MIXING CONSTRAINTS ON THE PROGENITOR OF SUPERNOVA 1987A

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Workshop on “The Progenitor-Supernova-Remnant Connection”
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Core-Collapse Supernova Relative Fractions

- II-P: 48.2%
- Ic: 14.9%
- Ib: 7.1%
- IIb: 10.6%
- II-L: 6.4%
- IIn: 8.8%

ordinary SNe IIP ~ 50% (Li et al. 2011, Smith et al. 2011)

SN 1987A-like events 1–3% (Pastorello et al. 2012)
Light Curve of Peculiar Type IIP SN 1987A

Open circles (Catchpole et al. 1987,1988); open triangles (Hamuy et al. 1988).
SN 1987A: Evidence for H and $^{56}$Ni Mixing

Not flat-topped H$\alpha$ profile on day 498 (Phillips et al. 1990) implies that there is no cavity free of hydrogen at zero velocity.

The [Ni II] 6.64 $\mu$m profile at day 640 gives $v_{\text{FWHM}} = 3100$ km s$^{-1}$ (Colgan et al. 1994).
SN 1987A: Bochum Event and Fast $^{56}$Ni Clump

Fast $^{56}$Ni clump: $v_{3D} \approx 4700$ km s$^{-1}$, $M_{\text{Ni}} \sim 10^{-3} M_{\odot}$ (Utrobin et al. 1995).
Modeling of Supernovae: Three Approaches

First approach

1D piston or thermal bomb

Second approach

3D simulations

Third approach

Fit
SN 1987A originates from BSG; its light curve is powered by radioactive decays.
## Presupernova Models for Blue Supergiants

<table>
<thead>
<tr>
<th>Model</th>
<th>(R_{\text{pSN}} (R_\odot))</th>
<th>(M_{\text{He}}^{\text{core}} (M_\odot))</th>
<th>(M_{\text{pSN}} (M_\odot))</th>
<th>(M_{\text{ZAMS}})</th>
<th>(X_{\text{surf}})</th>
<th>(Y_{\text{surf}})</th>
<th>(Z_{\text{surf}} (10^{-2}))</th>
<th>Rot. Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>B15</td>
<td>56.1</td>
<td>4.05</td>
<td>15.02</td>
<td>15.02</td>
<td>0.767</td>
<td>0.230</td>
<td>0.34</td>
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<tr>
<td>W16</td>
<td>28.8</td>
<td>6.55</td>
<td>15.36</td>
<td>16</td>
<td>0.474</td>
<td>0.521</td>
<td>0.50</td>
<td>Yes</td>
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<tr>
<td>W18</td>
<td>46.8</td>
<td>7.40</td>
<td>16.92</td>
<td>18.0</td>
<td>0.480</td>
<td>0.515</td>
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<tr>
<td>W18r</td>
<td>41.9</td>
<td>6.65</td>
<td>17.09</td>
<td>18</td>
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<td>0.453</td>
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<tr>
<td>W18x</td>
<td>30.4</td>
<td>5.13</td>
<td>17.56</td>
<td>18</td>
<td>0.713</td>
<td>0.281</td>
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<tr>
<td>N20</td>
<td>47.9</td>
<td>5.98</td>
<td>16.27</td>
<td>(\sim 20.0)</td>
<td>0.560</td>
<td>0.435</td>
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<td>W20</td>
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<td>5.79</td>
<td>19.38</td>
<td>(20.10)</td>
<td>0.738</td>
<td>0.256</td>
<td>0.56</td>
<td>No</td>
</tr>
</tbody>
</table>

Presupernova Models: Density vs. Radius

![Presupernova Models: Density vs. Radius](image-url)

- **B15**
- **W16**
- **W18r**
- **W18**
- **W20**
- **N20**
Pre-SN Models: Mass Fractions vs. Interior Mass

![Graphs showing mass fractions vs. interior mass for different models.](image-url)
## Hydrodynamic Models

