The Theory of Supernovae in Massive Binaries

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- the majority of massive stars are in interacting binaries
- the large diversity of observed supernova types and (sub-)types is almost certainly caused by the diversity of binary interactions

I. Binary Evolution and the Progenitor Appearance
II. The Fates of Stars in Binaries (vs. Single Stars)
III. Neutron-Star and Black-Hole Formation
IV. [Exotic Supernovae]
Binary Interactions

• most stars are members of binary systems

• a large fraction are members of interacting binaries (30 – 50%)

Sana et al. (2012):

70% for O stars with $M \gtrsim 15 \, M_\odot$

• note: mass transfer is more likely for post-MS systems

• binary interactions
  ▶ common-envelope (CE) evolution
  ▶ stable Roche-lobe overflow
  ▶ binary mergers
  ▶ tidal interactions (de Mink; → Marchant)
  ▶ wind Roche-lobe overflow (case D) (Podsiadlowski & Mohamed 2007; → Pols)

![Classification of Roche-lobe overflow phases](image)
Supernova lightcurves (core collapse)

LIGHTCURVES OF CORE-COLLAPSE SUPERNOVAE

- central explosion may be very similar in all cases (with $E \sim 10^{51}$ ergs)
- variation of lightcurves/supernova subtypes mainly due to varying envelope properties
  - envelope mass: determines thermal diffusion time and length/existence of plateau
  - envelope radius: more compact progenitor $\rightarrow$ more expansion work required $\rightarrow$ dimmer supernova
- binary interactions mainly affect stellar envelopes

Sequence of Mass Loss
SN II-P $\rightarrow$ II-L $\rightarrow$ IIb $\rightarrow$ Ib $\rightarrow$ Ic
Stable Mass Transfer

- mass transfer is ‘largely’ conservative, except at very mass-transfer rates
- mass loss + mass accretion
- the mass loser tends to lose most of its envelope → formation of helium stars → hydrogen-deficient supernovae (II-L, IIb, Ib, Ic)
- the accretor tends to be rejuvenated (i.e. behaves like a more massive star with the evolutionary clock reset)
- orbit generally widens

Unstable Mass Transfer

- dynamical mass transfer → common-envelope and spiral-in phase (mass loser is usually a red giant)
  - mass donor (primary) engulfs secondary
  - spiral-in of the core of the primary and the secondary immersed in a common envelope
- if envelope ejected → very close binary (compact core + secondary)
- otherwise: complete merger of the binary components → formation of a single, rapidly rotating star
PTF Rates

Table 2
Division of SN Types for Each Host-galaxy Class

<table>
<thead>
<tr>
<th>SN Type</th>
<th>No. in Giants (Fraction)</th>
<th>No. in Dwarf(s) (Fraction)</th>
<th>Likelihood</th>
</tr>
</thead>
<tbody>
<tr>
<td>II</td>
<td>42 (0.78±0.06)</td>
<td>9 (0.60±0.14)</td>
<td>6%</td>
</tr>
<tr>
<td>IIb</td>
<td>2 (0.04±0.05)</td>
<td>3 (0.20±0.15)</td>
<td>2%</td>
</tr>
<tr>
<td>Ib</td>
<td>2 (0.04±0.05)</td>
<td>1 (0.07±0.13)</td>
<td>29%</td>
</tr>
<tr>
<td>Ic</td>
<td>7 (0.13±0.05)</td>
<td>0 (0.00±0.05)</td>
<td>7%</td>
</tr>
<tr>
<td>Ic-BL</td>
<td>1 (0.02±0.04)</td>
<td>2 (0.13±0.15)</td>
<td>4%</td>
</tr>
<tr>
<td>Galaxies</td>
<td>55</td>
<td>15</td>
<td></td>
</tr>
</tbody>
</table>

Arcavi et al. (2010)
Podsiadlowski (1989, 1992)
Stripped Supernovae

How much mass remains after mass transfer?

- stable mass transfer
  - mass transfer ends when donor shrinks below Roche lobe
  - remnant H envelope (up to \( \sim 1\, M_\odot \); [Joss & Podsiadlowski 1988; PhP1992])
  - extended, stripped supergiant (SN II-L, extended IIb [SN 93J])
  - **Problem:** not enough? (Podsiadlowski+ 1992; Claeys+ 2011)
  - **Solution:** extend mass transfer parameter space: wind RLOF (case D)

- CE ejection
  - small amount of H left
  - stellar wind can remove H (metallicity dependence; compact SNe IIb vs. SNe Ib)
The SN Ic problem

Caution: there are different types of SNe Ic (broad-lined [engine]; normal SNe Ic’s)

