a typical single-star progenitor, and then for a binary progenitor scenario.

2.2.1 Evolution of very massive stars

The mass range at the start of the initial hydrogen burning stage (the ZAMS) for a star that could have strong enough mass loss to give rise to a WR star stripped of its envelope, and a subsequent Type Ibc or IIb SN, in a single massive star progenitor scenario is typically found to be on the order of 20 – 30 M⊙. This result is based on modeling (see e.g. Fig. 2.2 which is from Georgy et al., 2013). Observationally, from the WR stars found in the MW (Hamann et al., 2006), a range of 20 – 25 M⊙ is found. Stars within these mass ranges will be seen as luminous blue O-stars on the ZAMS (see Fig. 2.1), and such massive stars evolve very rapidly from a stellar evolution point of view. They will typically only spend 5 – 10 Myr in the hydrogen burning stage before the hydrogen in their cores is exhausted.

There are many subtypes of WR stars, given by a significant variety in the observed chemical abundances in their spectra (e.g. van der Hucht et al., 1988), which is likely tied to different initial masses,
metallicities and rotations, resulting in slightly different mass-loss and evolutionary scenarios. However, it is a difficult task to tie the observed WR spectra to the properties of the stars on the ZAMS before they lost their hydrogen and/or helium envelopes (see e.g. Langer, 2012 for some discussion). SN observations have not yet been successfully used to differentiate between such minute differences in their potential WR star progenitors spectral features, while some attempts have been made using very early SN spectra that show spectral features also present in some WR stars (see Gal-Yam et al., 2014, but also Groh, 2014 where it is found that an LBV progenitor was more likely for this SN). In any case, when doing the research that is the basis of this thesis, we were mainly interested in the end result - a star that can somehow became devoid of its outer hydrogen (and possibly helium) envelope. Thus, we do not consider the different WR subtypes in detail here. Instead, as an illustrative example, we take a look at the evolution of a typical Type Ib SN WR progenitor (a 32 M⊙ WR star of type WN7 with a nitrogen emission line dominated spectrum – which was suggested as a preliminary progenitor model for iPTF13bvn by Groh et al., 2013a).

On the ZAMS, the suggested massive star progenitor to iPTF13bvn has a very high temperature of log_{10}(T[K])=4.6 (39,800 K) and luminosity log_{10}(L/L⊙)=5.125 (133,350 L⊙), which means that it would be located in the top left corner of a typical HR diagram (see e.g. Fig. 2.1 and Fig. 2.2). When the hydrogen starts to become exhausted in the core of the star, the fusion at the center of the core will gradually stop. This results in an increasing amount of helium ash in the center of the star, which is surrounded by a hydrogen burning shell. During this hydrogen shell burning stage the energy production is increased, resulting in higher radiation pressure and a subsequent expansion and cooling of the envelope of the star. The helium core of the star also gradually increases in density, since its mass is increasing from the fusion end products and there is no radiation pressure behind the hydrogen burning shell to counteract
2.2. STRIPPED ENVELOPE SN PROGENITORS, STELLAR EVOLUTION AND MASS LOSS

Figure 2.2: HR diagram with stellar evolution tracks (starting from the end of the ZAMS) for massive single stars with rotation, from Georgy et al. (2013). Note that stars with initial masses above $20 \, M_\odot$ start to become significantly stripped of their envelopes and move all the way back to the blue side of the diagram after the red supergiant phase.
gravity. Eventually the electrons in the helium core will become degenerate, and at this point the core will not contract further (the pressure no longer depends on the temperature). Instead the temperature keeps increasing all the way until around 100 million K, after which the helium in the core will start to fuse (helium ignition). After helium ignition the core degeneracy is broken and the star enters a stable core helium burning stage surrounded by a hydrogen burning shell. A similar process is then repeated with a core consisting of the helium fusion end products (carbon), then neon, oxygen, silicon, and finally resulting in an iron core (that will collapse within minutes) surrounded by multiple layers of burning shells (see Fig. 2.3). Note the constantly increasing core temperature and density during the life of the star.

Prior to the helium core ignition during the hydrogen shell burning, the envelope of the star significantly expands and cools, moving it all the way to the right in the HR diagram over a timespan of approximately 1 Myr. The star effectively becomes a red supergiant (RSG). The RSG phase is important for the evolution of a very massive star, since the cooler temperatures from the expansion significantly increases the opacity, which makes it easier for photons to be caught by the outer envelope, resulting in increased radiation pressure (i.e. stronger line-driven winds). The outer layers are also less tightly bound, since the radius is now several hundred solar radii or larger. Both of these effects greatly increase the mass loss, which for a very massive star, such as the suggested $32 \, M_\odot$ progenitor for iPTF13bvn, will result in a loss of a significant part of the outer envelope. This will, in combination with helium ignition in the core, move the star back towards the blue side of the HR diagram. Note that this star also undergoes a second RSG phase with increased mass loss as it expands again when the helium becomes depleted in the core (follow the evolutionary track in Fig. 2.4). After the second RSG phase the entire hydrogen envelope of the star is lost, quickly moving it all the way to the blue supergiant (BSG), and then the WR part of the
2.2. STRIPPED ENVELOPE SN PROGENITORS, STELLAR EVOLUTION AND MASS LOSS

Figure 2.4: (a) HR diagram with stellar evolution tracks for two model stars with ZAMS masses $32 \, M_\odot$ and $40 \, M_\odot$. The suggested $32 \, M_\odot$ WR progenitor for iPTF13bvn is shown as a solid line. (b) Modeled optical spectrum for the pre supernova model. (c) Abundance structure (abundance fraction vs radius) for the $32 \, M_\odot$ pre-supernova star, when the remaining stellar mass is $10.9 \, M_\odot$. Figures from Groh et al. (2013a).

HR diagram, as it goes through the later core-burning stages. Finally, it explodes as a Type Ib SN. During the final WR stage, immediately prior to the explosion, the mass loss rate is predicted by the Groh et al. (2013a) model to be on the order of $10^{-5} \, M_\odot \, \text{yr}^{-1}$ (see also Table. 2.1). Note that this is also an important observable, which can be constrained via radio observations, since the stellar wind will give rise to free-free emission, and its strength will depend on the terminal velocity and the mass loss rate (Wright & Barlow, 1975; Panagia & Felli, 1975). However, other processes are also involved in producing the observed radio emission of a SN (see e.g. Fransson & Björnsson, 1998, for a detailed model of the radio emission of SN 1993J). Radio observations of iPTF13bvn, along with a simple stellar wind radio emission model was used by Cao et al. (2013) to find a mass loss rate value consistent with WR star mass loss for the SN. This was used as a supporting argument for a massive star progenitor model. However, in this model there is an initial assumption about the terminal velocity (1000 km s$^{-1}$), a number which cannot be constrained from the observational data collected on iPTF13bvn.

Note that depending on the initial parameters (mass, metallicity and rotation) the star might explode at different times during the evolution from the RSG phase towards the WR stage. A Type IIb SN might originate from a massive yellow supergiant (YSG) star that still has some hydrogen envelope left and is still moving from the RSG to the BSG part of the HR diagram, while Ib and Ic SNe would originate from stars that make it all the way to the WR stage. Note also again that the most massive stars ($> 40 \, M_\odot$) will likely already expel their envelopes during or immediately following the hydrogen core burning stage, turning the stars directly into luminous blue variables (LBVs) and then into WR stars, completely skipping the RSG phase. The spectra of these would likely be significantly different from the less massive WR stars, if such observations could be obtained.
Table 2.1: SN progenitor parameters predicted by Groh et al. (2013b) at solar metallicity. The columns correspond to the initial ZAMS mass ($M_{\text{ini}}$), the SN progenitor mass ($M_{\text{prog}}$), the age at the time of explosion, radius of the hydrostatic surface ($R_*$), photospheric radius ($R_{\text{phot}}$), mass-loss rate ($\dot{M}$) and the SN type.

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With the solar metallicity non-rotating and rotating model grids used in the investigation by Groh et al. (2013b), Type IIb, Ib and Ic SNe are predicted to happen as a function of initial mass, with Type Ic SNe originating from the most massive stars (see Table. 2.1). Note that there is a very significant difference in the ZAMS mass needed to produce a Type Ic SN with and without rotation (60 M⊙ vs 32 M⊙). Rotating models also predict a very narrow range where Type IIb SNe might be produced (18 M⊙ to 20 M⊙). The typical helium core (progenitor) mass for a Type Ib SN from these models is \( \approx 10 \, M_\odot \), or 10.9 M⊙ for the specific model suggested for iPTF13bvn by Groh et al. (2013a).

Groh et al. (2013b) also predicts the photometry and radius of the various SE SN progenitors, which can be directly used in combination with pre-explosion observations (photometry) and early LCs (radius) to constrain the progenitor models (see Sect. 2.3). The predicted radii for the least massive Ib SNe are on the order of 10 R⊙, but as the ZAMS mass of the models increases the radius drastically shrinks and becomes \(< 1 \, R_\odot \) for Type Ic SNe (see also Sect. 2.5). Cao et al. (2013) argued for a very small radius of iPTF13bvn based on early R-band photometry, in good agreement with the later Groh et al. (2013a) model.

While the progenitor photometry and radius seemed to be consistent with observations for the Groh et al. (2013a) model, it was later found that the helium core mass of iPTF13bvn seemed to be low (\( \sim 3.5 \, M_\odot \); Paper I), and very similar to other Type IIb/Ib SNe. Taddia et al. (2015b) found the ejecta\(^1\)-mass range of 3.6–5.7 M⊙, from observations of 20 Type Ibc SNe found by the Sloan Digital Sky Survey (SDSS) SN survey II. Similar results have also been found for IIb/Ib/Ic SNe by Cano (2013) and Lyman et al. (2016). Such low helium core masses are very difficult to reconcile with a massive star progenitor model, such as the one in Groh et al. (2013a) (10.9 M⊙), or the ones presented in Groh et al. (2013b). A star with a significantly lower mass is needed (\(< 20 \, M_\odot \)), and for such a star to be stripped of its hydrogen envelope, one needs to invoke a binary system. This was also the direction that later research on iPTF13bvn took as a consequence (Paper I, Bersten et al., 2014, Srivastav et al. (2014), Eldridge et al., 2015, Paper II, Kuncarayakti et al., 2015, Eldridge & Maund, 2016, Folatelli et al., 2016). However, note that very massive stars (\( \geq 30 \, M_\odot \)) seem to be well matched as the progenitors for Type Ic and Type Ic-BL SNe with very large ejecta masses corresponding to large (\( \geq 30 \, M_\odot \)) ZAMS masses (see e.g. Type Ic iPTF15dtg, which was likely the explosion of a \( \gtrsim 35 \, M_\odot \) ZAMS star; Taddia et al., 2016a, and Type Ic-BL SN 1998bw, likely the explosion of a \( \sim 40 \, M_\odot \) star; Maeda et al., 2006). While these stars might still be in binary systems, binary mass transfer is not needed for such massive stars to lose their envelopes.

### 2.2.2 Evolution of binary progenitor systems of SE SNe

In order to explain the low observed average helium core and ejecta masses of Type IIb/Ib/Ic SNe, stars with ZAMS masses in the range 10 – 20 M⊙ seem to be needed (see Cano, 2013, Taddia et al., 2015b and Lyman et al., 2016 for observational constraints, and Yoon, 2015 for a binary modeling review). Note that a star in this mass range is still a massive star that will evolve in a similar way, with strong mass-loss due to rotation and line-driven winds and multiple shell burning until iron core-collapse, as described in Sect. 2.2.1. However, the stellar wind mass-loss will not be strong enough to completely expel the stellar envelope of an individual star\(^2\). Instead, for a \(< 20 \, M_\odot \) star to become a SE SN, such as iPTF13bvn, significant mass transfer to a companion in a close binary system is needed. Note that the evolution of a binary star can be very complex, since some of the shell burning stages might be affected, or even prevented completely, by the mass transfer of shell material to the companion.

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\(^1\)The ejecta mass is typically assumed to be equal to the helium core mass minus 1.4 M⊙, the mass of the neutron star that remains at the center of the SN explosion.

\(^2\)Unless the rotational velocity is very high. But even in that case, the final helium core mass is not consistent with the observed averages for SE SNe.
When a suitable binary companion to a $< 20 \, M_\odot$ star is introduced to produce SE SNe, the effect of the single-star mass loss mechanisms (rotation, line-driven winds) will be overshadowed by the mass transfer due to tidal forces (see e.g. Yoon et al., 2010; Dessart et al., 2011; Yoon, 2015). In a typical binary system resulting in a SE SN explosion, mass is mainly transferred from a more massive star to a less massive one, due to the tidal forces. The initially more massive star is called the primary or donor star (i.e. the star that later explodes) and the less massive star is the secondary.

