Progenitors of Type Ibc Supernovae

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Progenitors of Supernovae & GRBs

How do they evolve throughout the cosmic ages?
Pre-SN Evolution of Massive Stars

- $150 < M_{\text{init}} < 250 \ M_{\odot}$: Pair Instability Supernovae (at low $Z$)
- $9 < M_{\text{init}} < 150 \ M_{\odot}$: SNe induced by core-collapse of the iron core
- $M_{\text{init}} \sim 8 - 9 \ M_{\odot}$: SNe induced by electron capture in the Chandrasekhar mass ONeMg core
- $M_{\text{init}} < 8 \ M_{\odot}$: Type Ia Supernovae in close binaries
Smith et al. 2011

Core-Collapse SN Fractions
Pre-SN Evolution of Stars

Metallicity

Initial Mass

Initial Rotation

Diversity of Supernovae/GRB

Mass & Angular Momentum Loss

Exchange of Mass & Angular Momentum

Binarirty
H envelope

core

Arcavi et al. 2012
Evolutionary paths of massive stars to SNe Ibc

- Mass Loss from Single Stars (cf. Conti Scenario)
- Binary Interactions
- Chemically Homogeneous Evolution with rapid rotation (Maeder 87, Yoon & Langer 05, Yoon et al 06, 12, Woosley & Heger 06)

SNe Ibc progenitors are related to all the major factors of massive star evolution
Importance of SNe Ibc in Astrophysics

• Their observational properties give us strong constraints on:
  ✤ History of mass loss from massive stars
  ✤ Binary star evolution
  ✤ Evolution of massive stars at low metallicity and high redshift
  ✤ Role of rotation, and connection to long gamma-ray bursts
Mass Loss
and
Type Ibc Supernovae
Mass loss from massive stars

- Line driven winds: high-Z preferred.
- Pulsations
- Other instabilities

Evolution of stars more massive than about 30 M$_{\odot}$ is dominated by mass loss.

WR stars are generally very bright, but all attempts to directly identify them have failed so far.
In the mass-loss scenario, the final masses are higher than about 8 Msun, but the nature of SN Ibc progenitors at the pre-SN stage look very different from most of the observed WR stars: **They are very compact, hot, and optically faint like WO stars.**

![Graph showing the relationship between log L/L_☉, log T_*, and M_☉ with data points differentiated by X^{12C} and stages (WNL, WNE, WC, WO).](image)
Binary Interactions and Type Ibc Supernovae
Observations indicate that more than 50% of massive stars are in close binary systems.

Sana et al. 2012
Binary interactions can produce relatively low-mass He stars ($2 < M < 10 \, \text{M}_{\odot}$).
mass transfer

low Z

Case A mass transfer

$M_{1,\text{init}} = 18M_\odot$

$M_{2,\text{init}} \approx 17M_\odot$

$P_{\text{init}} = 4\text{d}$

Case AB mass transfer

high Z

SN Ibc

H

He

He

He

He

SN IIb

Yoon et al. 2010
The He envelopes of relatively low-mass SN Ibc progenitors expands rapidly during the final evolutionary phases. 

They should appear fairly luminous in optical bands at the pre-SN stage, despite their low masses (Yoon et al. 2012)

- **Rapid Expansion during the last 1000 yrs**
- **Core He exhaustion**
- **End of mass transfer**
- **Mass transfer starts.**

**He star (3.8 Msun) main sequence**

**ZAMS:** 18 Msun
SN Ibc progenitors produced in binary systems have larger radii, than those of single stars.
Fairly bright plateau in the early phase of SN Ibc, mostly due to He recombination.
## Summary: Single v.s. Binary progenitors

<table>
<thead>
<tr>
<th></th>
<th>Single Star Progenitors</th>
<th>Binary Star Progenitors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Final mass</strong></td>
<td>$M/M_\text{sun} &gt; 8$</td>
<td>$1.4 &lt; M/M_\text{sun} &lt; \sim 8$</td>
</tr>
<tr>
<td><strong>Radius</strong></td>
<td>$\sim R_\odot$</td>
<td>$R_\odot &lt; R &lt; \sim 100 R_\odot$</td>
</tr>
<tr>
<td><strong>Bolometric luminosity</strong></td>
<td>$\log L/L_\odot &gt; 5$</td>
<td>$4 &lt; \log L/L_\odot &lt; 5$</td>
</tr>
<tr>
<td><strong>Optical magnitude</strong></td>
<td>$M_V &lt; -3$</td>
<td>$M_V = -4 \sim -5$</td>
</tr>
<tr>
<td><strong>Shock Breakout</strong></td>
<td>hard X-ray</td>
<td>soft X-ray</td>
</tr>
<tr>
<td><strong>Early light curves, for a given energy</strong></td>
<td>not that luminous</td>
<td>fairly luminous plateau</td>
</tr>
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</table>
Population:
Can the binary models explain the observed statistics of SNe Ibc?
The progenitor masses increase in the following order?

