The GRB-SN connection:

*Constraining GRB-SNe progenitors with multi-wavelength observations*

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• Introduction/Background
• Current Research
• Future Research
Background: Supernovae

- Two Types of Supernovae (Physically):
  - Thermonuclear Detonation of white dwarf (Ia)
  - Gravitational Core-Collapse (CC) of massive stars (types II, Ib, Ic)

- Two Types of Supernovae (Observationally):
  - Type I: No H lines in spectra
    - Ia: No H but Si lines
    - Ib: No H, some He
    - Ic: No H, little or no He
  - Type II: Hydrogen present in spectra
    - Further sub-classes depending on LC shape.
Type Ia Supernova Scenario
Core-Collapse Supernova Scenario
All SNe

SNe LCs & Spectra

Type II

Blue Magnitude

Days after maximum light
Background: Gamma Ray Bursts
Background: Gamma Ray Bursts

$T_{90} = 2 \text{ s}$
1. Progenitor
2. Central Engine
3. Outflow properties
4. Prompt emission (gamma, x-rays)
5. Afterglow (x-rays, optical, UV, IR, Radio)
1. Progenitor
GRB : Progenitor Scenarios

Short GRB : Merger of compact objects
GRB : Progenitor Scenarios

Long GRB : Collapse of a massive star
2. Central Engine
GRB: Central Engine

Two popular models:

1. Accretion near the neutrino Eddington Limit on a stellar black hole

   Pros: Similar accretion (at lower rates) is known for AGN and micro-quasars.

   Cons: Many unknowns in the way the engine works.

2. Millisecond Magnetar

   Pros: Once formed, the physics of the outflow launching is better understood and provides late-time engine activity.

   Cons: Severe disadvantage is the limited energy of $5 \times 10^{52}$ ergs.
3. Outflow properties
GRB: Outflow Properties

The outflow is relativistic.

Main evidence from the requirement for low \( \gamma \rightarrow e^- e^+ \) optical depth.

Emission in rest-frame is X-rays, detected at Earth as Gamma-Rays.

Also certain that at least some long GRB outflows are narrowly beamed.

Main open questions:

1. Actual Lorentz Factor of outflow?
2. What is the outflow geometry?
3. What component is the most dominant? Baryonic or Poynting-Flux?
4. Prompt emission (gamma,x-rays)
Popular Model

The popular model is the internal shock model, where the outflow is dissipated by hydrodynamical shocks created by the collision between "blobs" of material in the outflow. Electrons in the collimated outflow are accelerated by the shocks, which cool, radiating the energy in the form of synchrotron radiation.
5. **Afterglow (x-rays, optical, UV, IR, Radio)**
The late afterglow (X-ray, UV, optical, IR, Radio) is generated during the interaction of the collimated outflow with the circumburst medium.

Most popular model is the external forward shock model:

Electrons in the surrounding material are accelerated by the forward shocks, and radiate the energy as synchrotron radiation. The flux in the afterglow follow a power-law decay, both temporally ($t$) and spectrally ($\nu$).

$$\text{flux} \propto t^{-\alpha} \nu^{-\beta}$$
GRB: Afterglow
1. Progenitor (Long GRBs)
Long GRBs (L-GRBs) are thought to occur during the collapse and SNe of a massive star into a NS or BH.

So far five type Ic SNe have been spectroscopically connected to long-GRBs and XRFs:

<table>
<thead>
<tr>
<th>GRB</th>
<th>SN</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRB 980425</td>
<td>SN 1998bw</td>
</tr>
<tr>
<td>GRB 030329</td>
<td>SN 2003dh</td>
</tr>
<tr>
<td>GRB 031203</td>
<td>SN 2003lw</td>
</tr>
<tr>
<td>XRF 060218</td>
<td>SN 2006aj</td>
</tr>
<tr>
<td>XRF 100316D</td>
<td>SN 2010bh</td>
</tr>
</tbody>
</table>

All of the SNe are extremely energetic (> $10^{52}$ erg), leading to them being dubbed "Hypernovae".
GRB – SN Connection: GRB 980425

Galama et al. 1998

[Graph and images related to GRB 980425]
GRB – SN Connection: GRB 030329

Stanek et al. 2003

Matheson et al. 2003
GRB – SN Connection

In addition to the spectroscopic connection, numerous photometric inferences have been seen.

(1) Late-time “bumps” in optical/NIR LCs.

