The Empirical Grounds of the SN-GRB Connection

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Outline

• Supernova Taxonomy
• GRB-SN properties
• GRB-SN census
• GRB and SN rates
• Progenitors Properties
• New “entries” (GRB 100316D; GRB 081007; GRB 120422A)
Supernova taxonomy

thermonuclear $< 8M_\odot$

core-collapse $> 8M_\odot$

Thermonuclear $< 8M_\odot$

- Ia
- Si

Core-collapse $> 8M_\odot$

- Ib
- He

- IIb

- Ic

\(\rightarrow\) High KE SNe-Ic \(\rightarrow\) Hypernovae \(\rightarrow\) GRB-SNe
## GRB-SN census (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>
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<td>0.16</td>
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<td>GRB 031203</td>
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<td>0.11</td>
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<tr>
<td>GRB 060218</td>
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<td>Campana et al. 2006</td>
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<td></td>
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<td></td>
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<tr>
<td>GRB 100316D</td>
<td>SN 2010bh</td>
<td>0.06</td>
<td>Chornoch et al., Bufano et al., Starling et al. 2011</td>
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</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)

Very large luminosity: large 56Ni mass (≈ 0.5±0.2 M⊙)

Energy (non-relativistic ejecta) ~ 10^52 erg ≳ 10 larger than usual CC-SNe

Explosions are aspherical (profiles of nebular lines O vs. Fe and Polarization)
GRB-SNe are very energetic events.

Maeda et al. 2006, 2008

Aspherical explosion
see also Tautenberger et al. 2009

$E \sim 30 \times 10^{51}$ ergs

$E \sim 1 \times 10^{51}$ ergs
## GRB-SN census (z > 0.2)

<table>
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<th>GRB</th>
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<th>z</th>
<th>Ref.</th>
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<tr>
<td>GRB 021202</td>
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<td>Della Valle et al. 2003</td>
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<td>GRB 050525A</td>
<td>SN 2005nc</td>
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<td>GRB 081007</td>
<td>SN 2008hw</td>
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<td>GRB 091127</td>
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<td>Sparre et al. 2011</td>
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<td>GRB 060729</td>
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<td>GRB 090618</td>
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<td>Cano et al. 2011</td>
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<td>GRB 120422A</td>
<td>SN 2012bz</td>
<td>0.28</td>
<td>Melandri et al. 2012</td>
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</table>
At higher redshift secure SN identification becomes difficult because the SN gets fainter, which leads to problems of obtaining sufficient signal-to-noise in the spectra, a problem that is aggravated by contamination of the host galaxy and the afterglow.

Time consuming observations → single epoch spectrum
Della Valle et al. 2003

Bjornsson et al. 2001

Sahu et al. 2000

Lazzati et al. 2005

Della Valle et al. 2006

Garnavich et al. 2003

up to $z \sim 1$
Bumps can be produced by different phenomena such as dust echoes or thermal re-emission of the afterglow, or thermal radiation from a pre-existing SN remnant (e.g. Esin & Blandfors 2000; Waxman & Draine 2000; Dermer 2003).
Della Valle et al. 2003

SN 2002lt/GRB 021211

$z = 1.006$

Fe, Ti, Mg

Ca

SN 1991bg

SN 1994I

Della Valle et al. 2003

Rest wavelength (Å)
The near simultaneity of non-thermal (GRB) and thermal (SN) X-ray emissions indicates that the SN and GRB are coeval events within ~a few $10^{-2}$ s.

<table>
<thead>
<tr>
<th>GRB</th>
<th>SN</th>
<th>$+\Delta t(d)$</th>
<th>$-\Delta t(d)$</th>
<th>Ref.</th>
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<td>7</td>
<td>Lazzati et al.</td>
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<td>030329</td>
<td>2003dh</td>
<td>2</td>
<td>8</td>
<td>Kawabata et al Matheson et al</td>
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<td>0</td>
<td>2</td>
<td>Malesani et al.</td>
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<td>041006</td>
<td>Bump</td>
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<td>0</td>
<td>Stanek et al.</td>
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<td>050525A</td>
<td>2005nc</td>
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<td>060218</td>
<td>2006aj</td>
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<tr>
<td>080109</td>
<td>2008D</td>
<td>~0.06</td>
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<td>Mazzali et al. Soderberg et al</td>
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</table>
What is the fraction of SNe-Ib/c which produces (long)GRBs?