Besides depending on the initial masses of the stars in the binary (which sets the size of their Roche lobe), the evolution of the outer envelope of the primary will very strongly depend on the physical configuration of the binary system. The two main parameters governing this are the orbital period (or distance between the stars), and the eccentricity of the orbit. There is also a continuous and very complex interplay between the isolated stellar evolution of the primary and secondary (see Sect. 2.2.1) and the tidal mass transfer. As an example, during the red giant (RG) or RSG phase and hydrogen shell burning of the primary, its radius is greatly increased, which in a specific binary configuration could trigger the mass loss (or Roche lobe overflow, RLOF) if the envelope of the star grows large enough to surpass the Roche lobe (this is called Case B mass transfer). Note also that the orbital period might not remain constant during the lifetime of the binary. It can change due to angular momentum loss or transfer (due to e.g. magnetic braking), which might also trigger RLOF if the stars end up close enough to each other at some point prior to the explosion of the primary. This delicate interplay between the tidal mass transfer and massive star evolution gives rise to very complex evolutionary tracks on the HR diagram (see e.g. Fig. 2.5), especially for eccentric orbits.

To simplify the discussion on binary mass loss, three main scenarios have been identified (Kippenhahn & Weigert, 1967; Lauterborn, 1970). Tidal mass transfer on the ZAMS during hydrogen core burning is called Case A mass transfer. Mass transfer after the ZAMS when the star is in, or moving to, the RG or RSG giant phase (helium shell burning, but prior to helium ignition in the core) is called Case B mass transfer, and mass transfer after the helium core-burning phase is called Case C mass transfer. It is also possible to have a combination of several cases, for example Case AB mass transfer. The latter would be mass transfer from the primary after it has already undergone an episode of Case A mass transfer (see e.g. Yoon, 2015 for further details).

The mass transfer case(s) (which depends on the initial parameters of the binary) is critical for the evolution and final appearance of a SN progenitor and its companion star. By adjusting the orbital parameters and initial masses Type Ib (SN 2011dh, Claeyts et al., 2011, Benvenuto et al., 2013 and SN 1993J, Stancliffe & Eldridge, 2009), Type Ib (iPTF13bvn, Bersten et al., 2014, Eldridge et al., 2015, Eldridge & Maund, 2016), and Type Ic (SN 1987M, Nomoto et al., 1990) SNe can all be produced, with general properties that seem to match the observations. As another consequence of the effect of the various cases of mass transfer, it is also possible to produce a final helium core that is very similar, for quite different initial masses, by adjusting the other orbital parameters. For example, as the progenitor for iPTF13bvn (Paper I, Paper II), two quite different initial configurations have been suggested. One system with the initial masses $20 \, M_\odot$ (primary) and $19 \, M_\odot$ and a very short initial orbital period of 4.1 d (i.e. a very close binary model, suggested by Bersten et al., 2014, henceforth called the B14 model, see Fig. 2.6 for the evolutionary tracks). The B14 system undergoes strong Case A mass transfer, followed by a later episode of Case B mass transfer, with the last bit of remaining hydrogen removed by strong stellar winds during the later core-burning phases. Another scenario was later suggested by Eldridge & Maund (2016), henceforth the E16 model, who base their model also on post-explosion HST photometry (see Sect. 2.3). The E16 system has significantly lower initial masses, $11 \, M_\odot$ for the primary and $5.5 \, M_\odot$ for the secondary, and a significantly longer orbital period of 63 d. This system undergoes almost exclusively Case B mass transfer during helium core-contraction and hydrogen shell burning (see Fig. 2.8 for the
mass loss scenario and composition of the star and Fig. 2.5 for the evolutionary tracks). Both of these models produce a low mass helium core at the time of explosion, with a radius of 30–50 R$_\odot$, that can be considered consistent with both the observed LCs and spectra.

Note that the mass and chemical structure of the final helium cores in the B14 and E16 models are also quite similar (see Figs. 2.7 and 2.8). This is perhaps somewhat counter-intuitive, since the core of a 20 M$_\odot$ ZAMS mass star would be quite different (more massive) compared to a 11 M$_\odot$ star, when it leaves the ZAMS. After the main sequence, the evolution of the inner core (i.e. the amount of oxygen that can be produced from a specific exploding core) should largely be unaffected by the mass transfer from the envelope of the star. However, since the tidal effects and mass transfer in the B14 model are significant already during hydrogen burning on the ZAMS, due to the very short distance between the stars in the system, this has a strong effect on the final helium core mass (which is reduced) and the chemical composition of the exploding core. The final oxygen mass in the core of the B14 model is approximately 0.5 M$_\odot$, and in the E16 model it is around 0.3 M$_\odot$. These values are close to each other, but can still be be investigated via late-time nebular spectroscopy, when the supernova ejecta become transparent. The highest quality nebular spectra that were obtained give some support for the lower value for the oxygen mass of iPTF13bvn. A result based on nebular modeling (see Sect. 2.6.1). Similar oxygen mass constraints have been obtained for other SE SNe in the literature (e.g. SN 1993J, SN 2008ax and SN 2011dh.
Figure 2.6: Evolutionary tracks for the binary system for iPTF13bvn suggested by Bersten et al. (2014). The mass of the primary (solid line) is 20 M⊙, and the mass of the secondary (dashed line) is 19 M⊙ in this model. Figure from Bersten et al., 2014.

by Jerkstrand et al., 2015, and PTF12os in Paper II). When very late post-explosion imaging is introduced as a constraint on the companion such as in Eldridge & Maund (2016), a lower mass primary (containing < 0.3 M⊙ of oxygen) also seems to be preferred. Further HST observations, that might directly detect the companion\(^3\), in combination with more binary modeling efforts will give further insights and offer even stronger constraints on the progenitor system.

Regardless of minor intricacies and disagreements in the detailed models for iPTF13bvn, the main conclusion from binary modeling efforts of SE SNe is still that it is much simpler to reproduce the average ejecta masses of observed samples of Type IIb/Ib/Ic SNe with these models instead of with single massive stars (see Sect. 2.5 and Sect. 2.7). Binaries can also more easily produce Type IIb SNe with very low mass envelopes, as was seen in SN 2011dh (hydrogen mass < 0.1 M⊙), and also SN 1993J (hydrogen mass < 0.4 M⊙). Furthermore, observational evidence for the binarity of Type IIb SN progenitors exists; the binary companion of SN 1993J has likely been directly observed in post-explosion imaging (see Sect. 2.3, Maund & Smartt, 2009 and Fox et al., 2014). A similar observation might be obtained very soon for iPTF13bvn.

The binary models by Yoon et al. (2010) (and the specific models for iPTF13bvn suggested by Bersten et al., 2014 and Eldridge & Maund, 2016), also predict the radius of the SN progenitor to be significantly

\(^3\)In the Eldridge & Maund (2016) observations the post-explosion images where most likely still dominated by SN light.
larger compared to single star models. Binary models of Type Ib SNe typically have radii of several tens of solar radii at the time of explosion, while massive single star models tend to have radii \(< 10 \, R_\odot\) (Groh et al., 2013b). Type Ic SNe especially tend to have radii even \(< 1 \, R_\odot\) in massive star models. In contrast, binary models for Type IIb SNe typically have \(100 - 200 \, R_\odot\) radii. Note that differences in radius of the progenitors is observationally testable via early time LCs (Sect. 2.5).

2.3 Progenitor detections and observations

The most definitive way to disentangle between massive and binary star progenitor scenarios for SE SNe, would be to directly make observations of the progenitor systems both before the SN explosions and a long time after the SN faded. This can, with deep enough observations, show that the progenitor star either disappeared completely, which would be expected for a massive star progenitor, or that there is
something remaining at the SN position, which could be a binary companion if it is still intact and bright enough.

With current instruments, observations like this require a very nearby SN, ideally closer than $\sim 30$ Mpc, in order to have any chance of detecting a possible SE SN binary companion (see e.g. the predicted binary companion photometry for iPTF13bvn by Eldridge et al., 2015; Eldridge & Maund, 2016 and the discussion therein). Furthermore, the position where the SN exploded must have been previously observed in great detail (typically only possible if there are HST archival images of the position prior to the SN). Because of these limitations, there has been a very limited number of successful SE SN progenitor observations. A number of searches, mostly based on HST imaging, have been attempted (e.g. Barth et al., 1996; Van Dyk et al., 2003; Gal-Yam et al., 2005; Maund & Smartt, 2005; Crockett et al., 2007, 2008a,b; Eldridge et al., 2013; Elias-Rosa et al., 2013; Van Dyk et al., 2016). However, thus far only two Type IIb SN progenitors have been successfully identified. Maund & Smartt (2009) and Fox et al. (2014) present direct measurement of flux from a B-type companion star to the progenitor of the Type IIb SN 1993J, and Folatelli et al. (2014) suggest that the flux in (HST) images obtained $\sim 1160$ d past the explosion is consistent with a suitable binary companion to SN 2011dh (however, note that Maund et al., 2015 disagree with this conclusion).

Among Type Ibc SNe, the first progenitor detection was only very recently made. This was for the Type Ib SN iPTF13bvn, the main subject of this thesis, which has multiple HST observations of its host galaxy; one of the main reasons for the large interest by the community in this object. Eldridge & Maund (2016) were able to show, using pre and post HST images, that a source at the position of the SN (Cao
et al., 2013, Paper I) has become significantly fainter after the SN exploded, i.e. the progenitor system has been directly identified (see Fig. 2.9). However, Eldridge & Maund (2016) also found that the flux at the position of the SN was very likely still dominated by light from the fading SN in the observations. Thus, it is not yet possible to say if the source will disappear completely or if the first binary companion of a Type Ib SN has been detected, although constraints on binary models of the system were already possible (see also Sect. 2.2.2). Future HST observations as the SN fades even more, will hopefully solve this issue. Note that a similar conclusion was later reached by Folatelli et al. (2016).

Also very recently, a search by Van Dyk et al., 2016 for a possible binary companion to SN 1994I, a very nearby Type Ic SN with observables strongly hinting at a binary progenitor, turned out to be unsuccessful, even though this SN is significantly closer than the Type Ib iPTF13bvn. However, the upper limit of the observations roughly coincides with the predicted magnitude of the modeled binary system. Even deeper observations would have been needed to detect the companion directly, or to exclude a binary system as a possibility. If the binary companions of most Type Ibc SNe are similarly faint as seems to be the case for SN 1994I, it might be unfeasible to show direct detections with current instruments, unless an exceptionally nearby Type Ibc SN occurs.

Besides the progenitor systems being very faint, another significant challenge that presents itself when trying to identify progenitor candidates of SE SNe (and SNe in general) is to determine the exact position of the SN explosion in a pre-explosion image, to search for the progenitor. In the case of iPTF13bvn, Cao et al. (2013) initially suggested a progenitor candidate that was within a $2\sigma$ error circle of the position of the SN explosion, found via comparing ground-based adaptive optics images of iPTF13bvn to pre-explosion HST images. Later (in Paper I), we were able to use HST pre-explosion images from 2004 along with HST images of the SN itself to constrain the center of the SN explosion down to 0.2 HST pixels, which corresponds to a projected distance of 1 pc. The same source as suggested by Cao et al. (2013) was centered in our $5\sigma$ error circle, and it was the only source present within the error circle, i.e. we obtained a very robust progenitor identification (shown in detail in Fig. 2.10). The progenitor identification for iPTF13bvn found in Paper I was made possible using procedures developed in MATLAB. In this procedure common point-sources between the pre- and post-explosion images are very accurately centered using 2-dimensional gaussians (that can also be rotated). After the centers of a large number of common sources close to the position of the SN have been determined, a second-order geometric

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4Also later confirmed by Eldridge et al. (2015).
Figure 2.10: Progenitor identification of iPTF13bvn using an *HST* pre-explosion image (right panels) and an *HST* image of the SN itself (left panels). The position of the SN is marked by a red circle with a radius that represents a 5σ uncertainty in the position determination. Sources used for the registration of the images are marked by black diamonds. Figure from Paper I

transformation (with 6 free parameters) is applied to one of the images to put the centers of the sources at the same coordinates, or pixels in the transformed image as in the other image (see Paper I or Paper II for a detailed description).

Note that the absolute magnitudes and colors of the progenitor candidate to iPTF13bvn were shown by both Cao et al. (2013) and Groh et al. (2013a) to possibly be consistent with a massive WR progenitor star (Sect. 2.2.1). However, binary models have since also been able to reproduce the observed photometry (Bersten et al., 2014; Eldridge et al., 2015; Eldridge & Maund, 2016) with lower mass binary systems (see also Fig. 2.11).

In Paper II we have also used the method from Paper I to determine the position of PTF12os in pre-explosion *HST* images from 2004. From this we successfully located a point-like source at the SN position in the *HST* images. However the photometry of this source was found via population synthesis models to most likely be a cluster of massive stars. It was much too bright even for a supermassive single star progenitor. There was also no change in the pre and post-explosion photometry at the position (see Paper II, and Fig. 2.12). A difference image, where the pre-explosion image was subtracted from the post-explosion image, was also constructed using *hotpants* (Becker, 2015), to confirm this result (see the right panel of Fig. 2.12).
2.3. PROGENITOR DETECTIONS AND OBSERVATIONS

Figure 2.11: HST modeled photometry at the position of iPTF13bvn before (left) and 740 d after the explosion of the primary star. The black solid lines show the pre-explosion photometry and the dashed lines the post-explosion photometry. Colored lines show model predictions for the range of He abundances in the primary, as in Fig. 2.5. Figure from Eldridge & Maund (2016).

