Observational constraints on the progenitors of II-P SNe

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Overview and motivation

• Direct constraints on progenitor stars
• Test of final stages of stellar evolution
• Consistency with spectral and lightcurve modeling?
• Range in energy and ejected masses: link to explosions?
• Black hole and NS formation: which stars
Testing theory

Heger et al. (2003); Eldridge & Tout 2004: now can place observational constraints
Nearby SNe discovered by amateur astronomers, LOSS (Filippenko talk) and CHASE (Pignata poster)
Relative SN rates 10.5 yrs

Smartt et al., 2009

<table>
<thead>
<tr>
<th>Type</th>
<th>No.</th>
<th>/ per cent</th>
<th>Core-Collapse only / per cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>II-P</td>
<td>55</td>
<td>39.6</td>
<td>59.1</td>
</tr>
<tr>
<td>II-L</td>
<td>2.5</td>
<td>1.8</td>
<td>2.7</td>
</tr>
<tr>
<td>IIn</td>
<td>3.5</td>
<td>2.5</td>
<td>3.8</td>
</tr>
<tr>
<td>IIb</td>
<td>6</td>
<td>4.3</td>
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</tr>
<tr>
<td>Ib</td>
<td>9</td>
<td>6.5</td>
<td>9.7</td>
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<tr>
<td>Ic</td>
<td>17</td>
<td>12.2</td>
<td>18.3</td>
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<tr>
<td>Ia</td>
<td>37</td>
<td>27.6</td>
<td>...</td>
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<tr>
<td>LBVs</td>
<td>7</td>
<td>5.0</td>
<td>...</td>
</tr>
<tr>
<td>Unclassified</td>
<td>2</td>
<td>1.4</td>
<td>...</td>
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</tbody>
</table>

| Total | 139 | 100 | 100 |
| Total CCSNe | 93 | 66  | 100 |

- 19980101-20080630
- 139 SNe discovered in galaxies with $V_{\text{vir}} < 2000$ kms$^{-1}$ (13.2 SNe yr$^{-1}$)
~26% SN-HST image coincidence rate

VLT : NGC3621, Bresolin et al. 01

M101

NGC3949
Detection of progenitors

Within the volume limited, 10.5 yr survey for progenitors: three “gold” events
- SN2008bk, SN2005cs, SN2003gd
- Red star identified coincident with all three.
- Typical magnitudes: $M_v \sim -4.5 ; M_I \sim -6.5$
- Discovery papers:
  - Van Dyk et al. 03, Smartt et al. 04, Maund et al. 05, Li et al. 06, Mattila et al. 08.

Figures from Smartt 2009 ARAA
The disappearance of 2003gd

SN2003gd:
\[ V = 25.8 \pm 0.15 \]
\[ V-I = 2.5 \pm 0.2 \]
Smartt et al. 04, Van Dyk et al. 03

Maund & Smartt (2009)
Four confirmed cases of disappearance:
SN1987A, SN1993J, SN2003gd,
SN2005gl (Gal-Yam, later…!)
Mass estimates from stellar evolutionary tracks

Red points: Milky Way red supergiants (Levesque et al. 2005)
STARS stellar evolutionary tracks
SN progenitors: SN2003gd (black), SN2005cs (blue box)

See Gezari talk – UV shock breakout from II-P SNe implies RSGs
Other examples: no detection

- **SN1999gi** in NGC3184,
- HST $U+V$ pre-explosion
- $D=11$Mpc (Leonard et al. 2002)
- $M \leq 12$ M$_\odot$

- **SN2001du** in NGC1365
- HST $UVI$ pre-explosion
- $D=17$Mpc (Cepheid Key P.)
- $M \leq 15$ M$_\odot$