<table>
<thead>
<tr>
<th>Model</th>
<th>$M_{NS}$ ($M_\odot$)</th>
<th>$M_{env}$ ($M_\odot$)</th>
<th>$E_{\text{exp}}$ (B)</th>
<th>$M_{\text{Ni}}^{\text{min}}$</th>
<th>$M_{\text{Ni}}^{\text{max}}$</th>
<th>$M_{\text{Ni}}$</th>
<th>$\nu_{\text{Ni}}^{\text{bulk}}$ (km s$^{-1}$)</th>
<th>$\langle \nu \rangle_{\text{tail}}^{\text{Ni}}$</th>
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<tbody>
<tr>
<td>B15-2</td>
<td>1.25</td>
<td>14.21</td>
<td>1.40</td>
<td>3.11</td>
<td>9.36</td>
<td>7.28</td>
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<td>W16-1</td>
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<td>1.13</td>
<td>3.43</td>
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<td>2222</td>
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<td>15.52</td>
<td>1.36</td>
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<td>1101</td>
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<td>7.54</td>
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<td>N20-P</td>
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<td>14.72</td>
<td>1.67</td>
<td>4.16</td>
<td>12.11</td>
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<td>1635</td>
<td>1790</td>
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<tr>
<td>W20</td>
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<td>17.92</td>
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<td>7.24</td>
<td>1374</td>
<td>1482</td>
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</tbody>
</table>
Morphology of $^{56}$Ni-rich Matter in Model B15-2
Morphology of $^{56}\text{Ni}$-rich Matter in Model W18
More Massive Helium Core, Lower $^{\text{56}}\text{Ni}$ Velocity

Only model B15-2 yields maximum Ni velocity consistent with the observations!
Hertzsprung-Russell Diagram for SN 1987A Progenitors. 
Single Star Scenario

Sukhbold et al. (2016)
Two Possible Solutions of The Problem

- A rapid rotation of Fe core producing more extent of Ni mixing.

Credit: (ESA/STScI), HST, NASA
The triple-ring system was explained by Morris & Podsiadlowski (2009) in the scenario of a binary merger model.
Hertzsprung-Russell Diagram for SN 1987A Progenitors.

Binary Merger Scenario

$M_1 = 16 \, M_\odot$ \quad Menon & Heger (2017), see also A. Menon’s talk.
Bolometric Light Curves

The total $^{56}$Ni mass is scaled to fit the observed luminosity in the radioactive tail.
The total $^{56}\text{Ni}$ mass is scaled to fit the observed luminosity in the radioactive tail.
Summary

- 3D neutrino-driven explosion simulations of SN 1987A are able to synthesize the $^{56}$Ni mass estimated from the observed luminosity in the radioactive tail.
- The extent of outward $^{56}$Ni mixing in the framework of the 3D simulations decreases with He-core masses of the corresponding progenitor models.
- In 3D simulations only the model with He-core mass of $4 \, M_\odot$ yields a maximum velocity of the bulk of $^{56}$Ni consistent with SN 1987A observations.
- In a single star scenario Sk $-69^\circ$202 seems to require a progenitor with a $\sim 6 \, M_\odot$ He core, and a $4 \, M_\odot$ He core is not able to explain the color-luminosity properties before collapse.
- Rapid rotation of the iron core might lead to more mixing. Investigations are needed.
- Binary progenitor models with $\sim 4 \, M_\odot$ He cores can account for the color-luminosity properties of Sk $-69^\circ$202 (see A. Menon’s talk). But do they yield the extent of mixing to explain SN 1987A observations?
- Inward hydrogen mixing leads to minimum velocities of H-rich matter of less than 100 km s$^{-1}$ in a good agreement with SN 1987A observations.

Future

- 3D neutrino-driven explosion simulations on the basis of binary merger models of Menon & Heger (2017) for the progenitor of SN 1987A.