(2) Colour changes indicative of light coming from a core-collapse SN.

(3) Late-time spectrum similar to SN 1998bw.
many red bumps seen in the literature, but these bumps are usually not very well sampled.
GRB – SN Connection

Many questions remain:

1. For all of the GRB–SNe apart from GRB 030329, the GRBs are intrinsically underluminous.

2. Many events defy explanation:
   
   1. XRT 080109 – Shock breakout?
   
   2. GRBs 060505 & 060614 – no SNe.
   
   3. Through modelling it appears some events form a BH (980425, 031203), while others form only a NS.
So while the GRB-SN Connection has been established, many questions still remain:

1. What kind of progenitors produce these events?
2. Are the progenitors all the same?
3. Why do some massive stars form a GRB/XRF while most do not?

...Thus more data is needed to address these questions...
GRB 060729

Detected by Swift on July 29, 2007. (Grupe et al. 2006)

$T_{90} = 115$ s

$z = 0.54$ (Thoene et al. 2006; Fynbo et al. 2009)

Had a remarkably bright X-ray afterglow that was still visible 430 days after the initial trigger (Grupe et al. 2010)

Plateau phases seen in X-ray, UV and optical LCs, which was attributed to prolonged activity by the central engine (Xu et al. 2008)
Procedure:

(1) Optical photometry collected on HST & Ground-based telescopes

(2) Image subtraction on HST images (subtract host flux from Ground-based images)

(3) Model afterglow & subtract from the host-subtracted LCs to make *SN* LCs

**Important**

Three sources of flux for the event:

HOST, AFTERGLOW, SUPERNOVA
**GRB 060729**

![Graph of GRB 060729](image)

**Best-Fit parameters for GRB 060729**

<table>
<thead>
<tr>
<th>$\alpha_1$</th>
<th>$\alpha_2$</th>
<th>$T_{\text{break}}$ (days)</th>
<th>$\chi^2 / \text{dof}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01 ± 0.03</td>
<td>1.65 ± 0.05</td>
<td>0.75 ± 0.08</td>
<td>1.31</td>
</tr>
</tbody>
</table>

*Cano et al. 2011 (under review MNRAS)*
GRB 060729

Cano et al. 2011 (under review MNRAS)
GRB 060729

Cano et al. 2011 (under review MNRAS)
The SED modelling of the host of GRB 060729 indicates:

Best fit models are for a dusty galaxy with a young stellar population and low metallicity.

$$A_v,\text{host} = 1.8 \pm 0.5 \text{ mag}$$

However, at the site of the GRB, the rest-frame extinction is small:

$$A_v < 0.18 \text{ mag}$$

(Schady et al. 2010)

Cano et al. 2011 (under review MNRAS)
GRB 090618 was discovered by Swift on June 18, 2009 (Schady et al. 2009).

$T_{90} = 113 \text{ s}$

$z = 0.54$ (Cenko et al. 2009; Fatkhullin et al. 2009.)

$E_{iso} = 2.57 \times 10^{53} \text{ ergs}$ (Ghirlanda et al. 2010)

Optical data collected on 14 ground-based telescopes; Radio data collected on 3 telescopes; Swift XRT data.

Same procedure as for GRB 060729.

Cano et al. 2011 (under review MNRAS)
The break at $t - t_0 = 0.5$ days implies an opening angle of $\theta_{jet} = 1.5^\circ$, and a corrected gamma-ray emission of $E_{\gamma,\theta} = 8 \times 10^{49}$ erg.

Cano et al. 2011 (under review MNRAS)
Cano et al. 2011 (under review MNRAS)
Cano et al. 2011 (under review MNRAS)
GRB 090618

Determined rest-frame extinction from X-ray to optical SED.

Found:

(1) small rest-frame extinction:

\[ Av = 0.3 \pm 0.1 \text{ mag} \]

(2) Each epoch well fit by broken power-law:

\[ \beta_{\text{opt}} = 0.5, \beta_{\text{x}} = 1.0 \]

(3) Break freq. Decreasing with time—indicating ISM environment (not wind).

