Lecture 5: Basics of Core-Collapse Supernova Phenomenology

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Lectures on Core-Collapse Supernovae

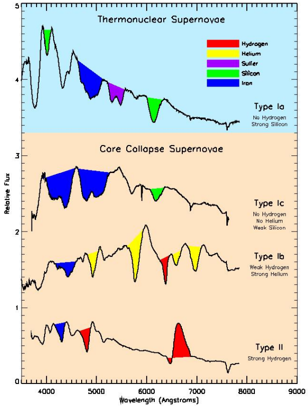
Recommended Reviews

- Branch & Wheeler, “Supernova Explosions”, Springer, Berlin (2017)
- Smartt 2015, Publications of the Astronomical Society of Australia 32 e016

Supernova Types

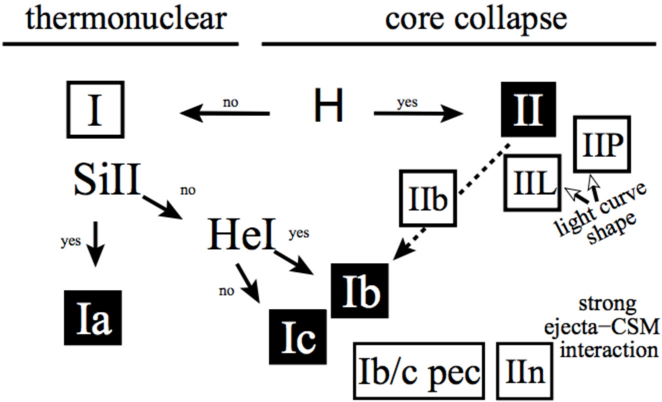
Based on their composition (no H/He spectral features) and environment, one identifies type Ia supernovae as thermonuclear explosions of C/O white dwarfs. The other types (II, Ib, Ic) are associated with explosions of massive stars (core-collapse SNe):

- Type II supernovae (including IIP, IIL, IIb) with H lines are most common, and for a number of them we also have a direct identification of a massive star as progenitor.
- Supernovae of type Ib and Ic have lost (part of) their envelope either by mass transfer in a binary (likely the most frequent case) or by extremely strong winds (Wolf-Rayet stars).



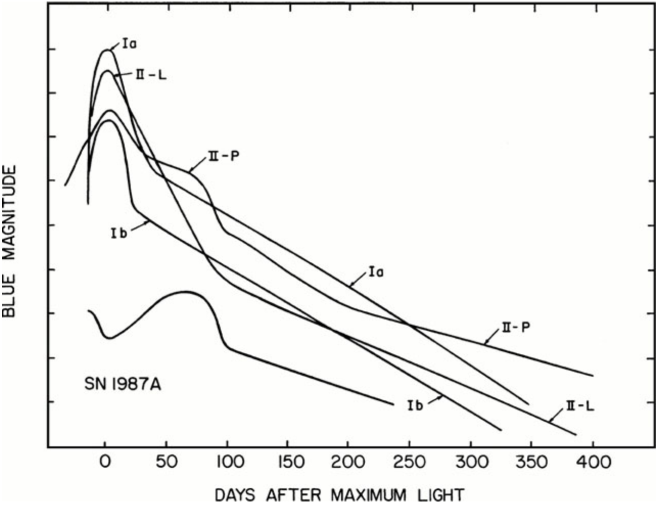
Credit: D. Kasen (https://supernova.lbl.gov/~dnkasen/tutorial/graphics/sn_types.jpg)

Sub-Classification



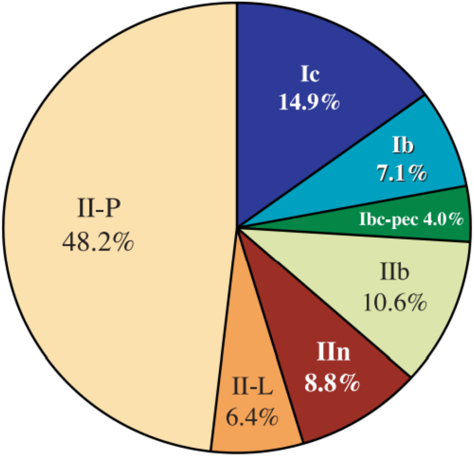
Credit: Turatto (2003)