- large fraction of SNe Ic compared to SNe Ib (latest: comparable numbers [Modjaz+ 2015])
- are they He free?
- Hachinger & Mazzali (2012): 
  \( < 0.1 \text{M}_\odot \)
- incompatible with all models
- He non-thermally excited by Ni decay: different mixing in supernovae? (PhP+ 2016)

PhP, Mazzali, Justham
Binary Accretion

On Main Sequence (Case A)

- rejuvenation (8%; de Mink; → Schneider)
- further evolution similar to single star

Post Main Sequence (Case B/C)

- change core to envelope mass ratio
- favours blue solutions (no red supergiant phase) (Podsiadlowski & Joss 1989)
Maund et al. (2004)
### Slow Mergers

Ivanova (2002)

**Example:** SN 1987A

### Dynamical Mergers

Nandez, Ivanova & Lombardi (2014)

Also collisional mergers in clusters
LBV Supernovae from Massive Binary Mergers
Justham, Podsiadlowski & Vink (2014)

- large number of O-star binary mergers (Sana et al. [2012]: 20–30%)
- for sufficiently small core mass fraction
  - with relatively low-mass loss rate
  - transition to the red only after He-core burning
  - possibility of SN explosion in LBV phase
    (with various amounts of H envelope masses)
Dashed sections are after core He exhaustion. Dotted curves show the first 10 kyr after the merger.
- even relatively massive stars may produce neutron stars rather than black holes (low entropy, plus core erosion)
- large diversity of outcomes: yellow supergiants, SNe II, interaction SNe, PISNe

Justham et al. (2014)
Core Collapse Supernovae

Iron core collapse
- inert iron core ($M_{\text{Ch}}$) collapses
  - presently favoured model: delayed neutrino heating to drive explosion

Electron-capture supernovae
- occurs in degenerate ONeMg core
  - at a critical density ($4.5 \times 10^9 \text{ g cm}^{-3}$), corresponding to a critical ONeMg core mass ($1.370 \pm 0.005 \text{ M}_\odot$), electron captures onto $^{24}\text{Mg}$ removes electrons (pressure support!)

  → triggers collapse to form a low-mass neutron star

  note: essentially the whole core collapses
  → easier to eject envelope/produce supernova
  → no significant ejection of heavy elements
Second dredge–up in AGB stars (around 10 Msun)

with H envelope

without H envelope

AGB envelope

CO core

dredge–up of the He core
--- > lower CO core masses
--- > ONeMg WD

(Podsiadlowski et al. 2004)

without dredge–up
--- > larger CO core mass
--- > electron–capture supernova
in ONeMg core
  o lower explosion energy
  o lower supernova kicks
  o NS mass: 1.25 Msun
Binary Evolution Effects

- **dredge-up** in AGB phase may prevent ONeMg core from reaching $M_{\text{crit}} \rightarrow$ ONeMg WD instead of collapse

- can be avoided if H envelope is removed by binary mass transfer
  
  $\rightarrow$ **dichotomous kick scenario**
  
  - e-capture SN in close binaries $\rightarrow$ low kick
  - iron core collapse $\rightarrow$ high kick
Subsequent Work: Single Stars

Arend Jan Poelarends (PhD Thesis):

- examined conditions for e-capture SNe on metallicity, wind mass loss, dredge-up efficiency in AGB stars
- **best model**: no e-capture SN at solar Z
Case BB Mass Transfer and Ultrastripped Supernovae

- low-mass He stars experience case BB mass transfer
- produces ultrastripped SN progenitors with very low ejecta masses ($\sim 0.1 \, M_\odot$)
- produces e-capture supernovae and core-collapse supernovae with very low iron-core masses
→ low-kick neutron stars
He–core–burning stars (M > 20 – 25 Msun)

with H envelope

H–burning shell

helium burning
convective core (growing)

--- larger CO cores with lower
C/O ratio --- no convective carbon burning
higher entropy (more massive) iron cores

---→ BLACK HOLE

without H envelope

No H–burning shell

shrinking
He–burning core

smaller CO cores with higher
C/O ratio --- convective carbon burning
lower entropy (mass) iron cores

----→ NEUTRON STAR (60/70 Msun?)
(Brown, Lee, Heger)
Carbon Burning and Final Fe Core Masses
(Brown et al. 2001)

- late He-core burning: $^{12}\text{C} + \alpha$ becomes dominant and determines the final $^{12}\text{C}$ fraction

- stars with H-burning shell: injection of fresh He $\rightarrow$ long $^{12}\text{C} + \alpha$ phase $\rightarrow$ low final C fraction

- stars without H-burning shell: short $^{12}\text{C} + \alpha$ phase $\rightarrow$ higher final C fraction

- C-core burning:

- high C fraction $\rightarrow$ convective C burning $\rightarrow$ higher neutrino losses $\rightarrow$ lower-entropy cores $\rightarrow$ lower-mass O and ultimately Fe cores $\rightarrow$ neutron stars