Figure 2.12: HST F555W filter pre-explosion (left) and post-explosion imaging (center, 3 years past the explosion) at the position of PTF12os. The right panel shows the pre-explosion image subtracted from the post-explosion image. Figure from Paper II.
2.4 Host galaxies and environments of SE SNe; metallicity studies

The most important observational constraint that can be obtained from studying the hosts of SE SNe is the metallicity of the host galaxies, or local host environments, if the hosts are very nearby and can be resolved such as for the host of PTF12os and iPTF13bvn, NGC 5806. This is because for single massive-star SN progenitors, the metallicity is directly correlated to the line-driven wind mass loss of the progenitor stars. SE SNe from massive stars in high metallicity environments should then logically tend to be more stripped compared to SNe in low-metallicity environments. The metallicity is not as important for binary systems (although it still can have an effect during the phases where the isolated stars would have strong line driven winds), and for SE SNe originating from binaries the metallicity should show a much weaker trend with respect to the SE SN subtypes (see Anderson et al., 2015, for a current review on host galaxy metallicity studies).

By comparing spectra of SN host environments (of H II regions) to model spectra of star-forming regions\(^5\) the age of the gas at the position of a SN can also be determined. This age can be translated to an upper limit on the progenitor mass by comparing with massive star evolution modeling predictions for the time-until explosion, such as those by Groh et al. (2013b). Massive stars have higher pressures in their cores, leading to faster evolution through the various core- and shell-burning stages, and are expected to explode earlier compared to less massive ones.

In SN host-environment studies the metallicity (or usually the oxygen abundance) is typically calculated via spectroscopic observations of the host galaxy center, or at or close to the SN location (if possible) based on strong line diagnostics, using the N2 method presented by Pettini & Pagel (2004). The N2 method uses the spectroscopically measured ratio of the Hα line compared to the [NII] λ 6584 line. We show an example in Fig. 2.13, where a simultaneous three component gaussian fit has been used to isolate the relevant line-ratio. This particular spectrum is of the galaxy center, but the method can be used at any position where the lines are measurable. The same method has been used in Taddia et al. (2013), Taddia et al. (2015a) and Paper II.

Photometry-based methods also exist to estimate the global metallicity of SN hosts, since the metallicity is related to the stellar mass of a galaxy, which is observable via the luminosity (see e.g. Lequeux et al., 1979 and Sanders et al., 2013). However, the global metallicity can significantly deviate from a locally measured one close to a SN position, since there is typically a galaxy-wide gradient in the observed metallicity of a galaxy (see e.g. Pilyugin et al., 2004 for Fig. 2.14 for an example). The observed metallicity gradient also typically appears to vary between otherwise similar galaxies (see e.g. Gusev et al., 2012 and Fig. 2.15). The average gradient of many similar galaxies (e.g. spiral galaxies with strong active star-formation) can still be used in combination with photometric metallicity estimates of the global metallicity to estimate the local metallicity at a certain distance from the galaxy center. However, it has also been shown that small-scale metallicity variations are possible even on scales less than 1 kpc (e.g. Niino et al., 2015). Because of these caveats we will largely focus on studies where local spectroscopic metallicity estimates at or very close to the SN positions have been used, minimizing the effect of interpolation via metallicity gradients.

The first study of the local host metallicities of SE SNe was performed by Thöne et al. (2009), who mapped the metallicity of H II regions in the very nearby galaxy NGC 2770, where three Type Ib SNe have exploded (SN 1999eh, SN 2007uy and SN 2008D). Thöne et al. (2009) found the oxygen abundance at the positions of the three SNe via the N2 method to be \(12 + \log_{10}(O/H) = 8.4 \) dex for SN 2008D, 8.5 dex for SN 2007uy and 8.4 dex for SN 1999eh. These values are slightly subsolar, and equivalent with a metallicity of 0.6–0.7 \(Z_{\odot}\), when using 8.7 dex as the solar value (see e.g. Asplund et al., 2009).

\(^5\)Generated using for example Starburst99 (Leitherer et al., 1999).
In Paper II we performed a very similar study of NGC 5806. In this galaxy three SNe and one giant LBV eruption have been observed. Among the SNe, two are of the SE variety. We found that the metallicity at the position of the Type IIb SN PTF12os and the Type Ib SN iPTF13bvn was $12 + \log_{10}(O/H) = 8.61 \pm 0.18$ dex and $8.67 \pm 0.19$ dex, respectively. Thus, both SNe likely exploded in environments of roughly solar abundance. Using a number of H II regions throughout the galaxy, we also estimated the metallicity gradient of NGC 5806 (see Figs. 1.2 and 2.15), which was consistent with other star forming spirals. However, note that the systematic error in the N2 method can be up to 0.2 dex. Thus, the measurements in Thöne et al. (2009) when considering the average and the errors, would be only very marginally sub-solar, and could certainly be considered to be consistent with our study of the metallicities of SE SNe in NGC 5806. The measurements by Thöne et al. (2009) are in any case not proof that Ib SNe tend to occur in subsolar environments. In order to robustly compare metallicities among the various SE SN subtypes, larger samples of SNe of all subtypes are needed.

A number of statistical sample studies of the metallicity of SE SN hosts have been performed, starting with Anderson et al. (2010), who studied spectra of 74 host H II regions and found tentative evidence for a trend where Type II SNe might originate from progenitors with the lowest metallicity, followed by Type Ib SNe, and finally by Type Ic SNe at the highest metallicities. However, there were considerable overlap between the metallicities of the subclasses when the uncertainty intervals of the measurements were taken into account. Modjaz et al. (2011) investigated the suggested metallicity difference between SE SNe by studying 35 new host-galaxy spectra, and the result was a substantiation of the claim that Type Ic SNe appear to explode from higher metallicity progenitors.

The results from Anderson et al. (2010) and Modjaz et al. (2011) were in beautiful agreement with SE SNe originating from single massive stars, with the metallicity driving the amount of mass loss and envelope stripping (see also Sect. 2.2.1). Leloudas et al. (2011) investigated another set of 20 Type Ibc SNe, and again found some evidence for this trend. However, via a careful analysis of the systematic
uncertainties, it was found that the result was not statistically significant. An upper limit on the average difference in metallicity between Type Ib and Ic SNe of \(~0.1\) dex was derived, showing that even if the suggested trend is real, the difference in metallicity cannot be large. Leloudas et al. (2011) also used stellar population synthesis to constrain the ages of the observed H\(_2\) regions, and found evidence that some of them were old enough that massive stars (> 25 M\(_\odot\)) that could produce SE SNe should have already exploded a long time ago. This was interpreted as evidence for some SE SNe originating from binaries (which explode later since their initial mass is lower leading to slower core evolution, see also Sect. 2.2.2).

Kelly & Kirshner (2012)\(^6\) investigated a large sample of SDSS host galaxy spectra of CC SNe (found mostly in targeted surveys), and found that both Type Ic-BL and Type Ib SNe tend to occur at lower metallicities compared to Type Ib and Ic SNe. The Type Ic-BL finding was statistically significant even in a sample restricted to only untargeted SNe. There was no statistically significant difference in the metallicity between Type Ib and Type Ic SN progenitor environments, in agreement with the result by Leloudas et al. (2011).

\(^6\)Note that this study does not measure the local metallicities directly as close to the SNe as possible. It is based on SDSS spectra at the center of their hosts, but has a very large sample size compared to other studies.
Figure 2.15: Metallicity measurements (solid circles), metallicity estimates (open circles), and gradient estimate (solid red line) for NGC 5806 compared to a sample of spiral galaxies (gray dashed lines, from Gusev et al., 2012). The dashed blue line shows a first-order polynomial fit which includes the central oxygen metallicity of the galaxy, and the dashed red line shows the same fit with the central metallicity excluded. Figure and caption adapted from Paper II.

In the study by Kelly & Kirshner (2012) it was also found that Type IIb SNe tend to happen in exceptionally blue regions (photometric colors) at large distances from the host galaxy center, leading to a low metallicity due to the galaxy gradients. Type Ic-BL were typically found in blue and faint lower mass galaxies, which also results in lower metallicity, via the mass-luminosity relation. Thus, while the metallicities appeared similar for Type IIb and Type Ic-BL SNe, they seemed to explode in quite different hosts. A faint and blue host would be expected to produce more massive SN progenitors, since the age found via population synthesis would typically be lower. However, Arcavi et al. (2010) previously found an excess of both Type Ic-BL and Type IIb SNe in dwarf hosts. This result was based on the PTF CC SN sample, and could indicate that some Type IIb SNe might also come from massive stars, which do not have enough metals and mass loss when born in dwarf hosts to become Type Ibc SNe. Another explanation is that SE SN progenitors in binary systems tend to become Type Ib SNe at higher metallicity and Type IIb SNe at lower metallicity, since the last stages in the binary evolution can be dominated by winds from the already highly stripped star. These winds could remove any remaining hydrogen that was not stripped due to tidal interactions. In Paper II we found that PTF12os (IIb) happened in the center of a young and blue H_2 region while iPTF13bvn (Ib) did not explode exactly at the position of any detectable H_2 region, consistent with the picture suggested by Kelly & Kirshner (2012).

In the earliest metallicity studies, most SE SNe that were used were found in targeted surveys, which could potentially lead to strong biases in the metallicity results. This problem was addressed by Sanders et al. (2012) who doubled the previous sample sizes of untargeted local SE SN metallicity estimates. Using 12 Type Ib and 21 Type Ic SNe it was found that the median metallicity of Type Ib SNe was 0.62 Z_⊙ versus 0.83 Z_⊙ for Type Ic SNe. However, this difference was again not statistically significant, and it was shown
that even if the small difference in the medians was true, it would only result in a small difference in the mass-loss due to the line-driven winds (on the order of 30%). Thus, it was suggested that such a weak effect might not be the dominant factor in producing Type Ib or Ic SNe. Sanders et al. (2012) also estimated that the number of Type Ibc SNe needed for a statistically significant result, if the underlying difference is on a 0.1 dex level, as first suggested by Leloudas et al. (2011), would be > 100 objects. Some additional work has since been performed on Type Ib and Type Ic metallicities (e.g. Kuncarayakti et al., 2013). However, even when combining all current and previous studies, we are nowhere close to this number.

In agreement with Kelly & Kirshner (2012), Sanders et al. (2012) also found that Type Ic-BL SNe tend to occur at a statistically significant and lower metallicity of 0.45 Z⊙. When combining all previous local Type Ibc host environment spectroscopy with the Sanders et al. (2012) sample (see the bottom right panel of Fig. 2.16) it was again found that there was no statistically significant difference between Type IIb, Ib and Type Ic SN metallicities. The bottom right panel of Fig. 2.16 does hint at a sequence in the metallicity from Type Ic-BL SNe at the lowest metallicities, then Type IIb SNe, Type Ib SNe and finally Type Ic SNe at the highest metallicities. However, the number of Type IIb SNe with local metallicity estimates is low (5 objects) and thus the Type IIb distribution cannot be considered very reliable. The statistical significance of Type Ic-BL SNe occurring at lower metallicities is reinforced in this combined sample.

Further work on CC SN hosts and metallicities focused on some more particular subclasses have also been performed. Taddia et al. (2013) study the hosts of 87A-like Type II SNe and their metallicities. Modjaz et al. (2008) studied Type Ic-BL host metallicities in detail, finding that Type Ic-BL SNe with associated GRBs are found at the lowest metallicities of all SE SNe, but see also the Type Ic-BL SN host study by Kelly et al. (2014). Taddia et al. (2015a) studied CSM interacting SN host metallicities, and also gathered all the SE SN host environment estimates (not including Type Ic-BL SNe) done using N2 line-diagnostic analysis in the previous literature and compiled them, we show this result in Fig. 2.17. Note the overlap of the Type Ib and Type Ic distributions, and the tentative difference between the Type IIb and Ibc distributions. This difference was again not found to be statistically significant due to the low number (only 5) of Type IIb SNe.

In conclusion, while it was initially suggested, there does not appear to be any statistically significant evidence for a difference in metallicity for Type IIb, Ib and Ic SN progenitors. Much larger sample sizes are needed to prove the minor differences suggested by some of the studies. However, it appears quite certain that Type Ic-BL SNe occur at lower metallicities, and in less massive hosts compared to other SE SNe. Some of the Type Ic-BL SNe are connected with GRBs, and they likely have very massive progenitors. Thus, in my view, Type Ic-BL SNe appear to be very good candidates for very massive progenitor WR stars that evolve according to ZAMS–LBV–WR–SN (as suggested in Sect. 2.2.1). There is also some indication that Type IIb SNe prefer dwarf hosts, but this finding is not reflected in any statistically significant lower metallicity for Type IIb SNe. Thus, it appears that even though metallicity would be expected to have a significant effect, especially for massive star progenitors, the metallicity differences among SE SNe, excluding Type Ic-BL SNe, appear to be rather modest (< 0.2 dex). On the other hand, a large increase in ZAMS mass will greatly increase the stellar wind, an effect that greatly overshadows the effect of a modest difference in metallicity. This scenario would be consistent with most Type Ic-BL SNe occurring at lower metallicities, in younger faint dwarf-host environments that can still produce very massive stars (> 35 M⊙). There is some indication from the lightcurves that Type Ic-BL on average have larger progenitor masses compared to the other SE SN subclasses, and individual Type Ic-BL have been found with very large ejecta masses corresponding to ZAMS masses of > 30 M⊙ (see Sect. 2.5). The lower metallicity for Type Ic-BL progenitors is then just a side-effect of the young environments required. In Paper II we found that iPTF13bvn (Ib) and PTF12os (IIb) occurred in regions of solar metallicity, which
Figure 2.16: Metallicity distributions of SE SNe from spectroscopic metallicity estimates. The bottom-right panel contains the arguably least biased result, and shows only local metallicity measurements. Figure from Sanders et al. (2012).

is roughly consistent with the binary system suggested as the most likely progenitor system for iPTF13bvn by Eldridge & Maund (2016).

