Wolf-Rayet Stars
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Wolf-Rayet stars as supernova progenitors

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In this review, I discuss the suitability of massive star progenitors, evolved in isolation or in interacting binaries, for the production of observed supernovae (SNe) IIb, Ib, Ic. These SN types can be explained through variations in composition. The critical need of non-thermal effects to produce He I lines favours low-mass He-rich ejecta (in which ^{56}Ni can be more easily mixed with He) for the production of SNe IIb/Ib, which thus may arise preferentially from moderate-mass donors in interacting binaries. SNe Ic may instead arise from higher mass progenitors, He-poor or not, because their larger CO cores prevent efficient non-thermal excitation of He I lines. However, current single star evolution models tend to produce Wolf-Rayet (WR) stars at death that have a final mass of $> 10\,M_\odot$. Single WR star explosion models produce ejecta that are too massive to match the observed light curve widths and rise times of SNe IIb/Ib/Ic, unless their kinetic energy is *systematically and far greater* than the canonical value of 10^{51} erg. Future work is needed to evaluate the energy/mass degeneracy in light curve properties. Alternatively, a greater mass loss during the WR phase, perhaps in the form of eruptions, as evidenced in SNe Ibn, may reduce the final WR mass. If viable, such explosions would nonetheless favour a SN Ic, not a Ib.

1 Introduction

Since the 80's, supernovae (SNe) Ibc have been associated with the explosion of Wolf-Rayet (WR) stars, resulting from either the single-star or binary-star evolution scenario (see, e.g., Wheeler & Levreault 1985; Ensman & Woosley 1988; Podsiadlowski et al. 1992; Woosley et al. 1995; Crowther 2007; Yoon et al. 2010; Georgy et al. 2012). Their spectroscopic classification as type IIb (presence of both H I and He I lines), Ib (H I lines absent, but presence of He I lines), and Ic (absence of both H I and He I lines) is commonly associated with distinct composition mixtures, hence tied to explosions of WNh, WN, and WC/WO stars, respectively.

SNe owe their extreme luminosity to their large photospheric radii ($\sim 10^{15}$ cm), while their photospheres are cool (5–10 kK). Their radiative flux emerges primarily within the optical range, exhibiting spectral signatures from neutral and once-ionised species. Broad spectral lines reflect the fast expansion of the emitting layers, of the order of 5000–15000 km s^{-1}, depending on time and object. Their spectra are initially composed of P-Cygni profiles, often affected by line overlap due to fast expansion and line blanketing. After a few months and the transition to the nebular phase, the spectra exhibit primarily symmetric broad profiles associated with forbidden lines, while the continuum flux disappears. This evolution from early to late times allows a full scanning of the progenitor envelope, from the surface layers during the photospheric phase to the core layers in the nebular phase.

Both single and close-binary evolution can produce stars with a pre-SN composition compatible with the spectral signatures of SNe IIb, Ib, and Ic. Here, I highlight important differences between them, in particular the pre-SN chemical stratification (e.g., for the production of He I lines) and the final mass (e.g., to match the light curve properties).

2 Numerical tools

With the exception of super-massive stars, all stars more massive initially than $\approx 8\,M_\odot$ eventually form a degenerate core, which inevitably collapses when reaching the Chandrasekhar mass. This gravitational collapse is dynamical and lasts few 100 ms. As the innermost regions reach nuclear density, the material becomes incompressible and the core "bounces". A shock wave forms, but following energy losses (neutrino emission, photo-dissociation), it quickly stalls and turns into a stationary accretion shock. A successful core-collapse SN (CCSN) results if fresh energy (probably in the form of neutrinos) is pumped into the post-shock region, to drive the shock outward all the way to the surface (Woosley & Janka 2005). After shock breakout, radiation pressure gradients accelerate the ejecta until homologous expansion is reached, i.e., all mass shells move at constant speed. In addition, explosive nucleosynthesis behind the shock (where temperatures are $\sim 5\times 10^9$ K during the first second) produce some ^{56}Ni and Si-group elements.