Cano et al. 2011 (under review MNRAS)
We have modelled our optical, X-ray and radio data at 1.68 days assuming:

1. Jet-like evolution
2. No self-absorption
3. $f_{\nu} \propto \nu^{1/3}$ for $\nu < \nu_m$

We find a typical freq of the electrons:

$\nu_m = 3.66 \times 10^{11} \text{ Hz}$

Then modelled the radio data using the above assumptions and the results of the SED modelling.
The SNe

**GRB 060729**

**GRB 090618**

**Supernova Properties**

<table>
<thead>
<tr>
<th>GRB</th>
<th>Filter (rest-frame)</th>
<th>$\Delta$ magnitude a</th>
<th>$A_\nu$ b</th>
<th>$M_\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRB 060729</td>
<td>V</td>
<td>+0.0</td>
<td>0.29</td>
<td>-19.43 ± 0.06</td>
</tr>
<tr>
<td>GRB 090618</td>
<td>V</td>
<td>-0.3</td>
<td>0.57</td>
<td>-19.75 ± 0.13</td>
</tr>
</tbody>
</table>

aFainter/Brighter than SN 1998bw

bTotal Extinction (Host & Foreground).
## GRB-SNe vs Local Ibc SNe

Cano et al. 2011 (under review MNRAS)

### Table 7. Peak Rest-Frame V-band Absolute Magnitudes for GRB & XRF-producing SNe

<table>
<thead>
<tr>
<th>GRB</th>
<th>SNe</th>
<th>Redshift (z)</th>
<th>$A_{V,\text{foreground}}$</th>
<th>$A_{V,\text{host}}$</th>
<th>$M_{V}^\text{peak}$ (mag)$^{b,c}$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRB 970228</td>
<td>-</td>
<td>0.695</td>
<td>0.543</td>
<td>0.15</td>
<td>$-18.56 \pm 0.30$</td>
<td>(1), (2), (3)</td>
</tr>
<tr>
<td>GRB 980326</td>
<td>-</td>
<td>$\approx$ 1</td>
<td>0.26</td>
<td>-</td>
<td>$\approx -19.5$</td>
<td>(4)</td>
</tr>
<tr>
<td>GRB 980425</td>
<td>1998bw</td>
<td>0.0085</td>
<td>0.18</td>
<td>0.05</td>
<td>$-19.42 \pm 0.30$</td>
<td>(3), (5), (6), (7), (8), (31)</td>
</tr>
<tr>
<td>GRB 990712</td>
<td>-</td>
<td>0.434</td>
<td>0.09</td>
<td>1.67</td>
<td>$-20.22 \pm 0.20$</td>
<td>(3), (10), (11), (12), (31)</td>
</tr>
<tr>
<td>GRB 991208</td>
<td>-</td>
<td>0.706</td>
<td>0.05</td>
<td>0.76</td>
<td>$-19.46 \pm 0.75$</td>
<td>(9), (16)</td>
</tr>
<tr>
<td>GRB 000911</td>
<td>-</td>
<td>1.058</td>
<td>0.38</td>
<td>0.20</td>
<td>$-18.31 \pm 0.15$</td>
<td>(9), (16)</td>
</tr>
<tr>
<td>GRB 011121</td>
<td>2001ke</td>
<td>0.36</td>
<td>1.33</td>
<td>0.39</td>
<td>$-19.59 \pm 0.33$</td>
<td>(3), (13), (14), (16)</td>
</tr>
<tr>
<td>GRB 020405</td>
<td>-</td>
<td>0.698</td>
<td>0.14</td>
<td>0.15</td>
<td>$-19.46 \pm 0.25$</td>
<td>(3), (15), (16), (31)</td>
</tr>
<tr>
<td>GRB 020410</td>
<td>-</td>
<td>$\approx$ 0.5</td>
<td>0.40</td>
<td>0.0</td>
<td>$\approx -17.6$</td>
<td>(3), (17)</td>
</tr>
<tr>
<td>XRF 020903</td>
<td>-</td>
<td>0.251</td>
<td>0.09</td>
<td>0.0</td>
<td>$-18.89 \pm 0.30$</td>
<td>(3), (18), (31)</td>
</tr>
<tr>
<td>GRB 021211</td>
<td>2002lt</td>
<td>1.006</td>
<td>0.08</td>
<td>0.0</td>
<td>$-18.27 \pm 0.60$</td>
<td>(9), (19), (16)</td>
</tr>
<tr>
<td>GRB 030329</td>
<td>2003dh</td>
<td>0.169</td>
<td>0.07</td>
<td>0.39</td>
<td>$-19.14 \pm 0.25$</td>
<td>(3), (16), (20), (31), (32)</td>
</tr>
<tr>
<td>XRF 030729</td>
<td>-</td>
<td>0.089</td>
<td>0.23</td>
<td>0.23</td>
<td>$\approx -17.9$</td>
<td>(3), (9), (34)</td>
</tr>
<tr>
<td>GRB 031203</td>
<td>2003lw</td>
<td>0.1055</td>
<td>2.77</td>
<td>0.85</td>
<td>$-20.39 \pm 0.50$</td>
<td>(3), (21), (22), (31)</td>
</tr>
<tr>
<td>GRB 040924</td>
<td>-</td>
<td>0.859</td>
<td>0.18</td>
<td>0.16</td>
<td>$-17.47 \pm 0.48$</td>
<td>(23)</td>
</tr>
<tr>
<td>GRB 041006</td>
<td>-</td>
<td>0.716</td>
<td>0.07</td>
<td>0.11</td>
<td>$-19.57 \pm 0.30$</td>
<td>(3), (16), (24)</td>
</tr>
<tr>
<td>GRB 050525A</td>
<td>2005nc</td>
<td>0.606</td>
<td>0.25</td>
<td>0.32</td>
<td>$-18.76 \pm 0.28$</td>
<td>(3), (25), (26), (33)</td>
</tr>
<tr>
<td>XRF 060218</td>
<td>2006aj</td>
<td>0.033</td>
<td>0.39</td>
<td>0.13</td>
<td>$-18.76 \pm 0.20$</td>
<td>(3), (27), (28), (31)</td>
</tr>
<tr>
<td>GRB 060729</td>
<td>-</td>
<td>0.54</td>
<td>0.11</td>
<td>0.18</td>
<td>$-19.43 \pm 0.06$</td>
<td>This paper</td>
</tr>
<tr>
<td>GRB 080319B</td>
<td>-</td>
<td>0.931</td>
<td>0.03</td>
<td>0.05</td>
<td>$-19.12 \pm 0.40$</td>
<td>(29), (33)</td>
</tr>
<tr>
<td>GRB 090618</td>
<td>-</td>
<td>0.54</td>
<td>0.27</td>
<td>0.3</td>
<td>$-19.75 \pm 0.14$</td>
<td>This paper</td>
</tr>
<tr>
<td>GRB 091127</td>
<td>2009nz</td>
<td>0.49</td>
<td>0.12</td>
<td>0.0</td>
<td>$-19.00 \pm 0.20$</td>
<td>(30)</td>
</tr>
</tbody>
</table>