One possible explanation for the weak (but still statistically not significant) hints at differences among Type IIb and Type Ibc SNe is that a higher metallicity is needed even for binary systems to remove the last part of the helium envelope to produce a fully stripped Type Ic SN. Another possible explanation is that the samples could contain a mix of both single massive star progenitors and binaries. It could be argued that binary models more easily produce Type IIb SNe, especially, compared to massive star models. Type Ic SNe can be produced for all single stars above a certain ZAMS mass, while there is a narrow mass-range where Type IIb SNe may be produced. This would suggest that the fraction of massive star progenitors compared to binaries increases from Type IIb SNe towards Type Ic SNe. If that is the case, larger samples obtained in the future might be able to constrain these fractions, or if the differences completely disappear, show that most SE SNe except possibly Type Ic-BL SNe really come from progenitors whose evolution is dominated by binary interactions.
2.4.1 Extinction

Another important effect related to the host environments of SNe, is the possible presence of dust in their hosts. Dust in the line-of-sight from the SN to the Milky Way (MW) causes extinction of the SN light. This extinction is wavelength dependent and depends on the dust properties (e.g. chemical composition, grain size, temperature; see Draine, 2003 for a review).

Another (usually minor) contribution to the total extinction comes from the dust in the MW as the light travels through our galaxy towards the Earth. However, the MW component can usually be determined with good accuracy via infrared emission dust maps of the MW (see Schlegel et al., 1998 and Schlafly & Finkbeiner, 2011). Thus, the main concern when studying SNe is the extinction within the SN host galaxies or local host environments, which can be considerable. An attenuation by 90% of the $B$-band flux of a supernova is not unusual. If the extinction of each SN in a sample study is not known, this would cause a large scatter in any analysis based on the photometry (see Sect. 2.5).

For some objects the extinction can be estimated by obtaining high-resolution spectroscopy to investigate the presence of absorption in the Na I D $\lambda\lambda 5890, 5896$ lines. The strength of these lines have been found to correlate with the amount of dust along the line of sight (see e.g. Poznanski et al., 2012). How-
ever, high-resolution observations are time-consuming and require nearby objects. It is also possible to use medium-resolution spectra where the Na I D lines are blended (see e.g. Turatto et al., 2003). However, this correlation has a large scatter (see, e.g. Poznanski et al., 2011, 2012). High-resolution spectra of iPTF13bvn were used by Ca áo et al. (2013) to determine that the host-galaxy extinction of iPTF13bvn appears to be low. We also adopted the results from Ca áo et al. (2013) in Paper I for the extinction of iPTF13bvn.

When dealing with a large sample of SNe in different hosts, methods requiring high-resolution spectra become unfeasible. Medium-resolution estimates are usually also avoided, due to the large scatter in the Turatto et al. (2003), or similar relations. Instead, in particular for SE SNe, photometric (color-based) methods, are currently being researched and used. We developed and used one such method in Paper II to re-calculate the extinction of iPTF13bvn, and to determine the extinction of PTF12os in NGC 5806, by matching the colors of the two SNe to those of SN 2011dh. In a color-based method, the assumption is that the intrinsic temperature (and thus the intrinsic color, see Sect. 2.5) should be very similar, during some epoch for typical SE SNe. In our method we assume that the extinction is known with good accuracy for SN 2011dh (see e.g. Ergon et al., 2014), and then we assume that the temperature or color of iPTF13bvn and PTF12os should be very similar between 5 days before the g-band peak until 15 days after the peak. This choice was a balance of where we had good quality and dense sampling of the LCs of all three SNe, along with comparisons to the observational study by Drout et al. (2011), where it is found that the colors of SE SNe seem to be the most similar at around 10 d after V-band peak. This result is also supported by the hydrodynamical and spectral modeling by Dessart et al. (2016). This is further discussed in Sect. 2.5 and illustrated in Fig. 2.21.

Using the color-based method, described in detail in Paper II, we found a low value of \(E(B - V)_{\text{host}} = 0.08^{+0.07}_{-0.04}\) mag for the host-galaxy extinction of iPTF13bvn. For PTF12os we found \(E(B - V)_{\text{host}} = 0.29^{+0.08}_{-0.05}\) mag. This would attenuate the B-band flux of PTF12os by just under 70%. These results are based on assuming a total extinction \(E(B - V) = 0.07^{+0.07}_{-0.04}\) mag for SN 2011dh (Ergon et al., 2014). For the MW color excess toward NGC 5806 we adopted \(E(B - V)_{\text{MW}} = 0.0437\) mag in Paper II. In Paper I and Paper II we applied all extinction corrections using the Cardelli et al. (1989) extinction law and by assuming \(R_V = 3.1\), which is the average for the MW. \(R_V\) is defined as the total extinction, \(A(V)\), compared to the selective extinction, or \(A(V)/E(B - V)\), where \(E(B - V) = A(B) - A(V)\) and \(A(B)\), \(A(V)\) are the total extinctions in the respective filters.

### 2.5 Light Curves; nickel and ejecta mass constraints

The LCs of SE SNe give us information about the temporal evolution of their luminosity and spectral energy distributions (SEDs; when multi-band observations are available). The LCs and SEDs of SNe can be compared directly using photometry in the individual bands, or using their colors (i.e. photometry in one filter subtracted from another). Comparing colors removes any uncertainties in their distances.

Under the assumption that the emission from a SN is roughly consistent with that of a black-body (BB), BB functions can also be fitted to the observed SEDs for each epoch the SN was observed, allowing temperature and radius evolution comparisons.

In Paper II we compared the multi-band photometry of PTF12os and iPTF13bvn directly with observations of SN 2011dh (e.g. Arcavi et al., 2011, Ergon et al., 2014, Ergon et al., 2015, Jerkstrand et al., 2015). SN 2011dh has been found to be typical in most aspects for a Type IIb SE SN, and we found that all of the photometric filters for both PTF12os and iPTF13bvn evolve in an extraordinarily similar way as for SN 2011dh (see Fig. 2.18). The colors and BB fits were investigated for iPTF13bvn and PTF12os in
Figure 2.18: Multi-band lightcurves of PTF12os (left) and iPTF13bvn (right). The LCs of SN 2011dh are overlaid in each observed filter as dashed black lines. Figure from Paper II.

Paper I and Paper II, with the conclusion that both SNe also had typical color, BB temperature and radius evolutions for SE SNe (see Fig. 2.19 and Fig. 2.20), with the BB temperature peaking around 8500 K and the BB radius at $1.7 \times 10^{15}$ cm. The colors in $g-r$ and $r-i$ are also remarkably similar from around 5 days past the explosions up until at least 25 d past maximum light. Note that this is partly by construction, since the extinction was determined based on the observed colors at similar epochs (Sect. 2.4.1). However, even outside this interval, only minor variations can be seen. Note also that in the first multi-band sample study of SE SNe, containing 25 Ibc SNe, by Drout et al. (2011), a very similar result was found for the color evolution of the sample. Type Ibc SNe seem to have very uniform colors, with a local minimum in $V-R$ (which is similar to $g-r$) color around 10 days past the peak in the LC, where this color is remarkably similar among different SNe (see the left panel of Fig. 2.21). This result has theoretical backing in the modeling efforts by Dessart et al. (2016), who found that most of the models in their grid have a similar ejecta composition and decay-heating rate during this epoch (see the right panel of Fig. 2.21). Observationally, similar results have since been seen in larger samples as well (e.g. Prentice et al., 2016).

Besides comparing the individual LC bands, when studying the LCs of SE SNe, even more powerful constraints can be obtained when observations in many photometric filters, spanning as broad a spectral range as possible, are combined in order to estimate the temporal evolution of the total luminosity originating from the SNe. This is usually referred to as the bolometric light curve. However, to construct a true bolometric LC, observations spanning all the way form the UV to IR are needed to collect most of the light from a SE SN. This kind of coverage is only possible for very few nearby SNe, with one example being SN 2011dh in M 51. Instead, a limited wavelength coverage is typically used to construct quasi-bolometric LCs, using for example only BVRI filters. The flux that is not included within these filters is then approximated via bolometric corrections, following for example Lyman et al. (2014), or by...
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Figure 2.19: Color evolution of PTF12os (filled circles) and iPTF13bvn (filled squares) and SN 2011dh (open symbols). Figure from Paper II.

Comparison to some well studied SN such as SN 2011dh (see Paper II, which also contains a detailed description on how we used the individual filtered LCs to construct quasi-bolometric and approximated fully bolometric LCs).

One important historical finding from the bolometric LCs of Type I SNe, is that they seem to behave as they are powered by radioactive $^{56}$Ni. Based on Type Ia SN observations it was first thought that $^{254}$Cf was the source of energy, since the late time LCs were declining at a very similar rate as what would be expected for the decay rate of this radioactive element (around 1.5 mag in 100 d, Burbidge et al., 1956). However, it was later shown that when accounting for leakage of some of the gamma-rays produced in the decays through a successively thinning ejecta (due to the expansion), $^{56}$Ni is much more likely to be the energy source (Colgate & McKee, 1969). For SE SNe the behavior is similar. The late-time bolometric LC tails (the LCs following the LC peaks, $\sim 40$ d after the explosions), of the most well-observed SE SNe (e.g. SN 2011dh; Ergon et al., 2014, SN 2008ax; Pastorello et al., 2008, SN 1993J; Richmond et al., 1994), follow a decline-rate that is consistent with the decay-rate expected from partial gamma-ray trapping from $^{56}$Co (77d half-life), which is produced as $^{56}$Ni decays. We found similar behavior for iPTF13bvn and PTF12os in Paper II (Fig. 2.22).

The main use of the approximated bolometric LCs is for comparisons to analytical or hydrodynamical LC models, which can constrain the properties of the explosions (such as the amount of kinetic energy that was released, and the amount of mass that was ejected in the explosions). The amount of ejected mass (the ejecta mass, $M_{ej}$) is related to the mass of the progenitor star immediately prior to the explosion (via an assumed mass for the neutron star remnant, typically 1.4 $M_\odot$). The mass of the SN progenitor star at the time of explosion is a product of the stellar evolution (see Sect. 2.2), and statistical studies of the bolometric LCs can thus give insights into e.g. the binary versus massive star progenitor issue for SE SNe.

When comparing bolometric LCs of SE SNe, the analytical model first developed by Arnett (1982) or some slight variation of this model is typically used (e.g. Valenti et al., 2008). The Arnett (1982) model is designed for SNe powered by radioactive decay, starting with $^{56}$Ni that is synthesized in the explosion of e.g. a SE CC SN. The initial assumptions of the model are that we have a spherical SN ejecta (largely consisting of the material outside the collapsing central iron core of the progenitor star) with mass ($M_{ej}$) that is expanding homologously at a characteristic velocity $v_{ph}$ from a very small initial radius. All of the radioactive nickel with mass ($M_{Ni}$) is placed at the center of the ejecta, and we are in the photospheric
phase (i.e. the diffusion approximation for photons is applicable\(^7\)). The model predicts the total bolometric output from the SN, which is why bolometric LCs are needed for a proper comparison. When fitted to suitable data the model can be used to estimate the ejected nickel mass \(M_{\text{Ni}}\), the ejecta mass \(M_{\text{ej}}\) and the kinetic energy \(E_k\), via \(\frac{\sqrt{2E_k}}{3M_{\text{ej}}} = v_{\text{ph}}^2\) (for a constant density sphere expanding homologously; Lyman et al., 2016). Note that the characteristic velocity \(v_{\text{ph}}\) is an input to the model, and some appropriate value for the SN type must be assumed, or measured from spectra (preferably obtained around the LC peak, see Sect. 2.6).

For detailed equations and descriptions of the Arnett (1982) and Valenti et al. (2008) models see the original references and e.g. Cano (2013) or Lyman et al. (2016), for implementations in practice. When comparing these models with observed bolometric LCs, the main things that can be learned are that the peak of a LC (the peak luminosity) is directly correlated with \(M_{\text{Ni}}\) (see Fig. 2.23), and that the width of the LC peak is correlated to \(M_{\text{ej}}\). However, \(v_{\text{ph}}\) will also affect the LC width with higher expansion velocities resulting in a faster photometric evolution and a narrower LC, which is why this parameter needs to be known initially to obtain meaningful constraints on the ejecta mass and kinetic energy. See also Fig. 2.24 for a visualization.

