The redshift distribution of Gamma-Ray Bursts: Evidence for evolution

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1. Long GRBs can be detected up to very large distances

As pointed out by several authors (e.g. Lamb & Reichart 2000)

• Long GRBs are intrinsically very bright;
• Gamma-rays are un-absorbed;

The brightest GRB could be detected up to $z > 10$.

• With appropriate instruments, it is possible to detect the optical/IR afterglow and measure the distance.

Bright afterglows could be detected up to $z \sim 8-10$. 
2. GRBs are expected to be produced even at very large distance.

Some have already been detected: SWIFT burst GRB 050904 at $z=6.29$

TAROT detection:
86 s after the burst: $I\sim16$
(Quasar: $z=6.37$, $I=23.3$)

Timescales are multiplied by $1+z = 7.3$ ! ($T_{90}>200$ s)
2. GRBs are expected to be produced even at very large distance.

Some have already been detected: SWIFT burst GRB 050904 at z=6.29
2. GRBs are expected to be produced even at very large distance.

However: a massive star is not enough. More conditions: rotation? binarity? metallicity?

It is not clear if pop. III stars can produce GRBs. See talk by T. Bulik.

Long GRBs are most probably associated with massive stars. First stars are probably massive and at z~10-15. (cf. WMAP results)
3. How to detect the afterglow of a high redshift GRB?

**GRB**: image mode (cf. GRB 050904); X-ray band, ...

cf. Nousek’s talk on SWIFT

cf. Schanne’s talk on ECLAIRs

**Afterglow**: (Near-)Infrared
Rapid follow-up

cf. Goldoni’s talk on X-SHOOTER

**Bonus (e.g. Lamb & Reichart 2001)**:

You observe … 10 min after the burst

This means in the source frame … 5 min after the burst @ z = 1
55 s after the burst @ z = 10

The afterglow is intrinsically brighter so that the decrease of the flux due to the larger luminosity distance is partially compensated.
4. What can be done using high z GRBs?

- Spectrum: intergalactic medium (cf. QSOs)
  host galaxy (interstellar medium)

Example: GRB 050730 @ z=3.969 (Chen et al. 2005)
R=17.7, 4 h after the burst.

ISM: N(HI)=22.15
Z/Z⊙~1/100

IGM: DLA @ z=3.564
LLS @ 3.022
MgII abs. @ z=2.253, 1.773
4. What can be done using high z GRBs?

- Spectrum: intergalactic medium (cf. QSOs)
  host galaxy (interstellar medium)
- Tracing the SFR up to high z: knowing the intrinsic properties of GRBs and understanding the progenitors is needed.
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- Learning something on pop. III stars, on the reionization epoch, …: OK if pop. III stars can produce GRBs…
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- Measuring cosmological parameters: OK if Amati/Ghirlanda/... relations are understood and if one can measure all required quantities (peak energy, break time).

Ghirlanda et al. 2005
4. What can be done using high z GRBs?

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  • Etc.

How many GRBs can be expected for such studies?
The redshift distribution of long GRBs


Motivation:
- Do long GRB trace the star formation rate?
- What is the expected rate of GRBs at high redshift?

Method: we use Monte-Carlo simulations. This allows:
- a « realistic » parametrization of the spectrum ($\alpha$, $\beta$, $E_p$ have dispersion).
- a « realistic » treatment of detection criteria by several instruments.
- a study of the impact of the uncertainties in the GRB intrinsic properties on the predicted GRB rate.
Luminosity function: power-law

3 free parameters: $L_{\text{min}}$ (or $L_*$), $L_{\text{max}}$ and $p$. 
Spectrum:

- Low-energy slope $\alpha$ : observed distribution (Preece et al. 2001)
- High-energy slope $\beta$ : observed distribution (Preece et al. 2001)

(1) "Amati-like" relation $E_p \propto L^{0.43}$ with normal dispersion $\sigma = 0.2$

and $E_p = 380$ keV @ $L = 1.6 \times 10^{52}$ erg/s

No free parameter.

(2) $E_p$ has a normal distribution with $<\log(E_p)> = \log(E_{p0})$ and $\sigma = 0.3$

One free parameter ($E_{p0}$).
Rate :

Rate(GRB) \propto \text{SFR} \ ; \ \text{constant } k = \frac{\text{Rate(GRB)}}{\text{Rate(SN)}} \ (\text{Porciani & Madau 2001}).

Fit to observed SFR (Hopkins et al. 2005) + Extrapolation at high redshift.