Rate for Ib/c: 0.2 SNu
1.2 \times 10^8 L_{B,\odot} \text{Mpc}^{-3} \rightarrow 2 \times 10^4 \text{SNe-Ibc Gpc}^{-3} \text{yr}^{-1}

GRB rate: 0.5-1.1 GRB Gpc^{-3} yr^{-1}

\langle fb^{-1} \rangle \sim 500 \quad \text{(Frail et al. 2001)} \quad (\vartheta \sim 4^\circ)
\langle fb^{-1} \rangle \sim 75 \quad \text{(Guetta, Piran \& Waxman 2004)} \quad (\vartheta \sim 10^\circ)
\langle fb^{-1} \rangle < 10 \quad \text{(Guetta \& DV 2007 for sub-lum GRBs)} \quad (\vartheta > 25^\circ)
\langle fb^{-1} \rangle \sim 1 \quad \text{(Ruffini et al. 2006)} \quad (\vartheta \sim 4\pi)

GRB/SNe-I_{(b)c}: 3\%-0.01\% \quad \text{Guetta and DV 2007}

Radio survey on nearby SNe-Ibc \rightarrow GRB/SNe <3\% \quad \text{(Berger et al. 2003)}
Discovery of a Relaxed Gamma-ray Trigger

A. M. Soderberg¹, R. A. Chevalier⁴, P. Chandra V. Chaplin⁷, V. Connaughton N. Chugai¹¹, M. D. Stritzinger E. M. Levesque¹¹, J. E. Grindl P. A. Milne¹⁶, M. A. P. Torres

¹ Howard Smithsonian Center for Astrophysics

GRB/SNe-Ibc $\sim 1/146$
GRB/SNe-Ibc $\sim 0.7$
< 4.5% at 99%

GRB/SNe-I(b)c $3\%-0.01\%$
the theoretical ratio $\text{GRB/\text{SNeIbc}} \rightarrow 0.1\text{-}0.01\%$

$\text{GRB/\text{SNe-Ibc}} \sim 0.7\%$ ($<5\%$) SN Radio Observations

$\text{GRB/\text{SNe-I}(b)c}: 3\%\text{-}0.01\%$ (GRB vs SN observed rates)
GRBs are very rare phenomena (compared to SN explosions)

GRB/SNe- I_{(b)c}: 3%-0.01%
Ibc/CC ~ 0.25
GRB/CC-SN < 1% or << 1%

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 \( \sim 30-50 \, M_{\odot} \)
Kelly et al. 2008 find that local SNe-Ic erupt in the brightest regions of their hosts (like GRBs, see Fruchter et al. 2006)
Long-GRBs have $\sim 40 \, M_\odot$ Raskin et al. 2008
Modeling lightcurves and spectra

<table>
<thead>
<tr>
<th>Year</th>
<th>Mass 1</th>
<th>Mass 2</th>
<th>Mass 3</th>
<th>Mass 4</th>
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<td>2003dh</td>
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Maeda et al. 2006
Mazzali et al. 2003
Mazzali et al. 2006
Mazzali et al. 2006
Tanaka et al. 2008
Special conditions are requested to stars to be GRB progenitors:

i) to be massive ~ 30-50 $M_\odot$ (Raskin 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)
What Stars are GRB Progenitors?

GRB 060218/SN 2006aj
(Campana et al. 2006; Pian 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
Campana et al. 2006

GRB 060218

XRT (0.3–10 keV)

UVOT

Campana et al. 2006

Time (s)
Campana et al. 2006
SNe-CC size progenitors

Red Supergiant
R~4x10^{13} cm

Blue Supergiant
R~4x10^{12} cm

The radius of the progenitor → W-R Star

R~4x10^{11} cm
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iii) low metallicity and star forming environments (Modjaz et al. 2008, Fruchter et al. 2006)
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v) high rotation (Yoon et Langer 2005; Campana et al. 2008)
A simplified Scheme for GRB-SN events

- an almost isotropic component carrying most energy $10^{52}$ erg and mass ($\sim 5-10M_\odot$) → SN event

- highly collimated component (4°-10° for HL-GRBs and > 25° for LL-GRBs) containing a tiny fraction of the mass ($10^{-4/-5} M_\odot$) moving at $\Gamma \sim x 10^{2-3}$ → GRB
End of the story?
What produces the observed variety in long duration GRB phenomenology?

i) HL-GRBs ($\geq 10^{51}$ erg) + bright Ic (GRB 030323/2003dh)

ii) LL-GRBs ($\leq 10^{49}$ erg) + bright Ic (GRB 060218/SN 2006aj)

iii) LL-GRBs ($\leq 10^{49}$ erg) + faint Ib (GRB 100316D/SN 2010bh)

iv) vLL-GRB ($\leq 10^{46}$ erg) + SN-Ibc (GRB 080109/SN 2008D)

v) HNe w/out GRBs (e.g. 2002ap)

vi) GRBs w/out (bright?) SN (GRB 060614)

vii) GRBs from IC triggered by SN (GRB 090618) \(\rightarrow\) Izzo, Ruffini & Rueda 2012
weak X-ray events ("failed" GRBs ?) + broad Ibc (2008D-like) + Local z LL-GRBs + broad line & bright Ic (2006aj-like) or broad & faint Ib (2010bh) or w/out (bright?) SN (060614);

"Cosmological" HL-GRBs + broad Ic (2003dh-like)

"Local" LL-GRBs + broad line & bright Ic (2006aj-like) or broad & faint Ib (2010bh) or w/out (bright?) SN (060614);