$^a$Host extinction where available.

$^b$Cosmological Parameters used: $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$ $\Omega_M = 0.27$ $\Omega_\Lambda = 0.73$.

$^c$Wherever errors are not quoted in the literature conservative errors of 0.4 mag are used.

### Table 8. Peak Rest-Frame V-band Absolute Magnitudes for Local type Ibc & Ic SNe

<table>
<thead>
<tr>
<th>Type</th>
<th>SNe</th>
<th>Redshift (z)</th>
<th>$A_{V,\text{foreground}}$</th>
<th>$A_{V,\text{host}}$</th>
<th>$M^{peak}_{V}$ (mag)$^{d,e}$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ib</td>
<td>1054A</td>
<td>0.000977</td>
<td>0.07</td>
<td>-</td>
<td>$-18.75 \pm 0.40$</td>
<td>(1)</td>
</tr>
<tr>
<td>Ic</td>
<td>1062L</td>
<td>0.00405</td>
<td>0.12</td>
<td>-</td>
<td>$-18.83 \pm 0.83$</td>
<td>(2), (3)</td>
</tr>
<tr>
<td>Ic</td>
<td>1064L</td>
<td>0.002702</td>
<td>0.07</td>
<td>-</td>
<td>$-18.38 \pm 0.65$</td>
<td>(2), (4)</td>
</tr>
<tr>
<td>Ib</td>
<td>1066J</td>
<td>0.002214</td>
<td>0.04</td>
<td>-</td>
<td>$-19.00 \pm 0.4$</td>
<td>(4)</td>
</tr>
<tr>
<td>Ib</td>
<td>1972R</td>
<td>0.002124</td>
<td>0.05</td>
<td>-</td>
<td>$-17.47 \pm 0.4$</td>
<td>(5)</td>
</tr>
<tr>
<td>Ic</td>
<td>1983I</td>
<td>0.002354</td>
<td>0.04</td>
<td>-</td>
<td>$-18.73 \pm 0.45$</td>
<td>(2), (6)</td>
</tr>
<tr>
<td>Ib</td>
<td>1983N</td>
<td>0.001723</td>
<td>0.20</td>
<td>-</td>
<td>$-18.58 \pm 0.57$</td>
<td>(7)</td>
</tr>
<tr>
<td>Ib</td>
<td>1983V</td>
<td>0.005402</td>
<td>0.06</td>
<td>1.18</td>
<td>$-19.12 \pm 0.41$</td>
<td>(2), (8)</td>
</tr>
<tr>
<td>Ib</td>
<td>1984I</td>
<td>0.01076</td>
<td>0.33</td>
<td>-</td>
<td>$-17.56 \pm 0.40$</td>
<td>(9)</td>
</tr>
<tr>
<td>Ib</td>
<td>1984L</td>
<td>0.005294</td>
<td>0.08</td>
<td>0.0</td>
<td>$-18.84 \pm 0.40$</td>
<td>(10)</td>
</tr>
<tr>
<td>Ib</td>
<td>1985F</td>
<td>0.003167</td>
<td>0.06</td>
<td>0.63</td>
<td>$-20.19 \pm 0.50$</td>
<td>(11)</td>
</tr>
<tr>
<td>Ic</td>
<td>1987M</td>
<td>0.004419</td>
<td>0.08</td>
<td>1.28</td>
<td>$-18.33 \pm 0.71$</td>
<td>(2), (12), (13)</td>
</tr>
<tr>
<td>Ic</td>
<td>1990B</td>
<td>0.007568</td>
<td>0.10</td>
<td>2.53</td>
<td>$-19.40 \pm 1.02$</td>
<td>(2), (14)</td>
</tr>
<tr>
<td>Ic</td>
<td>1991D</td>
<td>0.004752</td>
<td>0.19</td>
<td>-</td>
<td>$-20.01 \pm 0.60$</td>
<td>(15)</td>
</tr>
<tr>
<td>Ic</td>
<td>1991N</td>
<td>0.003119</td>
<td>0.07</td>
<td>-</td>
<td>$-18.67 \pm 1.06$</td>
<td>(15)</td>
</tr>