SN II => SN Ib => SN Ic
SN Ibc with long delay times

- 5-8 Msun
- ~ 2.2 - 4 Msun
- WD
- Long delay time (up to ~ G yr)
- Relatively low mass He star (~ 1.5 - 2.0 Msun)
- SN Ibc
Faint, Ca-rich peculiar SNe Ib

2005cz: Kawabata et al. 2010
Binary evolution can explain SN IIP and SN Ib from early-type galaxies. They must have delay times of $\sim 100$ Myrs.

Suh et al. 2011
Can SNe Ibc occur in the Early Universe?

If so, what would they tell us about the evolution of the first stars?
How do Pop III stars evolve?

<table>
<thead>
<tr>
<th>$Z = Z_{\text{sun}}$</th>
<th>$Z = 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strong winds resulting from metal lines</strong></td>
<td><strong>No line-driven winds</strong> (Krticka &amp; Kubat 2006)</td>
</tr>
<tr>
<td><strong>Unstable</strong></td>
<td><strong>Stable</strong> (Baraffe et al. 2001)</td>
</tr>
<tr>
<td><strong>Strong mass loss</strong></td>
<td><strong>Not much mass loss</strong></td>
</tr>
<tr>
<td><strong>The evolution of very massive stars is dominated by “mass loss”</strong></td>
<td><strong>The evolution of massive Pop III stars is dominated by “rotation”</strong></td>
</tr>
</tbody>
</table>
Role of Rotation in massive Pop III stars

- Pop III protostars are supposed to have large amounts of angular momentum (Stacy et al. 2011).

- When the surface of a star reaches the critical rotation, mass shedding can occur (Marigo et al. 2003, Efstroem et al. 2008, Yoon et al. 2012).

- Chemical mixing induced by rotation can change the history of nucleosynthesis (Efstroem et al. 2008, Yoon et al. 2012), as well as the evolutionary paths (Yoon et al. 2012).
Bifurcation of massive star evolution at low-metallicity

Yoon & Langer 05, Yoon et al. 06, Woosley & Heger 06, Yoon et al. 12
Bifurcation of massive star evolution at low-metallicity

Yoon et al. 2012
Bifurcation of massive star evolution at low-metallicity

These stars become He star without losing much mass. They produce more ionizing photons.

Yoon et al. 2012

\[ M_{\text{init}} = 100 \, M_\odot \]

\[ \frac{v_{\text{init}}}{v_K} = 0.0 \]

\[ \frac{v_{\text{init}}}{v_K} = 0.2 \]

\[ \frac{v_{\text{init}}}{v_K} = 0.3 \]

\[ \frac{v_{\text{init}}}{v_K} = 0.4 \]

\[ \frac{v_{\text{init}}}{v_K} = 0.6 \]
Final fates of the first stars

Final fates of rotating massive Pop III stars

- GRB / HN (SN Ibc)
- Puls. PISN (SN Ibc)
- PISN (SN II)
- Collapse to BH

- SN IIP
  - (NS remnant)

- Collapse to BH, or weak SN II

- Forbidden region

Yoon et al. 2012
Final fates of the first stars

Long gamma-ray bursts.

Yoon et al. 2012
Final fates of the first stars

Long gamma-ray bursts.

Hydrogen-rich pair-instability supernovae

Yoon et al. 2012
Final fates of the first stars

Hydrogen-free pair-instability supernovae

Hydrogen-rich pair-instability supernovae

Long gamma-ray bursts.

Yoon et al. 2012
Final fates of the first stars

- Both pulsational PISN and long GRB from the same progenitor: Extremely bright afterglows?
- Hydrogen-free pair-instability supernovae
- Long gamma-ray bursts.
- Hydrogen-rich pair-instability supernovae

Yoon et al. 2012
Final fates of the first stars

Both pulsational PISN and long GRB from the same progenitor: Extremely bright afterglows?

Long gamma-ray bursts.

Hydrogen-rich pair-instability supernovae

Hydrogen-free pair-instability supernovae

Super-collapsar is not likely to occur.

Yoon et al. 2012
Final Remarks

• The nature of SN Ibc progenitors are “different” from that of most WR stars.

• To correctly interpret the observational data, you need “realistic” binary star models of SN Ibc progenitors.

• The diversity of SN Ibc can be very large: its progenitor masses can vary from 1.4 Msun to 100 Msun, and the delay time from a few Myr to Gyr.

• We still do not understand well what makes Ib and Ic different.

• We still do not know what makes the so-called broad-lined Ic supernovae.
Dessart et al. 2012; red line: He transition excluded, black line: full solution