There has been a number of important statistical studies using bolometric LCs of SE SNe and the Arnett (1982) model (e.g. Drout et al., 2011, Cano, 2013, Taddia et al., 2015b, Lyman et al., 2016, Prentice et al., 2016). In the first study by Drout et al. (2011), the LCs of 25 SE SNe (12 Ib, 10 Ic, and 5 Ic-BL) were investigated, with the conclusion that there seemed to be no statistically significant difference between Type Ib and Type Ic SN LCs. However, the few Type Ic-BL SNe included in the study seemed to be more luminous on average, and their explosions were found to release significantly more kinetic energy. The

\(^7\)In the diffusion approximation, photons travel through the SN ejecta via multiple scatterings. They will not be absorbed before leaving the ejecta, and the path of a photon will be a random walk.
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Figure 2.21: Color evolution of a Type Ibc SN sample (left panel, $N = 25$). Color evolution of a numerical model grid of SE SNe by Dessart et al. (2016). The figure in the left panel is from Drout et al. (2011) and the figure in the right panel is from Dessart et al. (2016).

Figure 2.22: BVRI quasi-bolometric LCs of SN 2011dh (gray circles), PTF12os (blue circles) and iPTF13bvn (red circles). The dotted lines show fits to the decline rates past the LC peaks (black for SN 2011dh, blue for PTF12os and red for iPTF13bvn). The green dotted line is a fit to the points past 85 d for PTF12os only. Figure from Paper II, modified by adding the decay rate of $^{56}$Co as a purple arrow.

results for Type Ic-BL SNe have since been reinforced by all subsequent studies. Type Ic-BL SNe tend to have higher nickel masses and release more kinetic energy ($M_{\text{Ni}} \sim 0.6 \, M_{\odot}$ and $E_k \sim 11 \times 10^{51}$ erg) compared to Type Ibc SNe ($M_{\text{Ni}} \sim 0.3 \, M_{\odot}$ and $E_k \sim 2 \times 10^{51}$ erg). These values are from Taddia et al., 2015b). Type IIb SNe were also studied in the samples by Lyman et al. (2016) and Prentice et al. (2016), with the conclusion that these also seem to be similar to Type Ibc SNe, in all of the explosion parameters that can be deduced from Arnett (1982) model fits to their bolometric LCs.

Note that in terms of ejecta masses (and thus progenitor masses), all SE SN subclasses (including Ic-BL) seem to be very similar, with similar averages and standard deviations. There are some variations between the studies, e.g. Lyman et al. (2016) find ejecta masses in the range $2 - 3 \, M_{\odot}$ and Taddia et al. (2015b) find $M_{ej} = 3.6 - 5.4 \, M_{\odot}$. However, these results depend on a range of assumptions in the modeling approaches; values from different studies cannot be easily compared directly. In any case, there have been no statistically significant differences found, in $M_{ej}$, among any of the SE subclasses in any single study,
that remain robust when accounting for the sample sizes (see e.g. Fig. 2.25).

However, in Cano (2013), Taddia et al. (2015b) and Drout et al. (2011), the average ejecta mass, while not statistically significant, is still the highest in all three studies for Type Ic-BL SNe (especially when including Type Ic-BL SNe with GRBs in Cano, 2013). This could be due to the fact that a number of Type Ic-BL and Type Ic-BL with GRBs show very high ejecta masses (~10 M⊙), e.g. SN 2011bm (Type Ic; Valenti et al., 2012), iPTF15dtg (Type Ic; Taddia et al., 2016a) and SN 1998bw (Type Ic-BL with GRB; Galama et al., 1998). This kind of ejecta mass requires a progenitor star with a ZAMS mass > 30 M⊙.

Among Type Ib SNe there are fewer objects that seem very massive, but a few do exist; e.g. SN 2009jf (Type Ib; Valenti et al., 2011). Among Type IIn SNe, one of the objects with the highest progenitor mass is SN 2003bg (Hamuy et al., 2009). The ejecta mass (~4 M⊙) derived from the bolometric LC of this SN is consistent with a ZAMS mass for the progenitor star of 20 – 25 M⊙. Note that this is exactly in the range where the massive-star models by e.g. Groh et al. (2013b) can produce Type IIn SNe, but still significantly less massive than some of the highest mass Type Ic SNe observed.

In Lyman et al. (2016), some more evidence for Type IIn SN progenitors being, on average, less massive was also found. Type IIn SNe were found to have the lowest ejecta masses, velocities, kinetic energies, nickel masses, and the lowest standard deviations in all of these parameters among the subclasses, all at the same time. Individually the differences are not statistically significant when compared to the other subclasses, but they still offer a hint at some difference between the Type IIn subclass and the rest of the SE SN subclasses.

In my view, this finding is consistent with the metallicity studies indicating that Type IIn SNe are found at a systematically lower metallicity compared to the other subclasses (see Sect. 2.4). The lower metallicities in combination with the smaller standard deviations on all of the explosion parameters hint at Type IIn SNe coming from a rather specific progenitor system configuration, with low mass and low metallicity. This line of reasoning indicates that the Type IIn sample in Lyman et al. (2016) contains fewer
SNe with massive single star progenitors, compared to the other SE SN samples in the study, since the larger masses expected for massive star progenitors would likely increase the standard deviation of the Type IIb sample. However, typically a mass range of 20-25 \( M_\odot \) is where Type IIb SNe can be produced (Groh et al., 2013b). Higher masses give rise to Type Ib or Type Ic SNe. Thus, even if some Type IIb SNe come from massive stars, the ejecta masses of a sample would still not be very high, and with less spread in the distributions compared to the Type Ibc and Type Ic-BL subclasses. If massive stars are completely excluded as Type IIb progenitors, another possible explanation for the low standard deviation in the Type IIb sample could be that binaries in low-metallicity environments cannot produce completely hydrogen stripped Type Ib SNe below some metallicity threshold. In this case there would be strict requirements for both the environment and the binary configuration (the orbital period and Roche lobes must be such that a thin hydrogen layer must remain at the time of explosion). These requirements would then result in a narrower mass range for plausible Type IIb binary progenitors compared to Type Ibc progenitors, which would in turn cause less spread in the observed bolometric LCs. However, detailed binary evolutionary modeling in combination with stellar population synthesis models is needed to prove this hypothesis. Future bolometric LC sample studies will be able to shine more light on such small but possibly important differences between the subclasses as the sample sizes increase. Note also that a caveat when studying the ejecta masses is that it is typically assumed that there is no significant fallback onto the compact remnant formed by the collapsing core in the SN explosion. If a significant amount of material typically would fall back onto the remnant, this would affect the ZAMS mass derived from the ejecta mass found from the
widths of the observed bolometric LCs. It is thought that the GRB produced in connection with some Type Ic-BL SNe are a result of fallback onto a central black hole; the ZAMS masses might be systematically underestimated for these objects (and possibly also other SE SN subclasses).

In the study by Cano (2013), the very well observed GRB SN 1998bw was used as a template to constrain the explosion parameters for the SNe in the sample. This was done by stretching and scaling the individual filtered LCs of SN 1998bw to fit the LCs in the available photometric bands for each SN in the sample. In this approach, the Arnett (1982) model only needed to be fit once to the bolometric LC of SN 1998bw, and bolometric corrections for individual objects is avoided. The stretch and scale factors found for each individual photometric band for each SN was then used to scale the results on the explosion parameters for SN 1998bw. In Paper I we adopted a variation of this approach to constrain the explosion parameters of iPTF13bvn. However, instead of finding the scale and stretch factor for each individual band we used quasi-bolometric BVRI LCs of iPTF13bvn and SN 1998bw to find the stretch and scale factors. We show an updated result, with the distance to NGC 5806 from Paper II, in Fig. 2.26, with the stretch (k=0.18) and scale (s=0.8) factors found for SN 1998bw to achieve an excellent match to the LC of iPTF13bvn. These factors correspond to $M_{Ni} = 0.075 \pm 0.025 M_\odot$ and $M_{ej} = 1.66 \pm 0.28 M_\odot$, and the latter was the main finding that led us to the conclusion that this SN could not come from a massive WR star, as previously suggested by Cao et al. (2013) and Groh et al. (2013a). Note also that this was a remarkably similar result to those obtained by our hydrodynamical models for both iPTF13bvn and PTF12os in Paper II (see Sect. 2.7). This is not unexpected since the multi-band LCs and ejecta velocities (see Sect. 2.6) of PTF12os are extremely similar to those of iPTF13bvn and SN 2011dh (see Fig. 2.18). The bolometric LCs of these three SNe are shown in Fig. 2.22. Based on the comparison of the quasi-bolometric BVRI LCs in this figure we can already conclude that the explosion parameters for iPTF13bvn and PTF12os were typical for a Type IIb or Ibc SN, since the three LCs are almost identical. This means that all three SNe ejected far too little mass to have massive star progenitors. Lower mass progenitors in binary systems can on the other hand easily produce progenitor stars that would produce SNe with low enough ejecta masses (see Sect. 2.2.2).
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Figure 2.26: Quasi-bolometric BVRI LC of SN 1998bw (dashed line) stretched and scaled to fit the LC of iPTF13bvn (blue circles). As a comparison we also show the BVRI LC of SN 2011dh (gray circles). The stretch (k) and scale (s) factors found for SN 1998bw correspond to $M_{Ni} = 0.075 \pm 0.025 M_\odot$ and $M_{ej} = 1.66 \pm 0.28 M_\odot$.

2.5.1 Early lightcurves and shock breakout signatures

Recently, with large-scale systematic SN surveys such as the (i)PTF, it has become possible to detect SNe exceedingly early. At very early times it is expected that the emission from CC SNe will be dominated by emission from a cooling ejecta following shock-breakout (see e.g. Colgate, 1974 and Klein & Chevalier, 1978). Immediately following core-collapse, an outward-moving shock is formed which travels through the envelope of the progenitor star. This will heat the envelope behind the shock, and deposit kinetic energy, accelerating it outwards. As the shock approaches the outer parts of the envelope, at some point when the envelope becomes thin enough, photons from the heated material behind the shock will start to be able to escape. This is the shock-breakout, a rapid process where the shock dies out as the ejecta start to cool. The heated material behind the shock can reach very high temperatures ($> 100,000$ K), which will result in ultraviolet or X-ray emission (during the first minutes to hours since the explosion). However, as the temperatures decrease from the cooling, there can also be a significant optical signature (during the first few days). Analytical models describing the early time bolometric emission of SE SNe have been constructed (e.g. Rabinak & Waxman, 2011, Piro & Nakar, 2013 and Piro, 2015).

The cooling emission is stronger for progenitor star with larger radii. For progenitors with radii of a few times $100 R_\odot$ the early LCs will have two peaks. One initial sharp decline from the cooling emission and a second peak from when the $^{56}$Ni-heating starts to dominate. This has been observed in several cases for Type IIb SNe (see. e.g. the LC of SN 1993J, illustrated in Fig. 2.27). The large radius ($\sim 500 R_\odot$) of SN 1993J is due to a thin extended hydrogen envelope remaining around the progenitor. This envelope has
Figure 2.27: Bolometric LC of the Type IIb SN 1993J. Note the initial sharp decline due to shock-breakout cooling of the ejecta followed by the rise to the $^{56}\text{Ni}$-powered LC peak. Figure from Ray et al. (1993).

a very low mass compared to e.g. the envelope of a Type IIP SN, but will still soak up a lot of energy from the SN shock, resulting in the subsequent strong cooling emission. The cooling emission from extended SE SN progenitors has been modeled by Piro, 2015. However, most SE SNe, and especially Type Ibc SNe, are expected to be relatively compact ($< 50 \, R_\odot$, see Sect. 2.2). For such small radii, two distinct peaks will not be seen in the LCs. Instead, it is expected that there should be a period immediately following the collapse of the core, where the optical luminosity of the SN will gradually rise to a plateau, typically 3 – 4 magnitudes fainter than the main bolometric LC peak, with a duration of $\sim 7 \, d$ (Piro & Nakar, 2013, see also Taddia et al., 2015b). The duration of the plateau depends on how the $^{56}\text{Ni}$ is distributed in the ejecta. It could possibly take more than a week before the gamma rays from a centrally distributed $^{56}\text{Ni}$ can start to escape the thick early ejecta before it is diluted by the expansion.

The early LCs of a sample of Type Ibc SNe discovered by the SDSS-II SN survey have been investigated by Taddia et al. (2015b). This study constrains the duration of the plateaus for Type Ic and Ic-BL SNe to no longer than 2 – 4 days, based on pre-explosion non-detections. Note that this implies that a significant amount of $^{56}\text{Ni}$ must be mixed into the outer parts of the ejecta at the time of the explosion. For Type Ib SNe the constraints from this study are somewhat less strict. A plateau was detected based on the early bolometric LC for SN 2006lc (see Fig. 2.28). The duration of this plateau was at least $\sim 6 \, d$. Note that if most Type Ib SNe have initial plateaus of varying durations, it becomes very difficult to predict explosion times, based only on the main $^{56}\text{Ni}$-powered part of their LCs. Extremely early detections will be needed for accurate explosion-time (and radius) estimates. However, the number of objects (both Type Ic and Ib) with direct constraints on the plateau lengths and luminosities is still very low. In the statistical study by Taddia et al. (2015b), it was also found that SE SNe that show He signatures in their spectra (Type Ib SNe) tend to take a longer time to rise to their LC peaks compared to SE SNe that do not (Type Ic and Ic-BL SNe). The typical radius found for Type Ibc progenitors in Taddia et al. (2015b) was $< 30 \, R_\odot$.