Light Curves



Credit: Wheeler (1990)

Fraction of Supernovae Types



Smith et al. (2011)

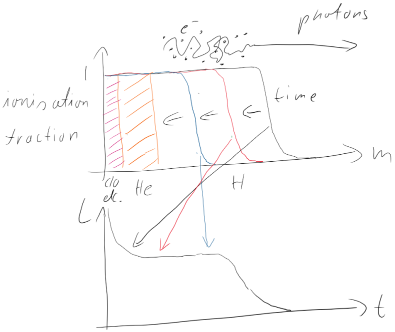
Type IIP Supernovae: Light Curves

The light curves of CCSNe depend both on explosion and progenitor properties. Unfortunately, we can't treat them extensively here, and consider only a few salient points:

- Most frequent type, progenitors with an extended H envelope
- After a brief burst at shock breakout, there is a plateau of a few months. During the plateau, the photosphere recedes through the envelope as hydrogen recombines at 5000–6000 K. Afterwards, there is a tail powered by the decay of $^{56}\mathrm{Ni}$
- Plateau luminosity and duration scale as (Popov 1993)

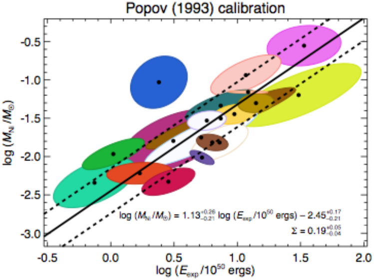
$$L \propto M^{-1/2} R_{\mathrm{prog}}^{2/3} E_{\mathrm{expl}}^{2/3},$$

$$\tau \propto M^{1/2} R_{\mathrm{prog}}^{1/6} E_{\mathrm{expl}}^{-1/6}$$



Type IIP Supernovae: Explosion Properties

- Range of explosion energy from $\sim 10^{50}\,\mathrm{erg}$ to $\sim 2 \times 10^{51}\,\mathrm{erg}$, typical value of $0.9 \times 10^{50}\,\mathrm{erg}$ (Kasen & Woosley 2009)
- Nickel masses are typically a few $0.01 M_\odot$, but may be higher by a factor of several and as low as a few $10^{-3} M_\odot$.
- There is a correlation between explosion energy and nickel mass, and both tend to be correlated with ejecta mass as well.



Pejcha & Prieto (2015)

Type IIP Supernovae: Progenitors

- Red supergiants have been directly identified as progenitors of Type IIP supernovae in some cases.
- The progenitors detections suggest that red supergiants only explode up to 15–18$M_\odot$ ZAMS mass (SMartt 2009, 2015).
- There is now a good case for the disappearance of a massive red supergiant as possible confirmation of collapse to a black hole (Adams et al. 2017).

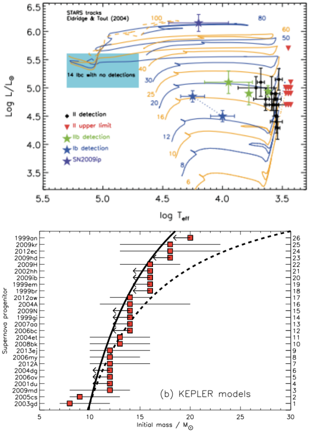
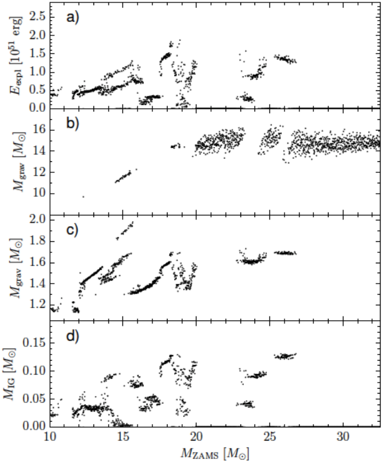


Figure 6. The progenitor detections are marked with error bars (data from Table 1 and the limits are marked with arrows (data from Table 2). The lines are cumulative IMFs with different minimum and maximum masses.

