The empirical grounds of SN-GRB connection

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Summary

1. Supernova Taxonomy
2. GRB-SN properties
3. Progenitors Mass
4. GRB and SN rates
5. Open Issues
Summary

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Supernova taxonomy

thermonuclear $< 8 M_\odot$

- I
- II
- III

- Ia
- Ib
- Ic

- sideronuclear $< 8 M_\odot$

- SuperBright
- hyperfaint

- IIL
- IIP
- IIn

- very bright
- faint
- bright

$\rightarrow$ High KE SNe-Ic $\rightarrow$ Hypernovae $\rightarrow$ GRB-SNe
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## SNe & GRBs at z < 0.2

<table>
<thead>
<tr>
<th>GRB</th>
<th>SN</th>
<th>Z</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRB 980425</td>
<td>SN 1998bw</td>
<td>0.0085</td>
<td>Galama et al. 1998</td>
</tr>
<tr>
<td>GRB 060218</td>
<td>SN 2006aj</td>
<td>0.033</td>
<td>Campana et al. 2006, Pian et al. 2006</td>
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<tr>
<td>GRB 080109</td>
<td>SN 2008D</td>
<td>0.007</td>
<td>Soderberg et al. 2008, Mazzali et al. 2008</td>
</tr>
<tr>
<td>GRB 100316D</td>
<td>SN 2010bh</td>
<td>0.06</td>
<td>Bufano et al. 2012, Chornock et al. 2010, Cano et al. 2011, Margutti et al. 2013</td>
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<tr>
<td>GRB 030323</td>
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<td>0.16</td>
<td>Hjorth et al. 2003, Stanek et al. 2003</td>
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<tr>
<td>GRB 031203</td>
<td>SN 2003lw</td>
<td>0.11</td>
<td>Malesani et al. 2004</td>
</tr>
<tr>
<td>GRB 130702A</td>
<td>SN 2013dx</td>
<td>0.15</td>
<td>D’Elia et al. 2014</td>
</tr>
</tbody>
</table>
Properties of GRB-SNe (broad-lined SNe-Ic)

Lack of H and He in the ejecta: SNe-Ic

Very broad features: large expansion velocity (> 0.1c)

Range of luminosity: in some cases large 56Ni mass (~ 0.5±0.2 M⊙)

Kinetic energy (non-relativistic ejecta) ~ 1052 erg ≳ 10 larger than Usual CC-SNe

Explosions are aspherical (profiles of nebular lines O vs. Fe and Polarization)
SN 1998bw = SN 1987A

Aspherical explosion

Maeda et al. 2006, 2008
see also Tautenberger et al. 2009

\[ E_K \sim 30 \times 10^{51} \text{ erg} \]

\[ E_K \sim 1 \times 10^{51} \text{ erg} \]
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Modeling lightcurves and spectra

<table>
<thead>
<tr>
<th>Year</th>
<th>Mass Range</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998bw</td>
<td>25-35 M(_\odot)</td>
<td>Woosley 1999;Maeda et al. 2006</td>
</tr>
<tr>
<td></td>
<td>35-40 M(_\odot)</td>
<td>Nomoto et al. 2003</td>
</tr>
<tr>
<td></td>
<td>40 M(_\odot)</td>
<td>Mazzali et al. 2006</td>
</tr>
<tr>
<td>2003dh</td>
<td>40-50 M(_\odot)</td>
<td>Mazzali et al. 2006</td>
</tr>
<tr>
<td>2003lw</td>
<td>20-25 M(_\odot)</td>
<td>Mazzali et al. 2006</td>
</tr>
<tr>
<td>2006aj</td>
<td>20-30 M(_\odot)</td>
<td>Tanaka et al. 2008</td>
</tr>
<tr>
<td>2010bh</td>
<td></td>
<td></td>
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</tbody>
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Distant GRB/SNe?
<table>
<thead>
<tr>
<th>GRB</th>
<th>SN</th>
<th>z</th>
<th>Ref.</th>
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</thead>
<tbody>
<tr>
<td>GRB 021202</td>
<td>SN 2002lt</td>
<td>1.002</td>
<td>Della Valle et al. 2003</td>
</tr>
<tr>
<td>GRB 050525A</td>
<td>SN 2005nc</td>
<td>0.606</td>
<td>Della Valle et al. 2006</td>
</tr>
<tr>
<td>GRB 101219B</td>
<td>SN 2010ma</td>
<td>0.55</td>
<td>Sparre et al. 2011</td>
</tr>
<tr>
<td>GRB 060729</td>
<td>SN no name</td>
<td>0.54</td>
<td>Cano et al. 2011</td>
</tr>
<tr>
<td>GRB 090618</td>
<td>SN no name</td>
<td>0.54</td>
<td>Cano et al. 2011</td>
</tr>
<tr>
<td>GRB 081007</td>
<td>SN 2008hw</td>
<td>0.53</td>
<td>Della Valle et al. 2008</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Zhi-ping et al. 2008</td>
</tr>
<tr>
<td>GRB 091127</td>
<td>SN 2009nz</td>
<td>0.49</td>
<td>Cobb et al. 2010</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Berger et al. 2011</td>
</tr>
<tr>
<td>GRB 120714B</td>
<td>SN 2012eb</td>
<td>0.40</td>
<td>Klose et al. 2012</td>
</tr>
<tr>
<td>GRB 130427A</td>
<td>SN 2013cq</td>
<td>0.34</td>
<td>Melandri et al. 2014</td>
</tr>
<tr>
<td>GRB 120422A</td>
<td>SN 2012bz</td>
<td>0.28</td>
<td>Xu et al. 2013</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Melandri et al. 2012</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.8;0.6;0.48</td>
<td>Cano et al. 2014</td>
</tr>
<tr>
<td>GRB 120729A; 130215A; GRB 130831A</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Della Valle et al. 2003