- SFR1 : SFR decreases for $z > 2$
- SFR2 : SFR constant for $z > 2$
- SFR3 : SFR increases up to $z=z_{\text{max}}=20$

One free parameter ($k$).
Three different observational constraints:

- BATSE Log(N)-Log(P) diagram (Kommers et al. 2000; Stern et al. 2001, 2002).

- Observed Epeak distribution of long bright bursts (Preece et al. 2001).

- Observed fraction of XRF+XRR by HETE-2 (Sakamoto et al. 2004).
Three instruments:

- **BATSE**: 50 keV – 300 keV; same sensitivity as in Kommers et al. 2000; Stern et al. 2001,02. Bright bursts (for comparison with Preece et al. 2001): $P > 5 \text{ ph/cm}^2/\text{s}$ (i.e. ~ 5-10 % brightest)

- **HETE-2 / WXM**: 2-10 keV; $P > 1 \text{ ph/cm}^2/\text{s}$
  30-400 keV; $P > 1 \text{ ph/cm}^2/\text{s}$

- **SWIFT**: 15 - 150 keV; $P > 0.2 \text{ ph/cm}^2/\text{s}$
  Bright SWIFT GRBs: $P > 1 \text{ ph/cm}^2/\text{s}$
(1) \( E_p \propto L^{0.43} \)

4 parameters: \( L_{\text{min}}, L_{\text{max}}, p, k \)
All simulated models.
All simulated models.

Best models: $\log N - \log P$. 

Parameter space
Figure: Parameter space

- All simulated models.
- Best models: $E_p$. 
All simulated models. 
Best models : XRF fraction.
All simulated models.

Best models: \( \log N - \log P \).
Best models: \( E_p \).
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Best models: \(\log N - \log P\).
Best models: \(E_p\).
Best models: XRF fraction.

Best models: All constraints.
Parameter space

All simulated models.

Best models: All constraints.
All simulated models.

Best models: All constraints.
Best fit: SFR1
Best fit: **SFR2**
Best fit: SFR3
## Results

<table>
<thead>
<tr>
<th>SFR</th>
<th>log $L_{\text{min}}$</th>
<th>log $L_{\text{max}}$</th>
<th>$\delta$</th>
<th>log $k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>49.9 ± 0.5</td>
<td>53.7 ± 0.4</td>
<td>1.70 ± 0.08</td>
<td>−5.4 ± 0.3</td>
</tr>
<tr>
<td>2</td>
<td>50.0 ± 0.5</td>
<td>53.7 ± 0.5</td>
<td>1.68 ± 0.10</td>
<td>−5.5 ± 0.3</td>
</tr>
<tr>
<td>3</td>
<td>50.3 ± 0.7</td>
<td>53.5 ± 0.4</td>
<td>1.54 ± 0.18</td>
<td>−6.0 ± 0.2</td>
</tr>
</tbody>
</table>

Amati-like relation $E_p \propto L^{0.43}$

### Rate

<table>
<thead>
<tr>
<th>Rate</th>
<th>All</th>
<th>SWIFT</th>
<th>Bright SWIFT</th>
</tr>
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<tbody>
<tr>
<td>SFR1</td>
<td>3.1</td>
<td>1.6</td>
<td>1.3</td>
</tr>
<tr>
<td>SFR2</td>
<td>8.0</td>
<td>1.9</td>
<td>1.5</td>
</tr>
<tr>
<td>SFR3</td>
<td>10.5</td>
<td>3.3</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Amati-like relation $E_p \propto L^{0.43}$
Best fit: intrinsic $E_{\text{peak}}$ distribution

The intrinsic $E_{\text{peak}}$ distribution is centered at low energy (~ a few keV).

The observed $E_{\text{peak}}$ distribution is not representative.
Best fit: **Amati-like relation**

The intrinsic slope is not modified by detection criteria.
**Best fit:** Redshift distribution (SFR1)

All GRBs
SWIFT observations (Jakobsson et al. 2005)
Best model: SWIFT GRBs (all/bright)
Best fit: Redshift distribution (SFR2)

All GRBs
SWIFT observations (Jakobsson et al. 2005)
Best model: SWIFT GRBs (all/bright)
**Best fit**: Redshift distribution (SFR3)

All GRBs
SWIFT observations (Jakobsson et al. 2005)
Best model: SWIFT GRBs (all/bright)
\[ (2) \quad E_p = C^{ST} \]

5 parameters: \( L_{\text{min}}, L_{\text{max}}, p, k \) and \( E_{p0} \)
## Results