Smartt (2015)

Type IIP Supernovae: Phenomenological Models

- Tuned 1D simulations (with artificial neutrino heating) and semi-analytic models explain the observed patterns of explodability and energetics quite well.
- Transition to black hole (BH) formation is not a sharp cut-off with some BH formation cases down to $\sim 15 M_\odot$ and some explosion even above $20 M_\odot$ (for single stars).
- A correlation between progenitor mass, explosion energy and nickel mass emerges naturally in the neutrino-driven mechanism because of longer accretion onto the PNS in more massive progenitors.



Mueller et al. (2016)

SN 1987A

- SN 1987A in the Large Magellanic Cloud was a Type IIpec (peculiar supernova) of a blue supergiant.
- Due to the more compact envelope, there was not bright plateau.
- Instead there was a dome-shaped light curve during the recombination phase. The brightening was due to radioactive energy release.
- The ejecta mass was in the range 15–20$M_\odot$ and the explosion energy was broadly in the region of $\sim 1.5 \times 10^{50}\,\mathrm{erg}$.
- The blue supergiant nature of the progenitor and other peculiarities like the presence of ring-shaped CSM structures may best be explained by a binary merger (e.g., Podsiadlowski, Joss, & Rappaport 19989; Menon & Heger 2017).
- IIpec supernovae like SN 1987A account for $\sim 1 \ldots 3\%$ of core-collapse supernovae.

Type Ib/c Supernovae – Light Curves

- Mostly powered by radioactive decay, and the peak luminosity can be related to the mass of $^{56}\mathrm{Ni}$, and the width of the light curve
- Arnett's rule $L_\mathrm{peak} \approx \dot{E}_\mathrm{decay}(t_\mathrm{peak})$ (Arnett 1982) holds well for Type Ia supernovae, but tends to overestimate the nickel mass substantially in Ib/c supernovae.
- Explosion energy and ejecta mass influence peak width also for Ib/c SNe.
- Both for Type IIP and Ib/c, light curves usually do not constrain E_expl and M_ejecta very well; supplementary information from the spectra is needed.

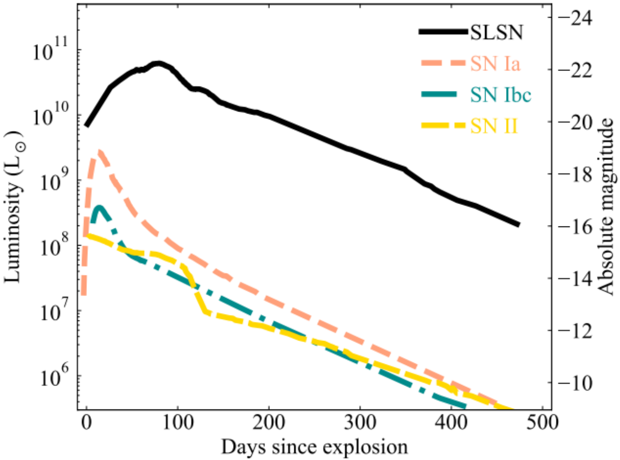
Type Ib/c Supernovae: Observational Findings

- There are still challenges and uncertainties in our understanding of SN Ib/c population properties (e.g., magnitude-limited vs. volume-limited surveys, reliance on Arnett's rule).
- Observations indicate higher Ni masses than in IIP supernovae.
- However, models suggest that an extra power source for the light curve (pulsar/magnetar spin-down) may by needed to explain their luminosity distribution (Ertl et al. 2020).
- Both Ib/c supernova rates and evidence for rather low ejecta masses suggest the majority of Ib/c supernovae come from stripping in binary systems.
- Ic supernovae do not necessarily lack helium. The presence of helium lines is sensitive, e.g., to the mixing of $56\mathrm{Ni}$ (Dessart et al. 2012).