Bjornsson et al. 2001

Sahu et al. 2000

Cano et al. 2014

Della Valle et al. 2006

Garnavich et al. 2003

up to $z \sim 1$
Berger et al. 2011
SN 2009nz @ z=0.49

Della Valle et al. 2003
SN 2002lt @ z=1

Zhi-Ping et al. 2013
SN 2008hw @ z=0.53
Kelly et al. 2008 find that SNe-Ic and LGRB erupt in the brightest regions of their hosts (see also Fruchter et al. 2006)
<table>
<thead>
<tr>
<th>Year</th>
<th>Mass Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998bw</td>
<td>40 M&lt;sub&gt;☉&lt;/sub&gt;</td>
</tr>
<tr>
<td>2003dh</td>
<td>35-40 M&lt;sub&gt;☉&lt;/sub&gt;</td>
</tr>
<tr>
<td>2003lw</td>
<td>40-50 M&lt;sub&gt;☉&lt;/sub&gt;</td>
</tr>
<tr>
<td>2006aj</td>
<td>20-25 M&lt;sub&gt;☉&lt;/sub&gt;</td>
</tr>
<tr>
<td>2008D</td>
<td>20-30 M&lt;sub&gt;☉&lt;/sub&gt;</td>
</tr>
<tr>
<td>2010bh</td>
<td>25 M&lt;sub&gt;☉&lt;/sub&gt;</td>
</tr>
</tbody>
</table>

The diagram shows the fraction of SNe as a function of mass, with various mass ranges indicated by different lines.
What Stars are GRB Progenitors?

GRB 060218/SN 2006aj
(Campana et al. 2006)

\[ z = 0.033 \]

faint: \( E_\gamma \sim 10^{49} \text{ erg} \)

\[ M_V (\text{host}) = -16 \]

Host has brightness
Similar to SMC

\[ Z/Z_\odot \sim 0.3 \]

2006aj = SN-Ic
Patat et al. 2001

Campana et al. 2006

4 x 10^{11} \text{ cm}

3 \times 10^4 \text{ km/s}
SNe-CC size progenitors

Red Supergiant
R~$4 \times 10^{13}$ cm

Blue Supergiant
R~$4 \times 10^{12}$ cm

The radius of the progenitor W-R Star
R~$4 \times 10^{11}$ cm
Summary

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What is the rate of SNe-Ib/c?

Asiago Survey (Cappellaro et al. 1999)

<table>
<thead>
<tr>
<th>galaxy type</th>
<th>N. SNe*</th>
<th>rate [SNu]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ia</td>
<td>Ib/c</td>
</tr>
<tr>
<td>E-S0</td>
<td>22.0</td>
<td>0.18 ± 0.06</td>
</tr>
<tr>
<td>S0a-Sb</td>
<td>18.5</td>
<td>0.18 ± 0.07</td>
</tr>
<tr>
<td>Sbc-Sd</td>
<td>22.4</td>
<td>0.21 ± 0.08</td>
</tr>
<tr>
<td>Others#</td>
<td>6.8</td>
<td>0.40 ± 0.16</td>
</tr>
<tr>
<td>All</td>
<td>69.6</td>
<td>0.20 ± 0.06</td>
</tr>
</tbody>
</table>

Rate for Ib/c: 0.152 ± 0.064 SNu

\[ 1.8 \times 10^4 \text{ SNe-Ibc Gpc}^{-3} \text{ yr}^{-1} \rightarrow 1.1 \times 10^4 \text{ up to } 2.6 \times 10^4 \]
What is the rate of SNe-Ib/c?

