Observational constraints on SN progenitors

S. J. Smartt
Queen’s University Belfast, UK

NGC7793 with VLT FORS

Afternoon talks:
N. Elias-Rosa,
S. Van Dyk
Until 2010:
All Nearby SNe discovered by amateur astronomers, and two professional search teams:
North: LOSS (Filippenko & Li)
South: CHASE (Pignata et al.)
Supernovae are classified by their optical spectra

No hydrogen

Type I

Si

Ia

He

Ib

He

Ic

Hydrogen lines

Type II

Photometry/spectra properties

II-P, II-L, II-n, IIb

Core Collapse

Supergiant
Core-collapse SN: progenitor to enrichment

Mattila et al. 08, Maguire et al. 2012
Summary of progenitor search project

- **Since 1998 to present**: for **ALL** core-collapse SNe in galaxies $V_{\text{vir}} \leq 2000 \text{ km s}^{-1}$, or $d < 27 \text{ Mpc}$
- Search HST archive for any pre-discovery imaging
- Supplement with any deep, high-resolution ground-based imaging
- Progenitor search for all – high resolution imaging (Ground-based AO or HST) for astrometry to ~30-50 milliarcsec
- Volume and time limited survey
Detected SN rates in Local Volume

Smartt et al., 2009; Eldridge et al. 2012, in prep. (14.25yrs)

<table>
<thead>
<tr>
<th>SN Type</th>
<th>Number</th>
<th>Relative rate (per cent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IIP</td>
<td>55 (73.6)</td>
<td>58.0 ± 6.8</td>
</tr>
<tr>
<td>IIL</td>
<td>3 (4)</td>
<td>3.2 ± 1.6</td>
</tr>
<tr>
<td>IIb</td>
<td>3 (3)</td>
<td>2.4 ± 1.4</td>
</tr>
<tr>
<td>IIpec (87A-like)</td>
<td>1 (1.3)</td>
<td>1.0 ± 0.9</td>
</tr>
<tr>
<td>Ib</td>
<td>9 (10.9)</td>
<td>8.6 ± 2.6</td>
</tr>
<tr>
<td>Ic</td>
<td>17 (20.7)</td>
<td>16.3 ± 3.6</td>
</tr>
<tr>
<td>Total</td>
<td>99 (126.9)</td>
<td></td>
</tr>
</tbody>
</table>

- 19980101-2012033121: 127 CCSNe discovered in galaxies with $V_{\text{vir}} < 2000$ kms$^{-1}$ (9 CCSNe yr$^{-1}$)
- LOSS: controlled, within $\sim$60Mpc. Leaman et al, Li et al., Smith et al. 11
Detection of progenitors

- SN2008bk, SN2005cs, SN2003gd
- Red star identified coincident with all three.
- Typical magnitudes: $M_v \sim -4.5$; $M_I \sim -6.5$
- Review in Smartt 2009
  - Van Dyk et al. 2003, 2010, Li et al. 2006
Progenitor disappearance


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

Disappearance
Maund & Smartt 09

SN2008bk
Mattila et al. 08
Mattila, Maund, Smartt et al. in prep
Other examples: no detection

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

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

Smartt et al. 02, Van Dyk et al 02
Photometry and stellar SED

Maund et al. 11; Van Dyk et al. 11

Single stellar SED
\( T_{\text{eff}} = 6000 \text{ K} \); F8 supergiant; 
\( M_V = -7.5 \)

Fraser et al. 12; Van Dyk et al. 12; Kochanek et al. 12

What is the extinction?
Kochanek et al.: \( R \neq 3.1 \), silicate dust
\[ \log L < 5.0 \text{ dex} \]

Dust extinction is largest uncertainty – CSM dominated?
Walmswell & Eldridge (2011): underestimate \( A_{V,I} \)
Kochanek et al. (2012): overestimate \( A_{V,I} \)

See also Elias-Rosa et al. 10, 11
Constraints on Type SNe Ib/Ic

- Example: SN2004gt - type Ic
- Ic SNe: Related to long Gamma-ray burst

Maund et al. 2004, Gal-Yam et al. 2005
Constraints on Type SNe Ib/Ic

- 1999.5 – 2012.5
- Volume limited (all SNe in galaxies with $V_{\text{vir}} < 2000 \text{ km s}^{-1}$)
- No detections
- Is this significant?
Wolf Rayet stars: not Ibc progenitors?

