THE SUPERNOVA – GRB CONNECTION

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Light Curves

Time of peak ($\tau_{peak}$) when diffusion time $\approx$ hydrodynamic time

$$\tau_{peak} \propto M_{ej}^{3/4} E^{-1/4}$$

Peak luminosity mainly depends on $M(^{56}\text{Ni})$

Models (Mazzali et al.)

<table>
<thead>
<tr>
<th>SN</th>
<th>$M(^{56}\text{Ni})$ ($M_\odot$)</th>
<th>$M_{ej}^{3/4} E_5^{-1/4}$</th>
<th>$M_{ej}$ ($M_\odot$)</th>
<th>$E$ ($10^{51}$ ergs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994I</td>
<td>0.07</td>
<td>0.9</td>
<td>0.9</td>
<td>1</td>
</tr>
<tr>
<td>1997ef</td>
<td>0.13</td>
<td>2.7</td>
<td>7.6</td>
<td>8</td>
</tr>
<tr>
<td>1998bw</td>
<td>$\sim$ 0.5</td>
<td>2.2</td>
<td>$\sim$ 10</td>
<td>30–60</td>
</tr>
<tr>
<td>2002ap</td>
<td>0.07</td>
<td>1.4</td>
<td>2.4</td>
<td>4</td>
</tr>
</tbody>
</table>
Supernova \[ \rho_{sn} \propto r^{-n} \]
Wind \[ \rho_w \propto r^{-2} \]
\[ \Rightarrow \] shock radius \[ R \propto t^{(n-3)/(n-2)} \quad (n \geq 5) \]

\[ n = 12 \quad R \propto t^{0.9} \]
Constant energy \[ R \propto t^{0.67} \]
Model for SN 1994I radio

Supernova \[ \rho_{sn} \propto r^{-12} \]
Wind \[ \rho_{w} \propto r^{-2} \]
Energy densities \[ e_B, e_{el} \propto e_{postshock} \]
\[ N(E) \propto E^{-p} \quad p = 3.0 \]
Synchrotron radiation + synchrotron self-absorption

Results for day 30:
\[ v_{sh} = 40,000 \text{ km s}^{-1}, \ B = 0.5 \text{ G} \]
\[ E_{min} \approx 10^{47} \text{ ergs (particles and fields)} \]

Nonrelativistic analog of GRB afterglow models, except that energy rises with time.
SN 1998bw

 Likely to be associated with GRB 980425

$z = 0.0085$

$E_{\gamma, isotropic} = 7 \times 10^{47} \text{ ergs}$
Models for GRB980425/SN 1998bw

1. Shock accelerated outer envelope (like radio supernovae)  
   (Woosley et al. 1999; Tan, Matzner, & McKee 2001)

2. Power from central engine comes out in collimated flow

   a) Low $\gamma$-ray energy burst unlike standard cosmological bursts  
      (Bloom et al. 1998)

   b) Standard burst observed off-axis

      i) Homogeneous jet with a sharp edge  
         (Nakamura 1999; Granot et al. 2002)

      ii) Inhomogeneous jet  
         (Granot et al. 2002)
Standard Burst

Jet (collimated flow) typically in uniform medium

\[ E_\gamma \approx 5 \times 10^{50} \text{ ergs, when corrected for the beam-} \]
\[ \text{ing angle} \]
(Frail et al. 2001)

\[ E \approx 5 \times 10^{50} \text{ ergs (within a factor } \sim 10\text{), total} \]
\[ \text{energy in afterglow from modeling afterglow light} \]
\[ \text{curves} \]
(Panaitescu & Kumar 2002)
GRB980425/SN 1998bw

Modeling of radio emission (afterglow) (Li & RAC 1999)

 Mostly constant energy, but increase from
$\sim 1 \times 10^{49} \text{ ergs}$ to $\sim 4 \times 10^{49} \text{ ergs}$ at days 20–40
(minimum energies)

Inhomogeneous jet?
SN bumps in GRB light curves

GRB 970228 ($z=0.695$)
Supernova like SN 1998bw

GRB 980326 ($z=?$)
Supernova like SN 1998bw if $z \approx 1$

GRB 011121 ($z=0.36$)
Supernova similar to SN 1998bw, but fainter by 55% and faster by 17%
Optical Afterglows of “SN”–GRB’s

\[ F_\nu \propto t^{-\alpha_\nu \nu^{-\beta}} \]