Smartt et al. 02, Van Dyk et al 02
Summary of II-P progenitors: 10.5yr search

<table>
<thead>
<tr>
<th>Supernova</th>
<th>SN Type</th>
<th>Galaxy</th>
<th>Galaxy Class</th>
<th>Distance</th>
<th>A_V</th>
<th>r_G (kpc)</th>
<th>r_G/r_25</th>
<th>[O/H] (dex)</th>
<th>log L/L☉ (dex)</th>
<th>ZAMS (M☉)</th>
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<tbody>
<tr>
<td>1999an</td>
<td>II</td>
<td>IC 755</td>
<td>SBBb</td>
<td>18.5 ± 1.5</td>
<td>TF</td>
<td>0.40 ± 0.19</td>
<td>4.7</td>
<td>0.82</td>
<td>8.3</td>
<td>&lt; 5.16</td>
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<td>1999br</td>
<td>II-P</td>
<td>NGC 4900</td>
<td>SBC</td>
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<td>Kin.</td>
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<td>NGC 1637</td>
<td>SBC</td>
<td>11.7 ± 1.0</td>
<td>Cep.</td>
<td>0.31 ± 0.16</td>
<td>1.6</td>
<td>0.28</td>
<td>8.6</td>
<td>&lt; 4.69</td>
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<td>1999ev</td>
<td>II-P</td>
<td>NGC 4274</td>
<td>SBab</td>
<td>15.1 ± 2.6</td>
<td>Kin.</td>
<td>0.47 ± 0.16</td>
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<td>NGC 3184</td>
<td>SABc</td>
<td>10.0 ± 0.8</td>
<td>Mean</td>
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<td>&lt; 4.64</td>
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<td>SBBb</td>
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<td>0.53</td>
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<td>&lt; 4.71</td>
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<td>2002hh</td>
<td>II-P</td>
<td>NGC 6946</td>
<td>SABc</td>
<td>5.9 ± 0.4</td>
<td>Mean</td>
<td>5.2 ± 0.2</td>
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<td>0.45</td>
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<td>&lt; 5.10</td>
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<td>NGC 628</td>
<td>Sc</td>
<td>9.3 ± 1.8</td>
<td>Mean</td>
<td>0.43 ± 0.19</td>
<td>7.5</td>
<td>0.58</td>
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<td>4.3 ± 0.3</td>
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<td>2003ie</td>
<td>II?</td>
<td>NGC 4051</td>
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<td>II-P</td>
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<td>20.3 ± 3.4</td>
<td>Mean</td>
<td>0.19 ± 0.09</td>
<td>6.7</td>
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<td>4.5 ± 0.25</td>
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<td>NGC 3034</td>
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<td>3.3 ± 0.3</td>
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<td>0.14</td>
<td>8.7</td>
<td>Cluster 12⁺⁻³</td>
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<td>2004dg</td>
<td>II-P</td>
<td>NGC 5806</td>
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<td>Kin.</td>
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<td>Cep.</td>
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<td>0.37</td>
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<td>Cluster 15 ± 3</td>
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<td>2004et</td>
<td>II-P</td>
<td>NGC 6946</td>
<td>SABc</td>
<td>5.9 ± 0.4</td>
<td>Mean</td>
<td>1.3 ± 0.2</td>
<td>8.4</td>
<td>0.92</td>
<td>8.3</td>
<td>4.6 ± 0.1</td>
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<td>2005cs</td>
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<td>NGC 5194</td>
<td>Sbc</td>
<td>8.4 ± 1.0</td>
<td>PNLF</td>
<td>0.43 ± 0.06</td>
<td>2.7</td>
<td>0.22</td>
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<td>4.25 ± 0.25</td>
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<td>&lt; 4.51</td>
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<td>Sbc</td>
<td>20.5 ± 2.6</td>
<td>Kin.</td>
<td>0.09</td>
<td>10.3</td>
<td>0.91</td>
<td>8.4</td>
<td>&lt; 4.53</td>
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<td>2008bk</td>
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<td>NGC 7793</td>
<td>Scd</td>
<td>3.9 ± 0.5</td>
<td>TRGB</td>
<td>1.0 ± 0.5</td>
<td>3.9</td>
<td>0.66</td>
<td>8.4</td>
<td>4.6 ± 0.1</td>
</tr>
</tbody>
</table>

Smartt et al. 2009, MNRAS: used Cambridge STARS code, homogeneous analysis, consistent luminosity and mass estimates
Does a Salpeter/Scalo IMF fit?