- LMC (or M31) WR magnitude distributions $\Rightarrow$ $\sim$5-10% probability we have had no detections by chance.

LMC WR stars from Massey (2002), converted to HST filters:
- Blue: F450W
- Green: F555W
- Red: F606W

Eldridge et al. (2012 in prep).


See also
- Van Dyk et al. 03
- Maund & Smartt 05
- Maund et al. 05
- Gal-Yam et al. 05
Results 1998 – 2012.5; within 28 Mpc (41 total)

For Salpeter IMF: 75% of 8-100M\(_\odot\) stars are 8-20M\(_\odot\) (13 “missing”)
What of the LBV-like progenitors?

- SN 2005gl (~66Mpc) Progenitor gone
- Gal-Yam & Leonard 09

- SN2010jl (~50Mpc) - either massive young cluster, or LBV
- Suggests $M_{\text{ZAMS}} > 30M$
- Smith et al. 2011

But both $d > 50\text{Mpc}$, can they be common enough to account for the “missing” high mass progenitors?
11 non-detections of Ib/c progenitors

Results 1998 – 2012.5; within 28 Mpc (41 total)

For Salpeter IMF: 75% of 8-100M_☉ stars are 8-20M_☉ (13 “missing”)
What of the LBV-like progenitors?

- SN 2005gl (~66Mpc) Progenitor gone
- Gal-Yam & Leonard 09

- SN2010jl (~50Mpc) - either massive young cluster, or LBV
- Suggests $M_{ZAMS} > 30M$
- Smith et al. 2011

But both $d > 50$Mpc, can they be common enough to account for the “missing” high mass progenitors?

- SN2006jc : LBV-like outburst detected (Pastorello et al. 07 Foley et al. 07)
- SN2009ip : see Nathan’s talk
Black hole formation

- Ugliano, Janka et al. 2012, arXiv1205.3657
- Neutrino driven explosions – no simple mass dependency
Core-collapse SN: progenitor to enrichment

Mattila et al. 08, Maguire et al. 2012
Nucleosynthesis: oxygen mass as function of progenitor mass

Data: stellar evolutionary calculations
Image credit: Anders Jerkstrand
Stockholm: Radiative transfer model

- Radioactivity
- Temperature, ionization and excitation solutions
- Radiative transfer
- Macroscopic mixing

SN 2004et compared to a 15 $M_{\text{sun}}$ model ($\sim 0.5M_{\text{sun}}$ oxygen)

Kozma & Fransson 1998
Jerkstrand et al. 2012; 2010
Type IIP line luminosities in nebular phase

[O I] 6300, 6364 Å

Jerkstrand et al. in prep
Maguire et al. 2012

We haven’t detected the cosmic oxygen producers
$^{56}\text{Ni}$ mass vs. ejecta mass

- Lower mass progenitors produce lower amounts of $^{56}\text{Ni}$
- Grey line – relative mass of O-core/He-core
- Perhaps due to steep density gradient in inner regions?

- The low luminosity, low KE, II-P SNe come from low mass progenitors
- E-capture explosions?

Smartt et al. 2009

Faint IIP: Pastorello et al. 09, 06
Kitaura et al. 04, Wanajo et al. 09
Summary

• Direct detections of progenitors – now routine
• Attempting to be complete within fixed volume, as far as data allows (14 yrs+)
• Statistical dearth of progenitors above luminosity 
  \[ \log \frac{L}{L_\odot} \sim 5.1 \text{ dex} \]
• No SN with ejected oxygen mass > 1M_\odot
• Implication: most, but not all, stars \( M_{\text{zams}} > 20M_\odot \) make black holes and no (or faint) SNe
• Future:
  – progenitor model consistent with pre-discovery log\((L/L_\odot)\) and ejected O mass
  – Find the cosmic oxygen producers
Results 1998 – 2012.5; within 28 Mpc (41 total)

For Salpeter IMF: 75% of 8-100M_☉ stars are 8-20M_☉ (13 “missing”)
Table 7. Properties and limits for the observed progenitors in our sample. The broad-band magnitudes with asterisks next to the value are in the standard Johnson-Cousins broad-band filters, the rest are HST filters with: $U$–F336W, $B$–F450W, $V$–F555W, $R$–F606W and $I$–F814W