The Type Ib SN iPTF13bvn was discovered extremely early by iPTF, at an estimated 0.6 d past the
explosion. Cao et al. (2013) used the early detection, and the Piro & Nakar (2013) model to constrain the radius of iPTF13bvn to only $1.5 \, R_\odot$, which was used as an argument to suggest a WR star progenitor to the SN. However, at the earliest epoch where iPTF13bvn was detected, there are only photometric observations, in the $R$ band, from the P48. Multi-band coverage started at approximately 2 days past the explosion. It was also not yet known that the later bolometric LCs would not match a WR star progenitor model. Rough estimates for the explosion parameters for a SE SN were also assumed in the Piro & Nakar (2013) equations.

In Paper II we found that the early LCs of iPTF13bvn indicate that the SN ejecta were cooling up to around 3 – 4 d past the explosion (see Fig. 2.29). Evidence for cooling was also seen in the earliest spectra taken at 2.15 d and 2.3 d past the explosion. Thus, we concluded that there was indeed a significant contribution from cooling following shock-breakout to the earliest parts of the LC, even though no plateau or double-peak can be discerned in the LCs. When we also used the explosion parameters derived from the bolometric LCs (see Sect. 2.7), we found that the earliest $R$-band point by itself is not enough to constrain the radius of iPTF13bvn using the Piro & Nakar (2013) model. We could fit radii up to $\sim 30 \, R_\odot$ using only this first $R$-band point. However, by using information about the temperature evolution with a black-body approximation to estimate the emission in the individual photometric bands, we were able to constrain the radius to $\lesssim 10 \, R_\odot$, based on fits to the early temperature evolution and the first epochs of multi-band photometry simultaneously (see Fig. 2.29). This is still a very approximative semi-analytical model, but hints that the progenitor was not as extremely compact as initially thought. It also shows that using early photometry from a single band might not be enough to put very strict constraints on the progenitors of SE SNe. Single massive-star WR SN progenitor models can still be consistent with this radius for Type Ib SNe (Sect. 2.2.1), but it is close to the upper range of the model expectations. Binary models can easily end up with progenitor radii of a few times $10 \, R_\odot$ for Type Ib SNe.

Hydrodynamical modeling has also been used by Bersten et al. (2014) to investigate the radius of iPTF13bvn, with the conclusion that radii of even up to $150 \, R_\odot$ cannot be excluded. The best fitting
radius was on the order of 50 R\(_{\odot}\). Note that only the R-band LC was used for their investigation, which is not extremely constraining by itself, as we showed in Paper II using the Piro & Nakar (2013) model. However, it is interesting that the Eldridge & Maund (2016) binary model utilizing both pre- and post-explosion HST photometry of the progenitor system also predicts a radius of 50 R\(_{\odot}\) for iPTF13bvn.

Finally, we note that for PTF12os, the other SE SN discovered in NGC 5806, the earliest photometric data we were able to obtain (see Paper II), were from an estimated 4 d past the explosion. Color information was obtained a few days later, and this data showed no signs of cooling, and were not sufficient to put any kind of meaningful constraints on the progenitor radius based on the LCs and the Piro & Nakar (2013) model. More early data are critically needed for more SE SNe, to investigate the early-time emission. We stress the importance of upcoming large supernova surveys, such as the ZTF or LSST. These surveys will detect many more objects, and hopefully also even earlier and with more color-information early-on than before.

### 2.6 Spectra and ejecta structure

Spectra of SE SNe are essential for classifying these SNe into their Type IIb, Ib and Ic subclasses (as already discussed in Sect 1.5). Spectral information can also be used to gain detailed information about the ejecta composition and evolution. Higher velocities cause broader features in a spectrum due to the doppler effect, and thus the expansion velocities of the various line-emitting regions in the SN ejecta can be mapped, giving rise to even finer subclassifications, such as the Type Ic versus Type Ic-BL SN classification. To estimate expansion velocities, typically the minimum of the absorption (P-Cygni) feature directly on the blue side of an emission line is used. The Fe II \(\lambda 5169\) line is especially useful. Since this line is formed in the inner parts of the ejecta, it can be used to trace the velocity evolution of the photosphere (see Dessart & Hillier, 2005). The velocity of the photosphere of the expanding ejecta is crucial for modeling the bolometric LCs of SE SNe, as already discussed in Sect. 2.5.

For SE SNe the properties of the He and H lines are naturally also very important, since these lines can give insights about the level, and possibly type, of envelope stripping experienced by the progenitor stars. Typically in early SE SNe spectra the conditions are such that the He I \(\lambda\lambda 5016,5876,6678,7065\) and the...
Figure 2.30: Spectral sequence of PTF12os (top panel). Spectral comparison of PTF12os to iPTF13bvn (Ib) and SN 2011dh (IIb) (bottom panel). Thick dashed lines indicate the central wavelengths of the emission lines at rest, except for the Balmer lines, marked by green dashed lines for an expansion velocity of 14,000 km s$^{-1}$. Figure from Paper II.
Balmer-series (e.g. Hα, Hβ, Hγ, Hδ for Type IIb SNe) dominate. As discussed in Sect 1.5, Type Ic SNe show no helium or hydrogen signatures in their spectra while Type Ib SNe show helium features and Type IIb SNe show both H lines and He lines at early times (Fig. 1.6). In the most simple picture, the spectral differences would be related directly to the presence or lack of these elements in the envelopes of the progenitor stars. However, one possibly important caveat is if the progenitors have experienced different amounts of mixing, which could significantly decrease or increase the signatures from these elements in the outer envelopes prior to the explosions. With regards to the mixing there are two contrasting models. Frey et al. (2013) predicts that Type Ic SNe would be more strongly mixed compared to Type Ib or Type IIb SNe, which would be the least mixed. However, Dessart et al., 2012 suggest that Type Ib would be more strongly mixed than Type Ic SNe.

The most comprehensive spectroscopic studies of SE SN spectra currently available have been performed by Modjaz et al. (2015) who study Type Ic and Type Ic-BL spectra, and Liu et al. (2016) who studied Type IIb, Type Ib and Type Ic spectra. Both studies were based on spectra from the CfA Stripped SN data release (Modjaz et al., 2014). Both absorption velocities and equivalent-widths are studied, based on the detected absorption lines of e.g. He I λλ5876,7065 and Hα lines along with the Fe II λ5169 line (see Fig. 2.30 for a spectral sequence of PTF12os, where all of the lines typically seen in SE SNe are present).

Modjaz et al. (2015) in combination with Liu et al. (2016) show, based on the Fe II λ5169 velocities, that there seems to be a trend in the expansion velocities among the various SE SN subclasses. Type IIb SNe are the slowest, followed by Type Ib SNe, and then Type Ic SNe, and finally Type Ic-BL SNe (see Fig. 2.31). Note that there is considerable overlap in the errors of the measurements in the various comparisons shown in the figure (e.g. Type IIb vs Type Ib). However, Type Ib SNe stay at faster average velocities consistently as a group at all the epochs where average measurements were possible. Similar trends are

Figure 2.31: Fe II λ5169 expansion velocity measurements for Type IIb, Ib, Ic and Ic-BL SNe. Measurements for each individual SN are shown in the top panels, and averages for the samples are shown in the bottom panels. Figures from Modjaz et al. (2015) and Liu et al. (2016).
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Figure 2.32: Equivalent width measurements of He I lines of Type IIb and Type Ib SNe. Figures from Liu et al. (2016).

also seen in the He I lines. Especially the Type Ic-BL velocities are significantly higher compared to the other subclasses, reaching up to 50,000 km s\(^{-1}\); not unexpectedly, since this is what defines this subclass. Note that this velocity trend among the subclasses is likely the cause for the findings that Type Ic-BL and possibly Type Ic tend to have higher explosion energies compared to the other subclasses when their bolometric LCs are modeled based on the observed expansion velocities, since no real differences are seen in e.g. the LC peak widths themselves (see Sect. 2.5).

In terms of the strength (equivalent widths) of the He lines, Liu et al. (2016) find that Type Ib SNe tend to show stronger signatures from the He I \(\lambda5876\) and He I \(\lambda6678\) lines at early times (before 10 days after \(V\)-band maximum, see Fig. 2.32), after which the strengths become similar. However, for the He I \(\lambda7065\) line, Type Ib and Type IIb SNe start out at similar strengths, but at later times the Type IIb SNe in the sample show significantly stronger signatures from this line. In my view, the early evolution of the He I \(\lambda5876\) and He I \(\lambda6678\) lines can be explained if at very early times, emission from the helium-line emitting region is blocked by the surrounding hydrogen envelopes of Type IIb SNe. The significantly stronger emission from He I \(\lambda7065\) in Type IIb SNe at late times, could offer a hint at these SNe being slightly less stripped on average compared to Type Ib SNe. This is not seen in the other He I lines, which could also hint at some other explanation. However, the He I \(\lambda7065\) line is typically the cleanest He I line in SE SN spectra. The He I \(\lambda5876\) can suffer from significant contamination from Na, and the \(\lambda6678\) line often suffer from host-galaxy contamination. Note also that He lines are by definition not present in Type
Figure 2.33: Velocity evolution of PTF12os, iPTF13bvn and SN 2011dh. The velocity evolution of our best-fitting hydrodynamical models of the three SNe are shown as dashed lines. Figure from Paper II.

Ic spectra, which was also found to be the case in the sample studied by Liu et al. (2016), except possibly for weak signatures from the He I λ5876 line.

The mixing issue was also addressed at length by Liu et al. (2016), by comparing model predictions from Dessart et al. (2012) and Frey et al. (2013) to the spectra in their sample. These two models both show that it could be a possibility that a significant amount of He from the outer envelope will be mixed into the deeper layers of the SN progenitor before the explosion, which would weaken any spectral signatures. These models offer contrasting predictions. The Dessart et al. (2012) models predict higher mixing and higher expansion velocities for Type Ib SNe and weaker mixing for Type Ic SNe. The models by Frey et al. (2013) predict higher mixing for Type Ic SNe, where the He that gets mixed into the deeper layers of the progenitor becomes burned into O, physically decreasing the He abundance in the outer layers. In any case the findings by Liu et al. (2016), based on the Fe II λ5169 line (as discussed previously), is in contrast with the predictions by Dessart et al. (2012). There is some support for a stronger O I λ7774 line in Type Ic SNe compared to Type Ib SNe, consistent with the predictions by Frey et al. (2013). However, Liu et al. (2016) still conclude that it seems significantly more likely that there is a real lack of He in Type Ic SNe. Note also that in the modeling effort by Hachinger et al. (2012), it was found that more than 0.06 M⊙ of He cannot be hidden in a SE SN. In our hydrodynamical models of PTF12os, iPTF13bvn and SN 2011dh (Paper II), and also in our hydrodynamical model for iPTF15dtg (Taddia et al., 2016a), we find that all these SNe require a similar and very high amount of mixing to fit their bolometric LCs (see Sect. 2.7).

Detailed spectroscopic analysis of iPTF13bvn and PTF12os can be found in Paper II. The results from the velocity measurements from the He I lines and the Fe II λ5169 line are shown in Fig. 2.33. In general, we found that the velocities and strengths of the He lines are similar among the two SNe, and also very similar to spectra of SN 2011dh. However, after a detailed analysis of the velocity evolution of iPTF13bvn, we found that this SN does show somewhat higher velocities compared to both PTF12os and SN 2011dh. This is seen in several He I lines (λ5876 and λ7065), and especially in the Fe II λ5169 line. At 10 d past the explosion, iPTF13bvn shows an Fe II λ5169 velocity of around 10,000 km s⁻¹, which is among the fastest expanding Type Ib SNe in the Liu et al. (2016) sample. PTF12os shows a velocity of around 8,000 km s⁻¹,
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Figure 2.34: Strength of the Hα absorption of the SE SN sample studied by Liu et al. (2016). Note the strong absorption feature seen in iPTF13bvn, comparable to what is seen in some Type IIb SNe. Figure adapted from Liu et al. (2016).

which is very similar to what was seen in SN 2011dh, and which also puts these two Type IIb SNe in the typical range of Type IIb Fe II λ5169 velocities compared to the Liu et al. (2016) sample.

Binary evolution models in some cases predict that SE SNe otherwise modeled to resemble Type Ib SNe also tend to retain thin hydrogen envelopes at the time of explosion (Yoon et al., 2010). These envelopes would be tinier and less massive than Type IIb SN envelopes, and might not show strong signatures in their spectra (Hachinger et al., 2012). In Liu et al. (2016) the Hα line is studied in detail for both the Type IIb and Type Ib SNe in their sample. From this analysis there was a potentially important conclusion; Type IIb and Type Ib SNe, observationally, seem to have very different equivalent widths of this line at all epochs (see Fig. 2.34). There is a detected absorption feature at the expected position of Hα in both subclasses, which means that the presence of hydrogen also in Type Ib SNe cannot be excluded. However, the clear difference makes it possible to make a Type Ib or Type IIb classification, based on the strength of this line, regardless of the epoch. This is significant, since it was previously though that the Type IIb classification might be time-dependent, since the hydrogen signature disappears after in some cases a very short amount of time (< 30 d past the explosion). Most SNe discovered later than this would then simply tend to be classified as Type Ib or Ic SNe, even though they might have had thin hydrogen envelopes (see Milisavljevic et al., 2013).