<tr>
<td>Ic</td>
<td>1992ar</td>
<td>0.1451</td>
<td>0.30</td>
<td>0.0</td>
<td>$-18.84 \pm 0.42$</td>
<td>(2), (16)</td>
</tr>
<tr>
<td>Ic</td>
<td>1994F</td>
<td>0.001544</td>
<td>0.11</td>
<td>1.39</td>
<td>$-17.40 \pm 0.58$</td>
<td>(2), (17), (18)</td>
</tr>
<tr>
<td>Ic</td>
<td>1995bf</td>
<td>0.011693</td>
<td>0.13</td>
<td>0.55</td>
<td>$-17.80 \pm 0.21$</td>
<td>(2), (19), (34)</td>
</tr>
<tr>
<td>Ic</td>
<td>1998as</td>
<td>0.127</td>
<td>0.09</td>
<td>-</td>
<td>$-21.23 \pm 0.20$</td>
<td>(20)</td>
</tr>
<tr>
<td>Ic</td>
<td>1999cq</td>
<td>0.026309</td>
<td>0.16</td>
<td>-</td>
<td>$-19.75 \pm 0.72$</td>
<td>(2), (21)</td>
</tr>
<tr>
<td>Ib/c</td>
<td>1999kn</td>
<td>0.00938</td>
<td>0.16</td>
<td>-</td>
<td>$-17.17 \pm 0.40$</td>
<td>(22)</td>
</tr>
<tr>
<td>Ib/c</td>
<td>1999ex</td>
<td>0.011401</td>
<td>0.06</td>
<td>-</td>
<td>$-17.67 \pm 0.26$</td>
<td>(23)</td>
</tr>
<tr>
<td>Ib/c</td>
<td>2001B</td>
<td>0.005227</td>
<td>0.30</td>
<td>-</td>
<td>$-17.12 \pm 0.40$</td>
<td>(24)</td>
</tr>
<tr>
<td>Ic</td>
<td>2002ap</td>
<td>0.002187</td>
<td>0.20</td>
<td>-</td>
<td>$-17.73 \pm 0.21$</td>
<td>(2), (25)</td>
</tr>
<tr>
<td>Ic</td>
<td>2003L</td>
<td>0.021591</td>
<td>0.06</td>
<td>-</td>
<td>$-18.90 \pm 0.40$</td>
<td>(27)</td>
</tr>
<tr>
<td>Ic</td>
<td>2003jd</td>
<td>0.018286</td>
<td>0.14</td>
<td>0.29</td>
<td>$-19.50 \pm 0.30$</td>
<td>(19), (26), (34)</td>
</tr>
<tr>
<td>Ic</td>
<td>2004aw</td>
<td>0.0175</td>
<td>1.15</td>
<td>0.0</td>
<td>$-18.65 \pm 0.30$</td>
<td>(28)</td>
</tr>
<tr>
<td>Ic</td>
<td>2004ib</td>
<td>0.056</td>
<td>0.07</td>
<td>-</td>
<td>$-19.94 \pm 0.40$</td>
<td>(29)</td>
</tr>
<tr>
<td>Ic</td>
<td>2005bf</td>
<td>0.018913</td>
<td>0.14</td>
<td>-</td>
<td>$-18.23 \pm 0.40$</td>
<td>(30)</td>
</tr>
<tr>
<td>Ic</td>
<td>2005fk</td>
<td>0.2643</td>
<td>0.19</td>
<td>-</td>
<td>$-20.41 \pm 0.40$</td>
<td>(31)</td>
</tr>
<tr>
<td>Ic</td>
<td>2005kr</td>
<td>0.13</td>
<td>0.31</td>
<td>0.27</td>
<td>$-19.08 \pm 0.40$</td>
<td>(19), (29), (34)</td>
</tr>
<tr>
<td>Ic</td>
<td>2005ks</td>
<td>0.10</td>
<td>0.79</td>
<td>0.0</td>
<td>$-17.64 \pm 0.40$</td>
<td>(19), (29), (34)</td>
</tr>
<tr>
<td>Ib/c</td>
<td>2007gr</td>
<td>0.001278</td>
<td>0.19</td>
<td>-</td>
<td>$-19.09 \pm 0.20$</td>
<td>(30)</td>
</tr>
<tr>
<td>Ic</td>
<td>2007tu</td>
<td>0.01546</td>
<td>0.89</td>
<td>-</td>
<td>$-19.09 \pm 0.20$</td>
<td>(31)</td>
</tr>
</tbody>
</table>

