Supernova SN 1987A: From progenitor to explosion

Athira Menon, postdoc, University of Amsterdam

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The first surprise: the progenitor, Sanduleak -69° 202

SN 1987A: the most well-observed Type II SN
Location: Large Magellanic Cloud

Progenitor:
Hot, compact, blue supergiant of 30-50 Rsun.
The progenitor, Sanduleak -69° 202

Rings ejected by progenitor 20,000 years before explosion → rotating star

Signs of CNO processing (Hydrogen burning): N/O, N/C and He/H ratios in rings

Image: Hubble space telescope
The second surprise: Light curve

Type II (normal) (R~500 Rsun)

Type II-peculiar (R~50 Rsun)
Origin of SN 1987A: Single star approach

- ‘Force’ a massive star to explode as a blue star → fine-tuned parameters
- Explosion of BSG single-star models does not reproduce observed light curve
- Single stars of LMC metallicity do not by themselves end their lives as BSGs (Schootemeijer, 2019)
Origin of SN 1987A: Merger of binary stars

- Over 50% of massive stars are in binary systems
- Under what circumstances, can a merger produce a BSG for 87A?
- Can its explosion reproduce the light curve?

Image from Hubble space telescope (left) and from 3D hydrodynamic simulation of Morris & Podsiadlowski (2009) (right)
A late binary merger scenario

Figure from Menon, PhD thesis
Based on Podsiadlowski 1992
and Podsiadlowski 2007

$t=0$ Myr

$\Delta t \sim 15$ Myr

Roche Lobe overflow - dynamic mass transfer

15 $M_{\text{Sun}}$

5 $M_{\text{Sun}}$

Primary (MS)

Secondary (MS)

Initial orbital period: 10 yr
Mixing of H-rich material into He/CO core (Ivanova et al. 2003)

Merger! \( \Delta t = 100 \text{ yr} \)

H-free core: where no hydrogen is present → shrinks in mass after merger

Structure contracts and explodes as a blue supergiant
## Initial parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
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<tbody>
<tr>
<td>Primary mass ($M_1$)</td>
<td>15, 16, 17, 18 Msun (rotating at 30% critical rate)</td>
</tr>
<tr>
<td>Secondary mass ($M_2$)</td>
<td>2, 3,..., 8 Msun</td>
</tr>
<tr>
<td>Fraction of He core-dredged up ($f_{c}$)</td>
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</tbody>
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## Stellar evolution code

- KEPLER (1D stellar evolution code)
  - Heger et al. 2002
  - Woosley et al. 2002
  - Woosley & Heger 2007

## Explosion

- 1D radiative hydrodynamics code, (Utrobin 2004, 2007)
- 3D hydrodynamic simulations, (Utrobin, Wongwathanarat, Janka et al. in prep)
Stellar evolution of a 16+7 Msun system

C-D: Contraction and C-ignition at D
~10^4 yr

Pre-supernova star: 23 Msun

A-B: 16 Msun

Merger (B-C): 16+7 Msun
100 yr

Checks for the progenitor model:

HRD position

Lifetime of BSG phase: 15,000-50,000 years

Nuclear abundances in rings

Menon & Heger 2017
Pre-supernova models from mergers

- BSGs Type II progenitors are very likely from binary mergers

- Of the 84 models computed, 56 were blue supergiants;

  6 matched the progenitor of ‘87A (filled blue symbols)

- No red supergiants from our grid!

Blue supergiants: 12,000-18,000 K
Yellow supergiants: 7000-12,000K

Menon & Heger 2017
Light curves
Observational constraints for explosion

- 56Ni mass is 0.075MSun

- Maximum velocity of the bulk of 56Ni reaches 3100 km/s

- Mass of hydrogen mixed within 2000 km/s is 2.2Msun

- Oxygen mass in the SN ejecta is between 0.7 to 2.0MSun
1D explosion of binary merger progenitor (Menon, Utrobin, Heger 2019)

- 1D radiative hydrodynamics (piston) code
- Set mixing requirements
- Set Ni mass
- Set explosion energy
3D + 1D explosions for 87A
(Utrobin, Wongwathanarat, Janka et al. in prep)

Best-fit: 15+7 Msun
Final thoughts

- First progenitor + light curve models from a binary merger for SN 1987A

- Most likely progenitor for SN 1987A: 15+7 Msun, with R=30Rsun, E=1.4 foe, NS mass=1.5Msun

- More refined progenitor models considering angular momentum evolution

- Follow up studies:
  MPA, Garching: 3D explosions
  MPA, Garching: Gamma-ray & X-ray emission
  NCSU: Nuclear yields (Frohlichich+ submitted)