- low C fraction $\rightarrow$ radiative C burning $\rightarrow$ lower neutrino losses $\rightarrow$ higher-entropy cores, etc. $\rightarrow$ black holes

Brown, Heger, Langer et al. (2001)
Compactness Parameter

Characterize the possibility of a (neutrino powered) explosion based on a compactness parameter \( (O'\text{Connor and Ott, ApJ, 730, 70 (2011)}) \):

\[
\xi = \frac{M/M_\odot}{R(M)/1000\text{km}}_{t=t_{\text{bounce}}} \quad \text{with } M=2.5M_\odot
\]

\( \xi \) big: \( R \) is small, the 2.5 \( M_\odot \) point lies close in \( \rightarrow \) hard to explode

Based on 1D models: stars with \( \xi \) larger than 0.45 difficult to explode

\( \xi \) for explosion < 0.45

Petermann, Langer & Podsiadlowski (2016)
Compactness Parameter

Petermann, Langer & Podsiadlowski (2016)
Black-Hole Formation

• single stars (case C binaries):
  ▶ fallback black holes (up to 40 $M_{\odot}$?; Fryer): faint supernova, NS-type kick
  ▶ ‘prompt’ black holes: no supernova, no kick

• binaries:
  ▶ may need case C (i.e. very late) mass transfer
  ▶ uncertain range of case C for massive stars (radius evolution, wind mass transfer?)

• accretion-induced collapse of accreting NS in I/LMXB
  ▶ for efficient accretion efficiency → form low-mass black holes in binaries
  ▶ not observed?

• accretion-induced collapse during in-spiral in massive envelope (e.g. Chevalier, Fryer, Brown)
Engine-Driven Supernovae

- **collapsar and magnetar** models for LGRBs and superluminous supernovae require *rapidly rotating, collapsing cores*

- **problem:** massive stars are known to observationally lose their angular momentum efficiently (*spins of WDs, young pulsars, asteroseismology*)

- binary models provide reservoir for angular momentum, in particular when it is extracted late (*case C/D*)

- numerous models

- **typical rates:** $1 : 10^4$ to $1 : 10^3$ per cc SN (*metallicity dependent*)

**MODELS**

- accretion models

- tidal spin-up models

- merger models
  - mergers of two compact stars (*e.g. He+CO stars, He+WD/NS/BH*)
  - merger in common envelope
Importance of Late Mass Transfer (Case C)

- core evolution fixed $\rightarrow$ BH/NS formation
- late spin-up, no spin-down $\rightarrow$ GRB progenitors

**but:** narrow range of **predicted** periods ($\sim 1\%$)

- at low metallicity $\sim 10\%$
- **Note:** present models probably underestimate the range of late mass transfer (case D, etc.)
Rayleigh-Taylor Instabilities and Mixing: Single vs. Binary Progenitors
(Podsiadlowski, Petermann, Langer, Yoon 2016)

• expect different density profiles in single stars and case B binaries
  ▷ single stars (case C binaries): steep $\mu$-gradient outside CO core
  ▷ He stars (case B): shallower gradient outside CO core
→ different Rayleigh-Taylor mixing in resulting supernova

• resolution of the Ib/Ic puzzle? (He non-thermally excited by gamma rays from Ni/Co decay)
  ▷ single stars/case C binaries: mixing of Ni with He $\rightarrow$ SN Ib
  ▷ case B binaries: no mixing $\rightarrow$ SN Ic
Single $21M_\odot$ star

He star from $21M_\odot$ Star (case B, with wind)
Homogeneous Evolution
  de Mink et al. (2009)

- Tidal locking in close binaries $\rightarrow$ rapid rotation $\rightarrow$ homogeneous evolution

- Potential model for
  - LGRBs
  - PISNe
  - BH+BH mergers (Marchant et al. 2016; Mandel, de Mink 2016a/b)

- Requires low $\dot{M}$ (low Z)
  - To avoid widening of orbit
  - To produce massive black holes
Marchant, Langer, Podsiadlowski, Tauris & Moriya (2016)
Cosmological Simulations of Exotic SNe
Lise du Boisson, Podsiadlowski

- use full cosmological simulations to simulate rates of GW sources as a function of z and Z (plus LGRBs, PISNe)
- simulations by Taylor & Kobayashi (2014)
  - self-consistent hydrodynamical simulations with star formation, SN and AGN feedback, and chemical enrichment
  - fit key observables, such as the galaxy mass-metallicity relations, metallicity gradients, etc.

\[^1\]: plus Kobayashi, Taylor, Marchant, Langer, Tauris, Mandel, de Mink

Based on Taylor & Kobayashi (2014)
- can simulate rate as a function of redshift for various events
  - transient surveys
- simulate galaxy correlations similar to observed ones