- **Solid**: Salpeter IMF, maximum mass of 16.5$M_\odot$
- **Dashed**: Salpeter IMF, maximum mass of 30$M_\odot$
- **Lower mass limit**: 7-8$M_\odot$ (WD limits: Williams talk)
Maximum likelihood approach

- $m_{\text{min}}$: is better measured with the detections only. Unconstrained IMF if limits used.
- $m_{\text{max}}$: calculated using both detections and limits:
  - $m_{\text{min}} = 8^{+1}_{-1.5} \, M_{\odot}$
  - $m_{\text{max}} = 16.5 \pm 1.5 \, M_{\odot}$
The “red supergiant problem”

- Most massive RSGs in MW and LMC are 25-30M$_\odot$
- Where are these progenitors?
- Would be the easiest to detect in the pre-explosion images
- From Salpeter/Scalo IMF we would have expected 4-5 bright, massive progenitors
- Do they produce IIn and II-L?

Levesque et al 05,06: new Teff for RSGs

Smartt, ARAA 2009
Probing the explosion

- Chugai & Utrobin: hydro models of LCs
- Factors of 2-3 higher masses (2005cs, 2004et, 1999em...)

- See Posters:
  Kate Maguire (explosion energies)
  Melina Bersten (Hydro models)
$^{56}$Ni mass vs. ejecta mass

- Nomoto et al. 2006: ejecta mass from lightcurve and spectral models
  - Assume WR stars and use stellar evolution models to determine initial mass
  - Faint, $^{56}$Ni poor branch: fallback SNe from high mass stars

- Direct progenitor identification results:
  - All faint II-P, have low KE, and low $^{56}$Ni
  - No evidence of high mass progenitors
  - Large diversity in explosion energies between 7-16M$_\odot$

Faint IIP: Pastorello et al. 09, 06
Kitaura et al. 04, Wanajo et al. 09
Wolf Rayet stars: not Ibc progenitors?

- LMC (or M31) WR magnitude distributions $\Rightarrow$ $\sim$5-10% probability we have had no detections by chance
- SN2008ax: detection of WNL progenitor of a IIb (Crockett et al. 08)

SN2008ax detection $M_V = -7.4$

From Crockett 2009 (PhD Thesis),
See also
Van Dyk et al. 03
Maund & Smartt 05,
Maund et al. 05
Gal-Yam et al. 05
Summary

- Red supergiants are progenitors of II-P SNe (as predicted by Chevalier, Falk & Arnett)
- Confident detections of 3 (+ several others) low luminosity progenitors: \( \log L/L \approx 4.3 \pm 0.3 \), colours imply M-type supergiants
- Suggests these stars do NOT go through 2nd dredge up

- Lower limit for core-collapse: no more than 7-8M\(_\odot\)
- Lack of high mass progenitors – statistically significant?
- No detection of Ibc progenitors – the known massive WR population is not the progenitor population of Ibc SNe
- Massive stars collapse to black holes – we have not yet detected the SN?

\[ 16 \rightarrow 60 \ ? M_{\odot} \]
Lessons Learned

- 10 years of searching – not as easy as first thought
- 93 CCSNe within 28Mpc: ~32 with good pre-explosion images
- 4 high significance, unambiguous detections. 3 questionable ones, plus 3 on unresolved host clusters
- 5-10% yield (but large number of upper limits restrictive)
- High resolution images (HST or 8m AO) crucial

The future:
- Extend to another 10-20 years (any takers…!)
- Focus on the 10Mpc volume: HST MCTP for all high SFR galaxies (800 orbits). Huge legacy science (D. Calzetti)
- Guaranteed ~15 CCSNe in 10 years. With full mosaic, deep WF3/ACS of the galaxies, discovery potential high
SN2008ax: IIb + WNL progenitor?

Crockett et al. 2008, Pastorello et al. 2008
8m AO imaging - new approach

Gemini and VLT diffraction limited $K$-band AO images

0.08" and \(~0.02" pixels = well sampled PSF

Typical \(~15 - 20\) stars identified in common between $K_S$ and $V$ or $I$ band

Differential astrometry \(~20\) milliarcseconds RMS
Comparison of codes