<table>
<thead>
<tr>
<th>SN</th>
<th>Type</th>
<th>Galaxy</th>
<th>Dist(Mpc)</th>
<th>E(B-V)</th>
<th>$M_U$</th>
<th>$M_B$</th>
<th>$M_V$</th>
<th>$M_R$</th>
<th>$M_I$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001B</td>
<td>Ib</td>
<td>IC391</td>
<td>25.5±2.5</td>
<td>0.14</td>
<td>-</td>
<td>-</td>
<td>-8.25</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2002ap</td>
<td>Ic</td>
<td>NGC628</td>
<td>9.3±1.8</td>
<td>0.09</td>
<td>-8.85*</td>
<td>-4.4*</td>
<td>-5.5*</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2003ig</td>
<td>Ic</td>
<td>NGC2997</td>
<td>12.5±1.2</td>
<td>0.11</td>
<td>-</td>
<td>-6.30</td>
<td>-6.16</td>
<td>-6.99</td>
<td>-</td>
</tr>
<tr>
<td>2007gr</td>
<td>Ic</td>
<td>NGC4527</td>
<td>Cluster</td>
<td>0.07</td>
<td>-9.15</td>
<td>-7.44</td>
<td>-6.07</td>
<td>-8.49*</td>
<td>-</td>
</tr>
<tr>
<td>2004gt</td>
<td>Ib</td>
<td>NGC4038</td>
<td>22±3</td>
<td>0.04</td>
<td>-</td>
<td>-</td>
<td>-6.81</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2005V</td>
<td>Ibc</td>
<td>NGC2146</td>
<td>17.1±3.2</td>
<td>0.90</td>
<td>-10.60</td>
<td>-</td>
<td>-8.80</td>
<td>-9.93</td>
<td>-</td>
</tr>
<tr>
<td>2004gn</td>
<td>Ic</td>
<td>NGC4527</td>
<td>14.2±1.3</td>
<td>0.07</td>
<td>-</td>
<td>-</td>
<td>-6.45</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2010br</td>
<td>Ibc</td>
<td>NGC4051</td>
<td>12.7±2.0</td>
<td>0.04</td>
<td>-</td>
<td>-</td>
<td>-4.92</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2011am</td>
<td>Ib</td>
<td>NGC4219</td>
<td>24.5±5.6</td>
<td>0.12</td>
<td>-</td>
<td>-</td>
<td>-8.06</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2011hp</td>
<td>Ic</td>
<td>NGC4219</td>
<td>24.5±5.6</td>
<td>0.12</td>
<td>-</td>
<td>-</td>
<td>-6.76</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
SN2008ax: IIb + WNL progenitor?

Crockett et al. 2008, Pastorello et al. 2008
Detected SN rates in Local Volume

Smartt et al., 2009; Eldridge et al. 2012, in prep.

19980101-20080630 : 139 SNe discovered in galaxies with $V_{\text{vir}} < 2000$ km s$^{-1}$ (13.2 SNe yr$^{-1}$)

LOSS : controlled, within ~60Mpc. Leaman et al, Li et al., Smith et al. 11
Detected SN rates in Local Volume

Smartt et al., 2009

<table>
<thead>
<tr>
<th>Type</th>
<th>No.</th>
<th>Relative / 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>
<td>6.5</td>
</tr>
<tr>
<td>Ib</td>
<td>9</td>
<td>6.5</td>
<td>9.7</td>
</tr>
<tr>
<td>Ic</td>
<td>17</td>
<td>12.2</td>
<td>18.3</td>
</tr>
<tr>
<td>Ia</td>
<td>37</td>
<td>27.6</td>
<td>...</td>
</tr>
<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>
</tr>
<tr>
<td>Total</td>
<td>139</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Total CCSNe</td>
<td>93</td>
<td>66</td>
<td>100</td>
</tr>
</tbody>
</table>

- 19980101-20080630: 139 SNe discovered in galaxies with $V_{\text{vir}} < 2000$ km s$^{-1}$ (13.2 SNe yr$^{-1}$)
- LOSS: controlled, within $\sim 60$ Mpc.

Leaman et al., Li et al., Smith et al. 11
Maximum mass : lowest mass that can produce a WR

- MW clusters: $M_{ZAMS} \approx 25M_\odot$ stars enter WR phase (WN) at $\sim$ solar metallicity (Massey et al. 2001, Crowther 2007)
- LMC clusters: $>30M_\odot$ become WN stars