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<tr>
<th>SFR</th>
<th>$\log L_{\text{min}}$</th>
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<th>$\delta$</th>
<th>$\log k$</th>
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<tr>
<td>1</td>
<td>50.2 ± 0.9</td>
<td>53.6 ± 0.8</td>
<td>1.62 ± 0.18</td>
<td>−5.6 ± 0.3</td>
</tr>
<tr>
<td>2</td>
<td>50.2 ± 1.1</td>
<td>53.6 ± 0.9</td>
<td>1.62 ± 0.27</td>
<td>−5.7 ± 0.3</td>
</tr>
<tr>
<td>3</td>
<td>50.5 ± 1.3</td>
<td>53.7 ± 0.9</td>
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<td>−6.2 ± 0.2</td>
</tr>
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**log-normal distribution peak energy distribution**

<table>
<thead>
<tr>
<th>SFR</th>
<th>$\log E_{p,0}$</th>
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<tbody>
<tr>
<td>1</td>
<td>2.74 ± 0.08</td>
</tr>
<tr>
<td>2</td>
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<td>3</td>
<td>2.79 ± 0.08</td>
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**log-normal distribution peak energy distribution**

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<td>SFR3</td>
<td>10.5</td>
<td>4.8</td>
<td>2.7</td>
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**log-normal peak energy distribution**
Best fit: intrinsic $E_{\text{peak}}$ distribution

The observed $E_{\text{peak}}$ is representative of the intrinsic distribution.
Best fit: Amati-like relation

Selection effects do not produce an Amati-like relation.
**Best fit**: redshift distribution (SFR1)

- **All GRBs**
- **SWIFT observations** (Jakobsson et al. 2005)
- **Best model**: SWIFT GRBs (all/bright)
Best fit: redshift distribution (SFRz)

All GRBs
SWIFT observations (Jakobsson et al. 2005)
Best model: SWIFT GRBs (all/bright)
Best fit: redshift distribution (SFR3)

All GRBs
SWIFT observations (Jakobsson et al. 2005)
Best model: SWIFT GRBs (all/bright)
Luminosity function:

- Slope very well constrained: $p \sim 1.5-1.7$
- Minimum and maximum luminosity less constrained:
  $L_{\text{min}} \sim 2 \times 10^{49} - 2 \times 10^{50} \text{ erg/s}$ ; $L_{\text{max}} \sim 2 \times 10^{53} - 4 \times 10^{53} \text{ erg/s}$

Intrinsic $E_{\text{peak}}$ distribution:

- AMATI: Peaks at low energy (a few keV) ⇒ many un-detected XRRs/XRFs.
- EPCST: Peaks at $E_{\text{peak}} \sim 100 \text{ keV}$ (Amati relation is not reproduced).
### Summary

#### Amati-like relation $E_p \propto L^{0.43}$

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<tbody>
<tr>
<td>Rate</td>
<td>$(z &gt; 6)$</td>
<td>$(z &gt; 7)$</td>
</tr>
<tr>
<td>SFR1</td>
<td>0.7%</td>
<td>0.4%</td>
</tr>
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<tr>
<td>SFR3</td>
<td>15%</td>
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#### log-normal peak energy distribution

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<td>0.6%</td>
</tr>
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<td>4.5%</td>
<td>2.9%</td>
<td>1.6%</td>
</tr>
<tr>
<td>SFR3</td>
<td>21%</td>
<td>17%</td>
<td>6.2%</td>
</tr>
</tbody>
</table>
Summary

Rate:

- One GRB for $10^5 - 10^6$ supernovae.
- The present redshift distribution of SWIFT GRBs strongly favors SFR3 (i.e. increases above $z=2$).
  - « Bright SWIFT GRBs » (P>1 ph/cm$^2$/s): 5% (9%) @ $z > 5$
    All SWIFT GRBs: 19% (27%) @ $z > 5$
  - « Bright SWIFT GRBs » (P>1 ph/cm$^2$/s): 2% (4%) @ $z > 7$
    All SWIFT GRBs: 12% (17%) @ $z > 7$

cf. Jakobsson et al. 2005: 7-40% @ $z > 5$
Bromm & Loeb 2006: 10% @ $z > 5$

The detected rate of high z GRBs can still be improved.
Summary

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  Bromm & Loeb 2006 : 10% @ $z > 5$

■ This SFR is unrealistic : it implies some evolution effects, i.e.
  ► higher efficiency for GRB production at high $z$ ?
  ► and/or higher GRB luminosity at high $z$ ?

Do GRB really trace the SFR ? (metallicity effects ? see E. Le Floch et al. 06)