Lick Survey (Li et al. 2011)

<table>
<thead>
<tr>
<th>Rate</th>
<th>SN Ia</th>
<th>SN Ibc</th>
<th>SN II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early (fiducial; SNuK)</td>
<td>$0.064^{+0.008}_{-0.007} (0.013)$</td>
<td>$0.008^{+0.006}_{-0.004} (0.002)$</td>
<td>$0.004^{+0.003}_{-0.002} (0.001)$</td>
</tr>
<tr>
<td>Late (fiducial; SNuK)</td>
<td>$0.074^{+0.006}_{-0.006} (0.012)$</td>
<td>$0.096^{+0.010}_{-0.009} (0.018)$</td>
<td>$0.172^{+0.011}_{-0.011} (0.036)$</td>
</tr>
<tr>
<td>Early (LF-average; SNuK)</td>
<td>$0.048^{+0.006}_{-0.005} (0.010)$</td>
<td>$0.006^{+0.004}_{-0.003} (0.002)$</td>
<td>$0.003^{+0.002}_{-0.001} (0.001)$</td>
</tr>
<tr>
<td>Late (LF-average; SNuK)</td>
<td>$0.065^{+0.006}_{-0.005} (0.010)$</td>
<td>$0.083^{+0.009}_{-0.008} (0.016)$</td>
<td>$0.149^{+0.010}_{-0.009} (0.039)$</td>
</tr>
<tr>
<td>Vol-rate ($10^{-4}$ SN Mpc$^{-3}$ yr$^{-1}$)</td>
<td>$0.301^{+0.038}_{-0.037} (0.049)$</td>
<td>$0.258^{+0.044}_{-0.042} (0.058)$</td>
<td>$0.447^{+0.068}_{-0.068} (0.131)$</td>
</tr>
</tbody>
</table>

Rate for Ib/c: $2.6 \times 10^4$ SNe-Ibc Gpc$^{-3}$ yr$^{-1}$

$2.2 \times 10^4 \rightarrow 3 \times 10^4$ SNe-Ibc Gpc$^{-3}$ yr$^{-1}$
The rate of (long) GRBs is a topic of interest in astrophysics. Various authors have estimated the rate in units of GRB Gpc$^{-3}$ yr$^{-1}$, with different values:

- 1.5: Schmidt 1999
- 0.15: Schmidt 2001
- 0.5: Guetta et al. 2005
- 1.1: Guetta & Della Valle 2007
- 1.1: Liang et al. 2007
- > 0.5: Pelangeon et al. 2008
- 1.3: Wanderman and Piran

The table below summarizes the rate ($z = 0$) and other parameters for different detection methods:

<table>
<thead>
<tr>
<th>Sample</th>
<th>Rate ($z = 0$) Gpc$^{-3}$ yr$^{-1}$</th>
<th>$L^*$ [50–300] keV $10^{51}$ erg/s</th>
<th>$a_1$</th>
<th>$a_2$</th>
<th>$\chi^2$/d.o.f. $^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GBM</td>
<td>0.5$^{+0.3}_{-0.2}$</td>
<td>5.5$^{+1.5}_{-2}$</td>
<td>0.3$^{+0.1}_{-0.5}$</td>
<td>2.3$^{+0.6}_{-0.3}$</td>
<td>1.1</td>
</tr>
<tr>
<td>BATSE</td>
<td>1.0$^{+0.2}_{-0.4}$</td>
<td>4$^{+2}_{-1.5}$</td>
<td>0.1$^{+0.3}_{-0.1}$</td>
<td>2.6$^{+0.9}_{-0.5}$</td>
<td>1.1</td>
</tr>
<tr>
<td>Swift</td>
<td>0.6$^{+0.3}_{-0.1}$</td>
<td>3.3$^{+2.5}_{-0.5}$</td>
<td>0.1$^{+0.3}_{-0.1}$</td>
<td>2.7$^{+1}_{-0.4}$</td>
<td>0.95</td>
</tr>
</tbody>
</table>

The data is based on various surveys and methods, with GBM, BATSE, and Swift being key instruments in these observations.
What is the local rate of (long) GRBs?

0.7 GRB Gpc$^{-3}$ yr$^{-1}$

(0.5-0.8)
What is the fraction of SNe-Ib/c which produces (long)GRBs?