Hypernovae and Gamma-Ray Burst Supernovae

- About 1% of core-collapse supernovae in the local universe are broad-lined Ic supernovae (Ic-BL) or hypernovae with unusually high explosion energies of up to $\sim 10^{52}\,\mathrm{erg}$.
- Some of these are associated with gamma-ray bursts (GRBs), i.e., relativistic jets must be involved.
- Polarisation indicates a pronounced bipolar geometry of the non-relativistic ejecta component as well.
- Both the fraction of broad-lined Ic SNe and GRBs increase at lower metallicity.
- Popular scenarios for hypernovae and GRB supernovae include magnetorotational explosions powered by a "millisecond magnetar" or by an accretion disk around a black hole (collapsar scenario).

Superluminous Supernovae



Credit: Nicholl (2021)

Superlumunious Supernovae (SLSNe)

General references on SLSNe: Gal-Yam 2019 Annual Review of Astronomy and Astrophysics 57, 305; Moriya, Sorokina & Chevalier 2018, Space Science Reviews 214, 59; Nicholl 2021, Astronomy & Geophysics, 62, 5.34.

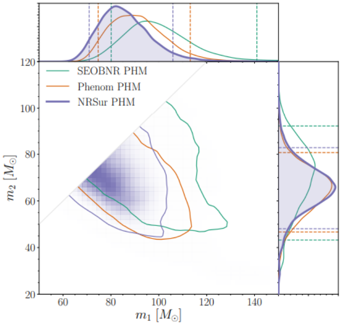
- Supernovae with peak absolute magnitude $M \lesssim -21\,\mathrm{mag}$ are classified as superluminous supernovae
- These are rare if corrected for detectability bias with 10^{-3} or less of all CCSN events (but probably more at low metallicity)
- Most hydrogen-rich SLNSe are IIn supernovae, i.e., there is evidence of interaction with circumstellar material
- The power source for the light curve of hydrogen-free and some hydrogen-rich SLSNe supernovae is less clear.

Physical Scenarios for Superluminous Scenarios

- Type IIn SLSNe clearly involve CSM interaction. The requisite large amount of CSM points to some form of eruptive mass loss, e.g., from LBV eruptions (which are not well understood theoretically) or from pulsational pair instability.
- SLSNe luminosities could be explained by the decay of several $M_\odot$ of $^{56}\mathrm{Ni}$ in a pair instability supernova. However, this would require a slower rise of the light curve than in most SLSNe, and the production of such vast amounts of Fe-group material is not supported by spectroscopy.
- The light curve could be powered by a long-lasting central engine, such as the spin-down of a rapidly rotating magnetar or a fallback disk. One concern about the magentar spin-down scenario is that real magentars are quite frequent ($\gtrsim 10\%$ of newly born neutron stars) and associated with fairly normal supernova remnants.

Pair Instability Supernovae and the Black Hole Mass Distribution

- Because of pulse-driven mass loss or complete disruption by pair instability, a gap in the black hole mass distribution between $50 M_\odot$ and $130 M_\odot$ was expected (Woosley etl al. 2007).
- Both gravitational wave observations (GW190521, Abbott et al. 2020) and electromagnetic observations (Liu et al. 2019) are now challenging this prediction.
- On closer inspection, the upper and lower limit of the gap are subject to substantial physical uncertainties (Woosley & Heger 2021 and references therein).
- Another smoking gun for pair instability supernovae in the early universe would be a strong odd-even pattern in the nucleosynthesis yields (Heger et al. 2005). Traces of such yield patterns in very metal-poor stars have not been identified yet.



Credit: Abbott et al. (2020)

Thank your for your attention!