<table>
<thead>
<tr>
<th>GRB</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>970228</td>
<td>1.58 ± 0.28</td>
<td>0.61 ± 0.32</td>
<td>Reichart 1999</td>
</tr>
<tr>
<td>980326</td>
<td>2.0 ± 0.1</td>
<td>0.8 ± 0.4</td>
<td>Bloom et al. 1998</td>
</tr>
<tr>
<td>011121</td>
<td>1.66 ± 0.06</td>
<td>0.76 ± 0.15</td>
<td>Price et al. 2002</td>
</tr>
</tbody>
</table>

Early decline rate is relatively rapid. Consistent with:

- interaction with Wind ($\rho \propto r^{-2}$)

\[ \nu_{\text{optical}} < \nu_{\text{cooling}} \]

- decelerated jet
**Gamma-ray energy (corrected for jet)**

Use observed range of $t^{-\alpha}$ behavior to set lower and upper limits on $t_{\text{jet}}$ and $E_\gamma$

<table>
<thead>
<tr>
<th>GRB</th>
<th>$t_{\text{jet}}$ (days)</th>
<th>$E_{\gamma, \text{isotropic}}$ (ergs)</th>
<th>$E_{\gamma}$ (ergs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>970228</td>
<td>$&lt; 0.7$</td>
<td>$1.4 \times 10^{52}$</td>
<td>$&lt; 3 \times 10^{49}$</td>
</tr>
<tr>
<td></td>
<td>$&gt; 10$</td>
<td></td>
<td>$&gt; 2 \times 10^{50}$</td>
</tr>
<tr>
<td>980326</td>
<td>$&lt; 0.5$</td>
<td>$3.4 \times 10^{51}$</td>
<td>$&lt; 8 \times 10^{48}$</td>
</tr>
<tr>
<td>($z = 1$)</td>
<td>$&gt; 5$</td>
<td></td>
<td>$&gt; 2 \times 10^{50}$</td>
</tr>
<tr>
<td>011121</td>
<td>$&lt; 0.5$</td>
<td>$1 \times 10^{52}$</td>
<td>$&lt; 2 \times 10^{49}$</td>
</tr>
<tr>
<td></td>
<td>$&gt; 7$ (radio)</td>
<td></td>
<td>$&gt; 2 \times 10^{50}$</td>
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</table>
## Afterglow models (Panaitescu & Kumar 2002)

<table>
<thead>
<tr>
<th>GRB</th>
<th>ISM preferred</th>
<th>Wind or ISM preferred</th>
</tr>
</thead>
<tbody>
<tr>
<td>970508</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>980519</td>
<td>X</td>
<td></td>
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<tr>
<td>990123</td>
<td>X</td>
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<tr>
<td>990510</td>
<td>X</td>
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<tr>
<td>991208</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>991216</td>
<td></td>
<td>X</td>
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<tr>
<td>000301c</td>
<td>X</td>
<td></td>
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<tr>
<td>000418</td>
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<td>000926</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>010222</td>
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<td>X</td>
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</table>
GRB 970508

Possible SN bump in $I$ band light curve, broader than SN 1998bw light curve (Sokolov 2001)

Wind interaction models:

Spherical model (Chevalier & Li 2000)
$E = 3 \times 10^{51}$ ergs

Off-axis jet model (Panaitescu & Kumar 2002)
$E = 1.6 \times 10^{51}$ ergs

Possible inhomogeneous jet
<table>
<thead>
<tr>
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<th>Wind or ISM preferred</th>
<th>SN, or X-ray lines</th>
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<tbody>
<tr>
<td>970228</td>
<td>X</td>
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<tr>
<td>970508</td>
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<td>980425</td>
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<tr>
<td>011121</td>
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<td>X</td>
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</tr>
<tr>
<td>011211</td>
<td>(X)</td>
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<td>X</td>
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Speculative hypothesis:

Among the long duration GRBs, there are two types of progenitors:

- massive stars that lead to interaction with a stellar wind and supernovae
- compact binaries that lead to interaction with the ISM

The massive star case may involve broader, structured jets