* Host extinction where available.

Cosmological Parameters used: $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.27$, $\Omega_{\Lambda} = 0.73$.

Wherever errors are not quoted in the literature conservative errors of 0.4 mag are used.

GRB-SNe vs Local Ibc SNe

When comparing these two samples of SNe we are attempting to answer the following question:

"Are the progenitors of GRB/XRF associated SNe the same as those of local type Ibc SNe without an accompanying GRB/XRF trigger?"

by testing if the distribution of the peak magnitudes are the two SNe are the different.

To do this we performed a Kolomogorov–Smirnov (KS) test on the two samples:

(1) GRB/XRF-SNe (N=22)
(2) Local Ibc SNe (N=34)
(3) Local Ic SNe (N=19)
We performed the KS test twice:

(1) Considering all events

(2) Considering only those events where the host extinction is known.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Number of Data points</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>P^a</th>
<th>D^a</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRB/XRF-associated SNe</td>
<td>22</td>
<td>-19.02</td>
<td>0.77</td>
<td>-</td>
<td>-</td>
<td>all events</td>
</tr>
<tr>
<td>Local type Ic SNe</td>
<td>19</td>
<td>-18.73</td>
<td>1.00</td>
<td>0.16</td>
<td>0.33</td>
<td>all events</td>
</tr>
<tr>
<td>Local type Ibc SNe</td>
<td>34</td>
<td>-18.59</td>
<td>1.04</td>
<td>0.12</td>
<td>0.31</td>
<td>all events</td>
</tr>
<tr>
<td>GRB/XRF-associated SNe</td>
<td>21</td>
<td>-19.00</td>
<td>0.78</td>
<td>-</td>
<td>-</td>
<td>only those with host A_V</td>
</tr>
<tr>
<td>Local type Ic SNe</td>
<td>12</td>
<td>-18.75</td>
<td>1.03</td>
<td>0.54</td>
<td>0.27</td>
<td>only those with host A_V</td>
</tr>
<tr>
<td>Local type Ibc SNe</td>
<td>17</td>
<td>-18.93</td>
<td>0.97</td>
<td>0.88</td>
<td>0.18</td>
<td>only those with host A_V</td>
</tr>
</tbody>
</table>

