Binary merger progenitor- explosion connection
Lessons from SN 1987A

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July 27th, 2017, Ringberg workshop
The progenitor, Sanduleak $69^\circ202$

Progenitor was a hot blue supergiant (BSG) ($T_{\text{eff}} = 15,000\text{K} \text{–} 18,000\text{K}$)

Unique dome-shaped light curve despite being a Type-II H-rich supernova

Rings ejected by the BSG progenitor--Inner ring ejected at least 20,000 years before explosion (Burrows+ 1995, Sugerman+ 2005)

Rings enriched in helium, nitrogen ($\text{N}$) over carbon ($\text{C}$) and oxygen ($\text{O}$) (Lundqvist & Fransson 1996); $\text{N/C} = 5\pm2$, $\text{N/O} = 1.1\pm0.4$
The 30 year story of progenitor evolution of SN 1987A

**Single Stars**
- Detailed explosion studies
- Ad hoc physics to obtain a blue supergiant pre-SN (rotation, mass-loss, convective overshooting etc.)
- Cannot explain triple-ring nebula ejection

**Binary Stars**
- Binary scenario and merger tracks: (Podsiadlowski, Joss, Hsu 1992; Podsiadlowski 1992)
- Physics in check, especially for triple-ring nebula (Morris & Podsiadlowski 2007, 2009)
- No pre-SN models from binary mergers that match all progenitor observations
- No explosion studies
• First systematic stellar-evolution study of Type II progenitors from 84 binary-merger models
  • Which of these models match the progenitor observations of SN 1987A?
    • What conditions can lead to Type II blue supergiant progenitors?
  
• How do the structures of binary merger models compare with single star models?
Distribution in HR diagram of all 84 merger pre-SN models

- Only chose initial parameters
- No fine tuning during evolution; pre-SN models come naturally from simulations
- HRD position
  N/C, N/O values in surface
  Lifetime >15,000 yr
Density profiles comparison of SN 1987A pre-SN models

Single star models,
(Utrobin et al. 2015)
Density profiles comparison of SN 1987A pre-SN models

**Binary merger models**

\[ M_1 = 16 \, M_\odot \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Binary mergers</th>
<th>Single stars</th>
</tr>
</thead>
<tbody>
<tr>
<td>He core mass (Ms)</td>
<td>2.9 – 4.1</td>
<td>~5–7</td>
</tr>
<tr>
<td>Envelope mass (Ms)</td>
<td>15 – 20</td>
<td>10–15</td>
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</table>
Chemical composition comparison

Binary merger model
16 + 2 $M_\odot$

Single star model
Woosley 1988, 18 $M_\odot$
Binary merger scenario
Podsiadlowski and Ivanova papers

Primary Red supergiant with CO core +
Secondary main sequence

Blue Supergiant pre-SN ?

Merger: Order of 100 years

He core is dredged up $\rightarrow$ He core shrinks after merger
Merger

$M_1 = 16 \, M_\odot$, rotating at $v/v_c = 0.30$

$M_2 = 7 \, M_\odot$

$\epsilon_c = 17\% \rightarrow$ mixing boundary

$(m_b) = 3.7 \, M_\odot$

(No common envelope physics included)

Fig 1. from Menon & Heger, MNRAS, 2017

Figure 1. Top panel, stage B in Fig. 4: Composition of the RSG model from a primary of $M_1 = 16 \, M_\odot$ consisting of a He core of $M_{He,c,1} = 4.92 \, M_\odot$ just prior to the merger. Middle panel, stage C in Fig. 4: Composition at the end of the merger with $M_2 = 7 \, M_\odot$. The boundary of mixing $m_b$ (dotted vertical line) is set for $\epsilon_c = 16.6\%$. At the end of the merger, the star has a smaller He core of mass $3.41 \, M_\odot$. Bottom panel, stage D in Fig. 4: Composition of the pre-SN model. The surface composition of the star does not change much from the one at the end of the merger.
HR diagram

Primary, 16 $M_\odot$ (AB): 16.7 Myr

Core C burning

PRE-SN

Contraction (CE): 49 kyrs

Merger (BC): 100 years

$M_{1,RSG} + 7 M_\odot$

$16 M_\odot + 7 M_\odot$, fc=17 %
Methodology

1. Choose a combination of three initial parameters:
   - primary mass ($M_1$)
   - secondary mass ($M_2$)
   - fraction of He core-dredged up ($f_c$): mixing boundary, He core mass after merger

**KEPLER**
(Woosley, Heger & Weaver 2002; Heger, Woosley & Spruit 2005)

2. Merge primary and secondary stars (no common envelope physics included)
3. Follow evolution until pre-SN stage (i.e. just before iron-core collapse)
4. Check if pre-SN model matches observational criteria of Sk-69° 202

**CRAB** (Utrobin 2004; Utrobin 2007)
5. Explode these models (Victor Utrobin)
What causes pre-supernova models to become blue?

And how do their explosions look?
(Light curve models by Victor Utrobin using CRAB)
• Relation between $M_{\text{core}}/M_{\text{env}}$ and $T_{\text{eff}}$ is not monotonic

• For a given $M_1$, $M_2$, decreasing $f_c$ decreases $T_{\text{eff}}$

• Accretion alone, without core dredge up, makes RSGs from mergers
Fraction of He core dredged up (fc)

Dredge-up from CO core will decrease N/C and N/O

Increasing $M_{\text{core}}/M_{\text{env}}$
Secondary Mass (M$_2$)

Fixed M$_1$, fc, monotonic increase in $T_{\text{eff}}$ and L, with increasing M$_2$
Light curves by changing He core fraction (fc)

Explosion parameters

\[ \frac{E_{\text{exp}}}{M_{\text{ejecta}}} = 1.5 \times 10^{51} \text{erg}/18 M_\odot \]

- Mixing width = 2 \( M_\odot \)
- Nickel mixing velocity = 3000 km/s
- \( M_{\text{Ni}} \) in ejecta = 0.073 \( M_\odot \)

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Light curves comparison between binary mergers and single stars

Utrobin et al. 2015, Single stars

B15
N20
W18
W20
Light curves comparison between binary mergers and single stars

Utrobin et al. 2015, Single stars

Black line: optimal (non-evolutionary) model

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B15  | 56.1 | 4.0 | 15.0 |
N20  | 47.9 | 6.0 | 16.3 |
W18  | 46.8 | 7.4 | 16.9 |
W20  | 64.2 | 5.8 | 19.4 |
Conclusions

**Stellar evolution**

- Blue supergiants are highly favoured via mergers, in the parameter space studied
- **Six models match the progenitor observations of SN 1987A**
- Sensitive to fraction of He core dredged up and secondary mass accreted
- More massive and smaller He core masses compared to single star models

**Supernova explosions**

- Light curves fit better with merger models
- Important consequences for 3D simulations (Janka, Utrobin, et al., work in progress)
- What are the other consequences/implications for supernova studies?