To extract information from SN radiation requires solving an energy problem for a fast-expanding shock-heated stellar envelope. The evolution is controlled by cooling (expansion of all mass shells; radiation leakage from the photosphere), heating (primarily from the radioactive decay of ^{56}Ni, whose half life is comparable to the expansion time scale of the ejecta; recombination), and transport (primarily through the photospheric region).

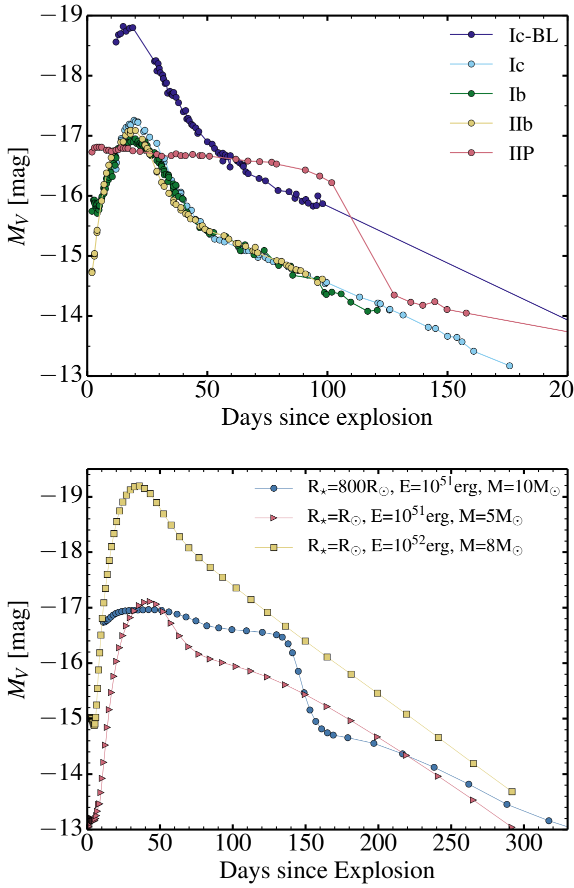

Fig. 1: *Left:* Representative observed light curves for a type II-Plateau (1999em; Leonard et al. 2002), a IIb (2011dh; Pastorello et al. 2009), a Ib (2008D; Modjaz et al. 2009), a Ic (2007gr; Valenti et al. 2008b), and a broad-line Ic (2003jd; Valenti et al. 2008a). *Right:* Light curve diversity obtained with CMFGEN by varying the progenitor massive star and explosion properties (for details, see Dessart et al. 2011, 2013; Dessart et al. in prep.).

One physically consistent approach is to first follow the star (either single or binary) from the main sequence to core collapse with a stellar evolution code (e.g., MESA, Paxton et al. 2015). The dynamical phase of the explosion is then simulated with a radiation-hydrodynamics code (e.g., V1D; Livne 1993; Dessart et al. 2010), using an artificial trigger (piston, thermal bomb), and stopped when homologous expansion is established. The final step is to follow the evolution of the ejecta and the radiation until late times, e.g., with the non local thermodynamic equilibrium (non-LTE) radiative transfer code CMFGEN (Hillier & Miller 1998; Dessart & Hillier 2010; Hillier & Dessart 2012). The code treats time dependence (Dessart & Hillier 2008) and non-thermal processes (Li et al. 2012; Dessart et al. 2012), a unique asset to model SNe IIb/Ib/Ic. It computes the emergent spectrum from the far-UV to the far-IR, thereby allowing a direct comparison to observed multi-band light curves and multi-epoch spectra.

3 Diversity of CCSN light curves

CCSNe exhibit two distinct light curve morphologies. One presents an extended plateau (which in fact may show a range of slopes; Anderson et al. 2014) of about 100 d, the other a bell shape. Both have a typical V-band brightness at maximum of -17 mag (top panel of Fig. 1), which corresponds to a bolometric luminosity of the order of a few 10^8 $L_\odot$.

SNe IIb, Ib, and Ic light curves show a relative uniformity in width (about 20–30 d) and in rise time to optical maximum (about 20–30 d) (Drout et al. 2011). Broad-lined type Ic, characterised by greater-than-average line profile widths, are, in addition, globally more luminous.