In Paper II we studied the Hα line of both PTF12os and iPTF13bvn, and found that there was indeed a possible absorption signature present in iPTF13bvn, indicating that this SN could also have had a thin hydrogen envelope surrounding its progenitor. This signature disappears quickly, after 20 d. We found an almost identical behavior for PTF12os. However, we could not show any signature from other Balmer lines (e.g. Hβ, Hy) in iPTF13bvn, which compelled us to retain the Type Ib classification. In Paper II we also studied near-infrared spectra, and compared them to spectra of the Type IIb SN 2008ax and...
SN 2011dh, with the conclusion that these spectra do not either exclude the presence of a similar amount of hydrogen as seen in SN 2008ax, since the spectra are almost identical (see Paper II). In the study by Liu et al. (2016), iPTF13bvn was also included in the Type Ib sample, and it was found that in terms of the strength of the Hα absorption feature, it is among the three strongest Type Ib SNe in the sample (Fig. 2.34). The Hα feature of iPTF13bvn was again comparable to e.g. SN 2008ax (also included in the sample), possibly indicating that iPTF13bvn is somewhat of an outlier. The rest of the observables of iPTF13bvn are also very similar to Type IIb SNe (e.g. PTF12os and SN 2011dh). In early spectra of PTF12os, signatures from Hα, Hβ and Hγ can all be seen at the same time, showing that there was really hydrogen present in this SN, making it an actual Type IIb SN. We show the regions around Hα and Hβ for selected spectra of PTF12os and iPTF13bvn in Fig. 2.35. See also the spectrum of PTF12os taken at 19.8 d past the explosion shown in the spectral sequence in Fig. 2.30.

It is difficult to put quantitative limits on the hydrogen masses for PTF12os and iPTF13bvn. Simple analytical models or arguments are not sufficient, and detailed numerical modeling is needed, which was beyond the scope of Paper II. However, the hydrogen signatures of e.g. SN 2011dh were much stronger compared to PTF12os or iPTF13bvn, and lasted for at least 90 d. Model spectra of SN 2011dh by Arcavi et al. (2011), estimate a hydrogen mass of 0.024 M⊙, for the progenitor of this SN. It seems safe to assume that the hydrogen masses of PTF12os and iPTF13bvn would be at least lower than this value, since the expansion velocities are roughly comparable. Furthermore, SN 2011dh is among the Type IIb SNe with rather strong Hα signatures. In most Type IIb SNe the hydrogen signatures disappear earlier. This implies that most Type IIb would have comparably low hydrogen masses in their envelopes.

Note that the findings on the Hα absorption strength difference among Type IIb and Type Ib SNe by Liu et al. (2016) would indicate that there is a difference in the envelope masses in these SNe, with Type
2.6. SPECTRA AND EJECTA STRUCTURE

Figure 2.36: Nebular spectra of PTF12os at +215 d (top panel) and iPTF13bvn (middle and bottom panels) compared to nebular models. For PTF12os nebular models with $M_{\text{ZAMS}} = 13 \, M_{\odot}$ (gray line) and $M_{\text{ZAMS}} = 17 \, M_{\odot}$ (red line) are also shown, along with a model scaled in oxygen mass to represent a star with $M_{\text{ZAMS}} = 15 \, M_{\odot}$ (green line, top panel). The observed spectrum of PTF12os is consistent with the model representing $M_{\text{ZAMS}} = 15 \, M_{\odot}$. For iPTF13bvn we show three spectra, one at +251 d (black line, middle panel), one at +345 d (gray line, bottom panel) and one at +346 d (black line, bottom panel). These spectra are consistent with a model having $M_{\text{ZAMS}} = 12 \, M_{\odot}$ (green lines, top and bottom panels).

Figure from Paper II.

Ib SNe likely being less massive. However, the difference in mass would be minor (e.g. consider the hydrogen envelope mass of just 0.02 $M_{\odot}$ derived for SN 2011dh), and would not show up in LC studies (see Sect. 2.5).

2.6.1 Nebular spectroscopy

At epochs beyond $\sim$ 50 d past the explosions of SE SNe, emission lines of [O I] λλ5577, 6300, 6364 along with the O I λ7774 triplet typically start to appear in their spectra. These lines are a tell-tale sign of the presence of heavy elements synthesized in the core of the SN progenitor, indicating that a core-collapse has indeed occurred (see Fig. 2.30, and also the stellar evolution section, Sect. 2.2). As the ejecta continue to expand and thin, as the supernova enters the nebular phase (typically 200 d past the explosion), the [O I] λλ6300, 6364 lines start to completely dominate the SN emission, along with the [Ca II] λλ7291, 7323 lines.

Detailed numerical models of the nebular emission of SE SNe have been constructed by Jerkstrand et al. (2015). These models can be compared with nebular spectra to put strong constraints on especially the oxygen mass at the time of explosion, which in turn constrains the evolution of the progenitor stars. This
was done for SN 1993J, SN 2008ax and SN 2011dh in Jerkstrand et al. (2015), with the result that these SE SNe likely all come from low mass stars with ZAMS masses $< 15 \, M_\odot$. We used the model grids by Jerkstrand et al. (2015) in Paper II to constrain the oxygen mass PTF12os and iPTF13bvn, and we show the results in Fig. 2.36. The best fitting models are shown as green lines in this figure. For iPTF13bvn we fit two epochs simultaneously at 250 d and 345 d past the explosion, and for PTF12os we fitted one epoch at 215 d past the explosion, using the same model. We were able to constrain the oxygen mass of iPTF13bvn to a very low value of $\sim 0.3 \, M_\odot$ using the exact same model as was found to be the optimal model for SN 2011dh in Jerkstrand et al. (2015). This implies a very low ZAMS mass for iPTF13bvn of $\sim 12 \, M_\odot$. For PTF12os we achieved slightly less stringent constraints, with an upper limit of $\lesssim 15 \, M_\odot$ on the ZAMS progenitor mass.

Note that the low ZAMS mass we found for iPTF13bvn assumes that the progenitor star evolved approximately like an isolated star until it leaves the main-sequence. In the binary model for iPTF13bvn by Bersten et al. (2014), a significantly higher initial mass for the exploding star is used ($19 \, M_\odot$). However, since significant mass transfer happens already on the main-sequence, the oxygen mass in the core of the progenitor is reduced to around $0.4 \, M_\odot$ at the time of the explosion. Thus, there is some degeneracy in the possible mass for the progenitor of iPTF13bvn. In the binary system proposed by Eldridge & Maund (2016), a very low mass of $10 - 12 \, M_\odot$ is used, in excellent agreement with our nebular models. This is expected, since the binary mass transfer sets in after the progenitor star leaves the main-sequence in this case. In any case, all SE SNe modeled by the most detailed code available to date (Jerkstrand et al. (2015)), i.e. SN 1993J, SN 2008ax, SN 2011dh, PTF12os and iPTF13bvn, have resulted in very low progenitor masses, that are not consistent with massive star progenitors. Binary progenitor models are again preferred.

In Paper II we also compared the results from the Jerkstrand et al. (2015) models to nebular models of iPTF13bvn and PTF12os based on the codes by Mazzali et al. (2007, 2010). The results from these models were also roughly consistent with low mass ZAMS stars ($< 17 \, M_\odot$) as the progenitors to PTF12os and iPTF13bvn. These codes have been used extensively in the literature to constrain SE SN progenitors based on nebular spectra (e.g. Type Ic SN 2002ap, Mazzali et al., 2002; Type Ic-BL SN 1998bw, Mazzali et al., 2001 and Type IIb SN 2003bg, Mazzali et al., 2009). The model for SN 1998bw results in a very high oxygen mass of at least $2 \, M_\odot$, which is consistent with the high progenitor mass expected for Type Ic-BL, based on their lightcurves (Sect. 2.5) and metallicities (Sect. 2.4).

### 2.7 Hydrodynamical modeling

Along with analytical LC models, such as Arnett (1982) (see Sect. 2.5), more detailed (numerical) hydrodynamical models are also used to model the bolometric LCs of SNe. The first simulations of this type were introduced by Falk & Arnett (1977), and the concepts from this work have since been refined and built upon in order to construct models of varying complexity. For Type Ia SNe, very advanced three-dimensional models now exist, that simulate observed LCs from any arbitrary viewing-angle (Kromer et al., 2016), which are also based on three-dimensional explosion models (e.g. Kromer et al., 2013a, Kromer et al., 2013b). However, for CC SNe, typically one-dimensional radiation hydrodynamics models (such as SNEC; Morozova et al., 2015, and STELLA; Blinnikov & Bartunov, 2011), or diffusion approximation models (e.g. Bersten et al., 2011) are used. In Papers I and II we have utilized a new model (HYDE), originally developed for investigating SN 2011dh (Ergon et al., 2015). This is also a flux-limited diffusion approximation model, and in Paper I and II it was used to explode stars evolved until core-collapse using MESA (Paxton et al., 2010), by thermal energy injection at the center of the progenitor stars.
Since HYDE is one-dimensional, it is possible to calculate a large amount of models. This allows fitting of observed bolometric LCs against model-grids that span a large parameter space, which in turn makes it possible to do a statistical analysis to determine the uncertainty of the solution with respect to the parameters of interest ($M_{ej}$, $M_{Ni}$ and $E_{k}$).

For Paper I, HYDE was used to constrain $M_{ej}$ for iPTF13bvn to a very low value of $M_{ej} < 1.9 M_{\odot}$, including the statistical uncertainty. This confirmed the semi-analytical fit based on comparison to the bolometric LC of SN 1998bw (see Fig. 2.26), and confirmed that the progenitor star could not have been a massive WR star. In Paper II, to allow as direct comparisons as possible of the bolometric LCs, we re-fitted the LCs of iPTF13bvn and SN 2011dh along with the LC of PTF12os, to the same model grid based on bare He-cores evolved until core-collapse with MESA. In doing this we adopted bolometric corrections based on SN 2011dh (see Paper II for details). In the fits to the grid we place equal weights on the early LC (1 d to 40 d past explosion), the LC tail (40 d to 100 d past explosion) and the photospheric velocity evolution measured from the spectra (see Sect. 2.6 and Fig. 2.33). The fits are shown in Fig. 2.37 and Table. 2.2.

We again find that all three SNe are remarkably similar, with similar best-fitting hydrodynamical models. Some discrepancies are seen in the early LCs; both PTF12os and iPTF13bvn rise to peak slightly faster compared to SN 2011dh (requiring higher nickel mixing in our models). The LC tail of PTF12os (beyond ~ 85 d past the explosion), is also declining slightly slower compared to both iPTF13bvn and SN 2011dh. This indicates that the ejecta mass of PTF12os could be somewhat larger than our best-fitting model, since larger ejecta leads to a slower evolution, at the same expansion velocity. This is reflected in a slightly larger upper limit on $M_{ej}$ for PTF12os (Table. 2.2). A similar result was found from spectra obtained in the nebular phase. PTF12os requires a slightly more massive ZAMS star (~ 15 $M_{\odot}$), compared to ~ 12 $M_{\odot}$) for iPTF13bvn and SN 2011dh to explain the observed late-time oxygen emission (see Sect. 2.6.1). Note that a ZAMS star with mass ~ 15 $M_{\odot}$ would produce an ejecta mass that is still consistent with the upper limit from our hydrodynamical model.

Similarly as for the semi-analytical LC analysis in Sect. 2.5, we also find the $^{56}$Ni masses derived from our hydrodynamical models to be virtually identical for iPTF13bvn, PTF12os and SN 2011dh (within the range 0.063 ~ 0.075 $M_{\odot}$). This is very close to the average for SE SNe (see Sect. 2.5). In terms of explosion energy, iPTF13bvn shows a somewhat higher value, likely due to the slightly higher observed expansion velocities. However, when the statistical uncertainties are taken into account, the difference is

![Figure 2.37: Approximated fully bolometric LCs of SN 2011dh (gray circles), PTF12os (blue circles) and iPTF13bvn (red circles). The lines show hydrodynamical model fits (gray for SN 2011dh, blue for PTF12os and red for iPTF13bvn). Figure adapted from Paper II.](Image)
not significant. In any case, there is a remarkable similarity of the bolometric properties of these three SE SNe. Especially since the similarity of iPTF13bvn and PTF12os is quite certain; we know that they occurred in the same host, at the same distance from us.

Table 2.2: Explosion parameters for PTF12os, iPTF13bvn and SN 2011dh computed with HYDE.