^a Probability and maximum difference between the GRB/XRF SNe sample and the local SNe sample.
GRB-SNe vs Local Ibc SNe

Table 9. Kolmogorov-Smirnov test results

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Number of Data points</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>P&lt;sup&gt;a&lt;/sup&gt;</th>
<th>D&lt;sup&gt;a&lt;/sup&gt;</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRB/XRF-associated SNe</td>
<td>22</td>
<td>-19.02</td>
<td>0.77</td>
<td>-</td>
<td>-</td>
<td>all events</td>
</tr>
<tr>
<td>Local type Ic SNe</td>
<td>19</td>
<td>-18.73</td>
<td>1.00</td>
<td>0.16</td>
<td>0.33</td>
<td>all events</td>
</tr>
<tr>
<td>Local type Ibc SNe</td>
<td>34</td>
<td>-18.59</td>
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<td>0.12</td>
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<tr>
<td>GRB/XRF-associated SNe</td>
<td>21</td>
<td>-19.00</td>
<td>0.78</td>
<td>-</td>
<td>-</td>
<td>only those with host A&lt;sub&gt;V&lt;/sub&gt;</td>
</tr>
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<td>12</td>
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<td>0.27</td>
<td>only those with host A&lt;sub&gt;V&lt;/sub&gt;</td>
</tr>
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<td>0.18</td>
<td>only those with host A&lt;sub&gt;V&lt;/sub&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup> Probability and maximum difference between the GRB/XRF SNe sample and the local SNe sample.

Cano et al. 2011 (under review MNRAS)
GRB-SNe vs Local Ibc SNe

We find:

(1) Considering all events

Modest probability that the GRB/XRF progenitors are drawn from the same parent population as all of the local Ibc SNe ($P=0.16$), and the local Ic SNe ($P=0.19$).

(2) Considering only those events where the host extinction is known.

Increased probability that the GRB/XRF progenitors are drawn from the same parent populations as the local Ibc SNe ($P=0.88$), and the local Ic SNe ($P=0.60$)

Cano et al. 2011 (under review MNRAS)
GRB-SNe vs Local Ibc SNe

General Conclusion:

The GRB/XRF associated SNe are generally brighter than the local Ibc SNe.

However:

The samples of local Ibc SNe are not complete, they include only those events where a measurement of the peak brightness has been made.

This test only addresses the SNe brightness, it does not address factors such as host and progenitor metallicity and typical outflow velocities.

Cano et al. 2011 (under review MNRAS)
Future Research

(1) XRF 100316D / SN 2010bh
   BVRI LCs (HST & FTS) - pseudo Bolometric LC

(2) GRB 030329 / SN 2003dh
   Afterglow-subtracted BVRI LCs of SN 2003dh - pseudo Bolometric LC
XRF 100316D – SN 2010 bh

Discovered by Swift on March 16, 2010 (Stamatikos et al. 2010) in a near-by disturbed galaxy ($z = 0.059$; Vergani et al. 2010)

X-ray LC similar to XRF 060218, as well as similarly low energy budget:

$$E_{iso} = 4 \times 10^{49} \text{ ergs}$$
(Starling et al. 2010)

Spectroscopic confirmation of type Ic SNe: 2010 bh
(Wiersema et al. 2010)
XRF 100316D – SN 2010 bh

HST photometry
XRF 100316D – SN 2010 bh

HST photometry
GRB 030329 - SN 2003 dh
GRB 030329 – SN 2003 dh

Spectra & photometry from Matheson et al. 2003
GRB 030329 – SN 2003 dh

Photometry from Matheson et al. 2003, Lipkin et al. 2004
Concluding Remarks

Work to date:

Two case-studies of GRB-SNe, similar in peak brightness and temporal evolution as SN 1998bw.

Included these two GRB-SNe with the complete GRB/XRF-SNe sample and compared them to local Ibc SNe (without a GRB-trigger), concluding that GRB/XRF SNe are generally brighter.
Concluding Remarks

Work to do:

XRF 100316D:

Obtain template images for image subtraction on FTS images; create BVRI LCs and create pseudo-Bolometric LCs.

GRB 030329:

Model afterglow & subtract from the host-subtracted LCs to create “SN” LCs.