These various light curve morphologies are qualitatively well understood (Falk & Arnett 1977; Ensman & Woosley 1988). A large progenitor radius, as typically found in red-supergiant (RSG) stars, is essential to reduce expansion cooling and produce a sustained brightness for a few months, as seen in type II-Plateau SNe. In these, the SN radiation stems from the release of shock-deposited energy. For smaller stars like a WR, the SN luminosity is powered primarily by radioactive decay of ^{56}Ni and ^{56}Co (this power source affects SN II-Plateau light curves too, but primarily at nebular times).

It is therefore chiefly the variation in progenitor radius, rather than mass, that differentiates CCSN light curves (Dessart et al. 2011). The bottom panel of Fig. 1 illustrates the good agreement between more recent models and the observed diversity of CCSN light curves.

4 Constraints from spectra

Figure 2 shows one set of models (others may exist) suitable to produce the types IIb, Ib, and Ic. The properties of these models (see Yoon et al. 2010 and Dessart et al. 2015 for details) are as follows. The SN IIb corresponds to the explosion of the He-rich primary from an initial 5 d-period $16\,M_\odot \oplus 14\,M_\odot$ binary system (model 3p65Ax1). The pre-SN star has $0.005\,M_\odot$ of H at its surface. The SN Ib corresponds to the explosion of the He-rich primary from an initial 10 d-period $25\,M_\odot \oplus 24\,M_\odot$ binary system (model 6p5Ax1). The SNe Ic corresponds to the explosion of the CO-rich He-poor primary from an initial 3 d-period $60\,M_\odot \oplus 40\,M_\odot$ binary system (model 5p11Ax1). The SN IIb/Ib/Ic spectral diversity can thus be well explained by the changes in composition in the spectrum formation region.