Rate for Ibc: $2.4 \times 10^4$ SNe-Ibc Gpc$^{-3}$ yr$^{-1}$
GRB rate: 0.7 GRB Gpc$^{-3}$ yr$^{-1}$
What is the fraction of SNe-Ib/c which produces (long)GRBs?

Rate for Ibc: \(2.4 \times 10^4\) SNe-Ibc Gpc\(^{-3}\) yr\(^{-1}\)

GRB rate: \(0.7\) GRB Gpc\(^{-3}\) yr\(^{-1}\)

\(<fb^{-1}> \sim 500\) (Frail et al. 2001; Ghirlanda et al. 2013) \((\theta \sim 4^\circ)\)

\(<fb^{-1}> \sim 75\) (Guetta, Piran & Waxman 2004) \((\theta \sim 9^\circ)\)

\(<fb^{-1}> < 10\) (Guetta & DellaValle 2007) \((\theta > 25^\circ)\) for sub-lum GRBs

\(<fb^{-1}> \sim 1\) (Ruffini et al. 2006) \((\text{up to } \theta \sim 4\pi)\)

\(\text{GRB/SNe-Ibc: 1.5\%-0.003\%}\)
GRBs are very rare phenomena

GRB/SNe-Ibc: 1.5%
Ibc/CC ~ 0.30
GRB/CC-SN ~ 5 \times 10^{-3}

\[
\frac{N(30M_\odot-120M_\odot)}{N(8M_\odot-30M_\odot)} \sim 0.15 \text{ (Salpeter IMF)}
\]

What causes some small fraction of CC-SNe to produce observable GRBs, while the majority do not?
Special conditions are requested to stars to be GRB progenitors:

i) to be massive $\sim > 30M_\odot$ (Maeda et al. 2006; Raskin et al. 2008; Tanaka et al. 2008)

ii) H/He envelopes to be lost before the collapse of the core, i.e. the GRB progenitor is a WR star (Campana et al. 2006)


iv) binarity (Panagia 1988 and Smartt et al. 2008 $\rightarrow$ a significant fraction of SNe-Ibc progenitors are binaries)

v) high rotation (Yoon et Langer 2005; Campana et al. 2008, Yoon et al. 2012)

vi) asymmetric explosion (Taubenberger et al. 2009; Maeda et al. 2008)
Open Issues
To BEam or not to BEam
Energy Crisis

Fluence: $10^{-7} \div 10^{-5}$ erg cm$^{-2}$

Distanza: up to $z \sim 10$

Energy: $E_{\text{iso}}$ up to $\sim$ few $\times 10^{54}$ erg

$10^{54}$ erg $\sim 1 \, M\odot \sim \times 5$
But similarly to other astrophysical sources also GRBs are expected to be jetted sources. If this is the case we should expect a clear signature in their light curve time decay due to the presence of a jet. Here is the explanation of the jet break time

Jet effect

Relativistic beaming: emitting surface $\propto 1/\Gamma$

Jet Break $\theta \sim 1/\Gamma$

Log($F$) vs. Log($t$)
$E_{p,i}$ (keV)

$E_{iso}$ (erg)

$E_K$

$E_R$

$PNS \ M=2.5 \ M_\odot;13\text{km} \ ; \ Haensel \ et \ al. \ 2009$

Ghirlanda et al. 2013

Normalized Number of GRBs

Normalized Number of GRBs

$\theta_{gr}$
e.g. Smartt 2009
Induced Gravitational Collapse
(aka binary-driven hypernova scenario)

Izzo et al. 2012
Penacchioni et al. 2013
Fryer et al. 2014, 2015
Ruffini et al. 2014
Stellar Explosions Sequence

Nova system: 
WD + (low mass) MS star 
$M_{WD} \sim 1 M_{\odot}$ 
$10^{44}$ erg 
Rate $\times 10^3$

Supernova Ia system: 
WD + (subgiant) MS star or WD+WD 
$M_{WD} \sim 1.4 M_{\odot}$ 
$10^{51}$ erg 
Rate $=1$

HL-GRB system: 
NS + SN 
$M_{NS} \sim 2 M_{\odot}$ 
$10^{53-54}$ erg 
Rate $< 10^{-2}$
GRBs are very rare phenomena

GRB/SNe-Ibc: 1.5%
Ibc/CC ~ 0.30
\( \frac{N(30M_\odot - 120M_\odot)}{N(8M_\odot - 30M_\odot)} \) ~ 0.15 (Salpeter IMF)

What causes some small fraction of CC-SNe to produce observable GRBs, while the majority do not?