<table>
<thead>
<tr>
<th>SN</th>
<th>(M_{\text{He}} (M_\odot))</th>
<th>(E (10^{51} \text{ erg}))</th>
<th>(M_{\text{Ni}} (M_\odot))</th>
<th>(\text{Mix}_{\text{Ni}})</th>
</tr>
</thead>
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<td>SN 2011dh</td>
<td>3.31^{+0.53}_{-0.57}</td>
<td>0.64^{+0.38}_{-0.31}</td>
<td>0.075^{+0.028}_{-0.020}</td>
<td>1.05^{+0.08}_{-0.00}</td>
</tr>
<tr>
<td>PTF12os</td>
<td>3.25^{+0.77}_{-0.56}</td>
<td>0.54^{+0.41}_{-0.25}</td>
<td>0.063^{+0.020}_{-0.011}</td>
<td>1.55^{+0.07}_{-0.16}</td>
</tr>
<tr>
<td>iPTF13bvn</td>
<td>3.38^{+0.57}_{-0.50}</td>
<td>0.94^{+0.63}_{-0.43}</td>
<td>0.072^{+0.024}_{-0.016}</td>
<td>1.28^{+0.46}_{-0.00}</td>
</tr>
</tbody>
</table>
Conclusions and future outlook

We have investigated two SE SNe (iPTF13bvn and PTF12os) that occurred in the same host-galaxy (NGC 5806) in great detail, finding that they are remarkably similar in all observable aspects. Compared to larger samples of SE SNe, the physical parameters (synthesized $^{56}$Ni mass, the ejecta mass and the explosion energy) that can be derived from the observed LCs and spectra are very close to the averages observed for Type IIb or Type Ibc SNe. Thus, the main conclusion from the work presented in this thesis is that it is very unlikely that iPTF13bvn could have been the explosion of a massive WR star, as initially suggested by Cao et al. (2013) and Groh et al. (2013a). Since PTF12os is similar in all aspects, the same should be true also for this SN. We instead propose that both SNe originated from binary systems (likely very similar to the system proposed for iPTF13bvn by Eldridge & Maund, 2016).

The exceptional spectral and photometric coverage that enabled our work presented in Papers I and II also made it possible to find some very minor, but possibly important discrepancies, especially when aided by comparison to the even more well-observed SN 2011dh. From the Fe $\lambda$5169 absorption velocity, we found that the expansion velocity of iPTF13bvn is somewhat higher, compared to SN 2011dh. The bolometric LC of iPTF13bvn also rises to its peak slightly faster. These results are reflected as a somewhat higher explosion energy (the velocities), and a higher $^{56}$Ni mixing (the fast rise) in our hydrodynamical model fits. Given these discrepancies, it might seem surprising that the nebular spectroscopy obtained at $> 300$ d past the explosion can still be virtually identical for both SN 2011dh and iPTF13bvn. If the early time behavior is different it would be logical to assume that the differences would be amplified at later times. However, if we consider three-dimensional explosions where the outer layers are ejected asymmetrically, it might be possible to explain the observed discrepancies; asymmetries at early times when the ejecta are not yet fully transparent might have a larger effect on the observed LCs, depending on the viewing angle with respect to the observer, compared to at later times when the light from all parts of the ejecta is reaching the observer, regardless of the viewing angle. In such a picture it is possible that there really are no real discrepancies in the explosion energy and the amount of mixing for iPTF13bvn and SN 2011dh. This hypothesis is somewhat in contrast with polarimetry observations; e.g. Tanaka et al., 2012 who find different polarization, and likely different geometries and different clumpy ion distributions (i.e. mixing), among different SE SNe. Consistent three-dimensional models of both the core-collapse itself and the subsequent LCs need to be developed to investigate these small discrepancies in detail, similarly as what has been done for Type Ia SNe.

One fundamental difference between iPTF13bvn, PTF12os and SN 2011dh exists; SN 2011dh showed strong spectral signatures of H$\alpha$, H$\beta$, and H$\gamma$, for several months after the explosion, while PTF12os showed H$\alpha$, H$\beta$, and H$\gamma$ for only around 20 d, and iPTF13bvn showed only a possible weak signature from H$\alpha$ during the first 20 days after the explosion. Thus, it appears that the binary configuration at least in some respect must have been different between SN 2011dh and the two SNe studied in Paper II. Either in terms of the dynamics, or the initial properties (e.g. masses, rotation) of the stars. One simple explanation would have been if iPTF13bvn and PTF12os had higher metallicities compared to SN 2011dh. In such a picture, the higher metallicity would allow stronger line-driven winds after the binary interactions have
ceased, which would blow away any small amount of remaining hydrogen during the final stages in the lives of the progenitor stars as they approach core-collapse, even if the initial masses and orbital periods of the binary systems were otherwise identical. In Paper II we found that iPTF13bvn and PTF12os occurred at solar metallicity, and in sample studies it has been found that Type IIb SNe on average have lower metallicities (see Sect. 2.4), which would fit nicely to this picture. Individual metallicity measurements of the environment of SN 2011dh (Van Dyk et al., 2011) are also close to the solar value. However, individual measurements come with large errors, and small scale variations in the host environments are possible. Larger sample studies are needed to investigate the host-environments of SE SNe.

A similar spectroscopic sample study as the one performed by Liu et al. (2016) on the CfA sample of SE SNe would be very interesting to see performed on the spectroscopic datasets collected by the (i)PTF collaborations. This could confirm the findings on the Hα equivalent widths being systematically different between Type Ib and Type IIb SNe at all observed epochs, and give further insights into the stripping mechanisms of SE SNe.

Finally, it would also be of great interest to investigate the properties of a large sample of SE SNe based on a similar methodology as we used in Paper II, by fitting the entire sample of LCs to the same hydrodynamical model grid in a consistent way. This should offer greater accuracy in the derived bolometric properties, compared to the previous semi-analytical sample studies discussed in Sect. 2.5. Especially with the upcoming SN projects such as the ZTF or LSST, robust machinery to analyse large amounts of LCs in a consistent way is needed. ZTF will also discover many more SNe even earlier than what has previously been possible, with many discoveries being comparable to iPTF13bvn or even earlier. This will create a need for new, preferably three-dimensional, numerical models for the early-time LCs to supplement to the semi-analytical and one-dimensional models in use today to obtain constraints on the progenitor radii of Type IIb and Ibc SNe.
In order to produce host-subtracted LCs of SNe detected by the iPTF, various host subtraction photometry pipelines are used for the observations collected by the P48 and P60 telescopes. The pipeline currently in use in a fully automatic mode on the P60 telescope, for both of its imaging cameras (GRBCam, and the Rainbow Camera), was developed as a by-product of doing the research presented in Paper I and Paper II in this thesis. This pipeline, the Fremling automated pipeline (FPipe), can operate in both fully automatic mode by using images obtained by the SDSS (SDSS; Ahn et al., 2014) as the reference image, or in manual mode by operating on reference images provided by the user. The pipeline is described in detail in Paper II, and we give a brief outline of how it operates below. Bias-subtracted and flat-fielded science images are assumed to be the input.

The pipeline starts by constructing a reference image from mosaiced SDSS frames, by stacking them using SWarp (Bertin, 2010), to make sure that the entire field that was observed by the P60 in each science frame is completely covered. The science frames are then registered to the reference mosaics using transformations of increasing complexity depending on the number of common point sources found in the frames. This starts from just a rotation, scaling and shifting for less than 7 common sources, and ends with a third order polynomial transformation for above 25 common sources, which we find necessary in some cases, to achieve an RMS of ~ 0.1 pixels in the registrations. The detection threshold used in SExtractor (Bertin & Arnouts, 1996) is also progressively increased, depending on the number of common sources identified, to maximize the amount of common sources detected while also minimizing the amount of false detections by SExtractor. This is done in an iterative process, and starts from a very low detection threshold and allows up to 6 variations of our registrations to be performed, among which the best combination of RMS and number of sources are identified.

After registration the PSF is estimated in each frame using PSFex (Bertin, 2013). The reference and science frames are PSF matched in pairs using the CPM method (first proposed by Gal-Yam et al., 2008). In the CPM method the PSFs of the science and reference frames are measured empirically, and the PSF of the science frame is convolved with the reference image and the PSF of the reference with the science frame in order to obtain images with the same PSF. PSF photometry is performed on common SDSS stars, to find the zero-points (ZPs) of both frames. The ZPs are then used to put the science and reference frames on an equal intensity scale, after which the reference image is subtracted from the science frame, and the final photometry is measured via a PSF fit at the expected position of the transient. Limits and uncertainties are determined via insertion of artificial sources, and detections are determined from the quality of the fit of the PSF model to the transient (see Paper II for details). For the SEDM adaptation of FPipe we have also added a simulation of the potential photometric error due to the image registrations. This is done by redoing the subtraction process after the registration step for a number of small shifts of the reference image with respect to the science frame, with the shifts corresponding to the RMS of the registrations.
Figure 4.1: Example output from FPipe. The left panel shows a P60 $g$-band observation of a transient discovered in NGC 2770. The center panel shows the SDSS reference image, and the right panel shows the subtraction of the reference from the science image. The PSFs of the images have been matched with the CPM method. The position of the transient is indicated by the teal colored dashed circle in each panel.

The turnaround time for one photometric measurement is on the order of 90 seconds. With most of the processing time being consumed by the iterative registration process. This allows rapid checks of newly discovered transients using the P60 telescope.

Since the method used to match the image PSFs in the pipeline is non-parametric (PSFs are empirically measured), this makes it relatively easy to perform subtractions with science and reference images obtained at different telescopes, as long as the imaging filters are similar. Using SDSS references, a source can typically be followed until $\sim 22$ mag in the $g$ band, if in the outskirts of a galaxy, and to $\sim 21.5$ mag in the center of a galaxy core. These results are based on insertion of simulated transients into the science data in order to determine when the transient can no longer be detected reliably. In Fig. 4.1 we show an example PSF matched observation, a PSF matched SDSS reference image and difference image in the $g$ band of a transient discovered in NGC 2770.

The pipeline has been extensively tested with reference images from the SDSS for the P60. However, both science and reference images from e.g. the NOT, the Liverpool Telescope, the NTT and the Las Cumbres Observatory Global Telescope Network (LCOGT) 1-m and 2-m telescopes have also been successfully used in the pipeline to obtain host-subtracted magnitudes of SNe.
5.1 Paper I; The rise and fall of the Type Ib supernova iPTF13bvn. Not a massive Wolf-Rayet star

In this paper we investigate iPTF13bvn, a SE CC SN in the nearby spiral galaxy NGC 5806. This object was discovered by iPTF very close to the estimated explosion date and was classified as a stripped-envelope CC SN, of Type Ib. Furthermore, a possible progenitor detection in pre-explosion HST images was reported, making this the only SN Ib with such an identification. Based on the luminosity and color of the progenitor candidate, as well as on early-time spectra and photometry of the SN, it was argued that the progenitor candidate is consistent with a single massive WR star. In the paper we analyze a large set of observational data, consisting of multi-band light curves (UBVRI, g′r′i′z′) and optical spectra. A bolometric lightcurve is constructed and we perform hydrodynamical calculations to model this light curve to constrain the synthesized radioactive nickel mass and the total ejecta mass of the SN. We also use HST images of the SN to confirm the location of the progenitor candidate of iPTF13bvn. Based on the hydrodynamical modeling we find the total ejecta mass to be 1.9 M⊙ and the radioactive nickel mass to be 0.05 M⊙ for this SN. We also find that the late-time nebular r′-band luminosity is not consistent with predictions based on the expected oxygen nucleosynthesis in very massive stars. In conclusion, in Paper I we find that the bolometric light curve of iPTF13bvn is not consistent with the previously proposed single massive WR-star progenitor scenario. The total ejecta mass and, in particular, the late-time oxygen emission are both significantly lower than what would be expected from a single WR progenitor with a main-sequence mass of at least 30 M⊙.
5.2 Paper II; PTF12os and iPTF13bvn. Two stripped-envelope supernovae from low-mass progenitors in NGC 5806

In this paper we continue the investigation of iPTF13bvn and we also investigate PTF12os, another SN discovered in the nearby galaxy NGC 5806 by iPTF. These two SNe exploded within roughly 520 days of one another at a similar distance from the host galaxy center, and are both of the stripped-envelope variety. We classify PTF12os as a Type IIb SN, and iPTF13bvn has previously been classified as a Type Ib SN, with a progenitor with zero-age main-sequence (ZAMS) mass below $\sim 17 \, M_\odot$. Because of the nearby host we were presented with a unique opportunity to compare a Type IIb to a Type Ib supernova. In our analysis of the LCs and spectra of the two SNe, we find that our nebular spectroscopy of iPTF13bvn remains consistent with a low-mass progenitor, likely with a ZAMS mass of $\sim 13 \, M_\odot$. Late-time spectroscopy of PTF12os is also consistent with a low ZAMS mass ($\lesssim 15 \, M_\odot$). We use hydrodynamical models based on the LCs and spectral data to show that the progenitor for PTF12os had a compact He-core of $3.25^{+0.77}_{-0.56} \, M_\odot$ and that $0.063^{+0.020}_{-0.011} \, M_\odot$ of strongly mixed $^{56}\text{Ni}$ was synthesized in the explosion which had a total kinetic energy of $0.54^{+0.41}_{-0.25} \times 10^{51} \, \text{erg}$. Semi-analytical arguments based on spectral comparisons to the Type IIb SN 2011dh indicate that the progenitor of PTF12os was surrounded by a thin hydrogen envelope with a mass of $< 0.02 \, R_\odot$. We also find tentative evidence that the progenitor of iPTF13bvn could have been surrounded by a small amount of hydrogen prior to the explosion. In this paper we also present a new automatic reference-subtraction pipeline, the Fremling automated Pipeline (FPipe).


BIBLIOGRAPHY