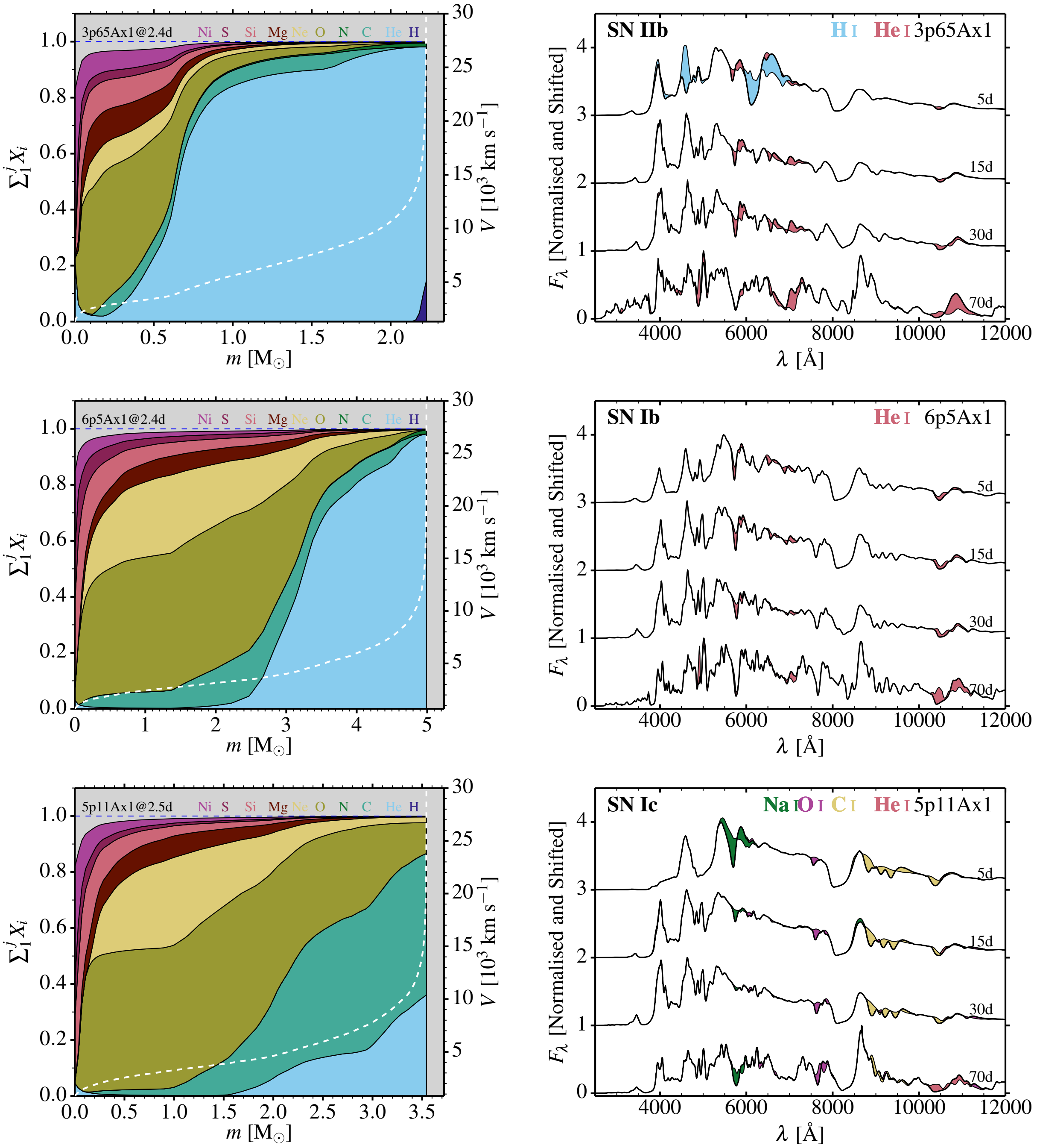

Fig. 2: *Left:* Chemical stratification in mass space for 3 ejecta (the dashed line corresponds to the velocity) suitable to produce a SN IIb (top), a Ib (middle), and a Ic (bottom) – see Dessart et al. (2015) for details. *Right:* Multi-epoch synthetic spectra calculated with CMFGEN and corresponding to the models shown at left. The color coding corresponds to the flux associated with selected ions.

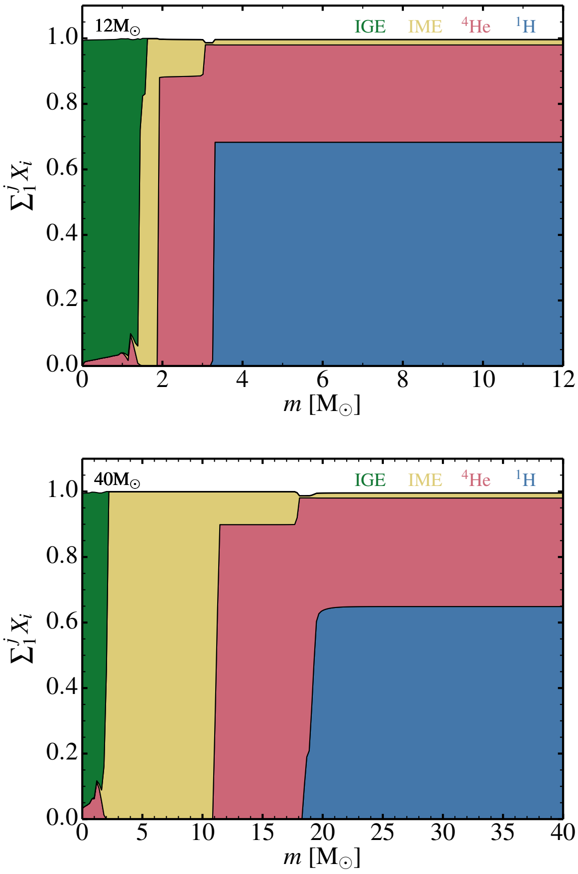

Fig. 3: Illustration of the pre-SN chemical stratification in mass space computed by MESA for a 12 M$_\odot$ and a 40 M$_\odot$ single massive star. IME (IGE) corresponds here to the cumulative mass fraction of intermediate-mass (iron-group) elements. The pre-SN evolution is computed with mass loss disabled.

However, a key problem concerns the production of He I lines. In massive stars (e.g., OB, WR), the photospheric temperatures are large enough to partially ionise He and produce He I and/or He II lines. The cool photospheric temperature of CCSNe prevents this. For example, in SN II-Plateau from RSG star explosions, He I lines are present during the first 2–3 weeks after explosion (when the photosphere is hot), but absent at the recombination epoch (when the photosphere is cool), although the RSG H-rich envelope is ≈ 35% He by mass (Dessart et al. 2008). For the same reason, in SNe IIb, Ib, Ic, He I lines may be absent, even if He is present.

γ-rays emitted by ^{56}Ni–^{56}Co decay produce, through Compton scattering and absorption, high energy electrons that modify the non-LTE state of the gas. The associated non-thermal effects can in theory produce a strong He I line spectrum even at low temperature (Lucy 1991). But the process works only if significant ^{56}Ni is mixed with the He-rich material (Dessart et al. 2012). Because of this sensitivity, a SN IIb/Ib requires both the presence of a large amount of He and the efficient mixing of ^{56}Ni and He. It is not adequate to postulate a SN IIb/Ib classification based solely on the presence of He at the progenitor surface.

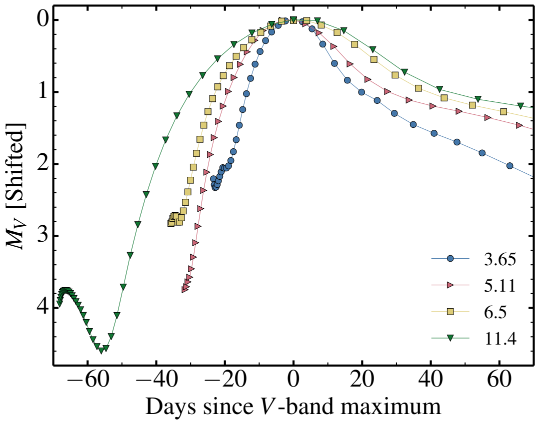

Fig. 4: SNe IIb/Ib/Ic V-band light curves (shifted vertically to peak at 0 mag) for ≈ 10^{51} erg explosions of progenitors arising from moderate-mass interacting binaries (the pre-SN masses are 3.65, 5.11, and 6.5 M$_\odot$) and from a single 40 M$_\odot$ massive star (pre-SN mass of 11.4 M$_\odot$) – see Dessart et al. (2015) for details.

5 Chemical stratification at death

Let us now inspect the pre-SN envelope structure of massive stars at death (Fig. 3) and ask what mass loss is needed to produce the distinct chemical stratifications responsible for the various SN types discussed above.

For the 12 M$_\odot$ model, wind mass loss in a RSG phase would produce a progenitor suitable for a ≈ 10 M$_\odot$ ejecta SN II-Plateau. Mass transfer in an interacting binary could get rid of the H-rich envelope and may produce a ≈ 4 M$_\odot$ bare He core, suitable for a SN IIb/Ib progenitor (see Fig. 2). Weak mixing might instead produce a SN IIc/Ic (see Dessart et al. 2012).

For the 40 M$_\odot$ model, whatever the mass loss, a SN IIb/Ib would require the ejection of ≈ 20 M$_\odot$, although the large CO core would strongly inhibit the non-thermal excitation of He in this case, favouring a SN Ic classification. In contrast, the ejection of a fraction of the CO core would suffice to produce a SN Ic (ejecta mass < 10 M$_\odot$).

We can test the validity of these ejecta masses by confronting the associated light curve properties to observations. For that purpose, we now turn to stellar evolution models with mass loss enabled, through mass transfer in a binary system and/or a wind.

6 Constraints from light curves

Figure 4 shows the V-band light curves computed with CMFGEN for models 3p65Ax1, 5p11Ax1, 6p5Ax1 (produced by binary-star evolution – see Fig. 2), together with the explosion of a single $40\,\mathrm{M}_\odot$ star that dies as a $11.4\,\mathrm{M}_\odot$ WC star. The ejecta kinetic energy is $\approx 10^{51}$ erg for all 4 models.

Is is evident that these light curve widths are compatible with the observed ones, of 20–30 d (Drout et al. 2011), only for the lower mass ejecta models. The mismatch of the higher mass ejecta model reveals the fundamental discrepancy of single WRs (at least, as produced presently in the literature) to match the properties of observed SNe Ibc. In contrast, moderate-mass massive stars in binaries that shed their envelope through mass transfer can produce lower mass ejecta compatible with SN Ibc light curve properties. These objects are quite unlike the typical massive WR stars studied by the massive star community (Crowther 2007).

It is however possible to reconcile massive single WR stars as SN Ibc progenitors. First, one may invoke a larger WR mass loss rate than presently used in the stellar evolution calculations, perhaps in connection to non-steady mass loss observed in SNe Ibn (Pastorello et al. 2007). This would facilitate the trimming of the He core and may allow a reduction of the final mass to a few $\mathrm{M}_\odot$. Another option is to consider that more massive WRs explode and yield ejecta with a systematically larger kinetic energy. Indeed, SN Ibc light curves show a degeneracy with the ratio of kinetic energy over mass (E/M). It is in fact hard to distinguish spectroscopically and photometrically two WR star explosions with a similar E/M (Dessart et al. 2015, in prep.). Both options would, however, make such explosions a SN Ic rather than a SN Ib. Whatever the alternative, single massive WR stars should not produce the SNe IIb/Ib we observe, which should instead arise primarily from moderate mass massive stars in interacting binaries.

An alternate fate of WR stars is that a SN shock explodes the star, but a large fraction of the CO core material falls back onto the neutron star, leading to black hole formation. This trimming of the inner envelope/ejecta would likely deplete the ejecta of its ^{56}Ni-rich material, producing a SN without a ^{56}Ni-powered peak. The shock breakout signal should, however, be detectable in such a “dark” SN.

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Paul Crowther: What does the fact that energetic SNe Ic tend to be rare in giant metal rich hosts and common in dwarf metal poor galaxies tell us about the explosions of massive Wolf-Rayet stars?

Luc Dessart: Highly energetic explosions require a large energy per unit mass in the associated ejecta, significantly greater than the standard for SNe Ibc. This suggests a more efficient engine at the origin of the explosion. A potential explanation is that the higher explosion energy occur from progenitors with a fast-spinning pre-collapse iron core. After collapse, these may turn into a ms-period proto-neutron star, which holds of the order of 10^{52} erg of rotational energy, and this may boost the explosion energy to values far greater than typically expected from standard SNe powered by neutrino energy deposition alone. This larger angular momentum budget in pre-collapse iron cores may exist only at lower metallicity and permit these energetic SNe Ic in dwarf hosts.

Single massive Wolf-Rayet stars are characterized by a large total binding energy, and very flat density profiles above the iron core. Such a structure presents a challenge for explosion because of the large accretion rate during the first second after collapse. So, an intriguing possibility is that single massive Wolf-Rayet stars have a greater tendency to explode in such environments because of the greater explosion energy delivered by faster-spinning cores. In contrast, a standard enery *deposition* (i.e., without the additional contribution from rotation), may simply fail in a massive Wolf-Rayet star.

Jose Groh: It seems that many conclusions on the fate of massive stars depend on the determination of the ejected mass. Could you clarify how the ejected masses are obtained and their uncertainties?

Luc Dessart: One approach is to use a simplistic one-zone diffusion model of the light curve and an estimated expansion rate of the ejecta to determine the explosion properties (this approach derives from the early work of Arnett 1982). This approach is attractive because of its simplicity but it bears numerous uncertainties (fixed opacity independent of composition and ionization; uniform density etc.). Despite these uncertainties, results based on this approach suggest that SNe Ibc ejecta have a low mass of about 2–3 $M_{\odot}$, while highly energetic SNe Ic are more massive.

The other approach is to do detailed time-dependent radiative transfer calculations of the spectra and light curves. As presented in this talk, ejecta masses of 2–3 $M_{\odot}$ are confirmed if one invokes a standard ejecta kinetic energy of 10^{51} erg. For that same energy, a 10 $M_{\odot}$ ejecta from a more massive WR star produces a broader light curve in disagreement with the observed narrower light curves of SNe Ibc. As I emphasize in this talk, light curve and spectral properties have some degeneracy, e.g., ejecta with the same E/M show relatively similar properties.

Overall, and in particular for SNe Ic, it is possible that inferred ejecta masses are not known to better than a factor of two.