Current Status of GRB observations

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What’s GRB?

• GRBs = Gamma-Ray Bursts
  sudden and unpredictable bursts in hard X to
gamma rays with huge intensities.
Discovery

- In late 1960’s by Vela satellites (Klebesadel et al 1972).
Spatial distributions

2704 BATSE Gamma-Ray Bursts

Counts per Second

Time in Seconds

Fluence, 50-300 keV (ergs cm$^{-2}$)
The GRB zoo: light-curves

- measured rate (by an all-sky experiment on a LEO satellite): \(~0.8 / \text{day}\); estimated true rate \(~2 / \text{day}\)

- fluences (= av.flux \(*\) duration) typically of \(~10^{-7} \text{ - } 10^{-4} \text{ erg/cm}^2\)

- diverse and unclassifiable light curves
GRB ENERGY SPECTRA ARE PROBABLY THE HARDEST OF ALL THE KNOWN ASTROPHYSICAL OBJECTS

![Graph showing energy spectra of different objects.](image)

- **Gamma-Ray Burst**
- **Crab Nebula + Pulsar**
- **X-Ray Binary**

**Energy Spectrum**

- Energy per decade, keV/cm² s keV
- Energy, keV

Log-log plot with energy on the x-axis and energy per decade on the y-axis.
Gamma-ray Spectra: Broken power-law ("Band" form)
Empirical spectral models of GRBs

$E_0 = \frac{E_{\text{peak}}}{2 + \alpha}$

$E_{\text{break}} = (\alpha - \beta) E_0$

$E_\alpha \exp \left( -\frac{E}{E_0} \right)$

$E_\beta$
Spectral parameters of GRBs (BATSE)

Band function

\[
\alpha
\]

\[
E_p
\]

\[(\beta \sim -2.5)\]

\[
200 - 300 \text{ keV}
\]

(BATSE spectral catalog, Preece et al. 2000)
Synchrotron Shock Model (SSM) with electron cooling (Sari et al. 1996, 1998)

Electron distribution of energies $\gamma$:

$$N(\gamma) \propto \gamma^{-p} \quad (\gamma_{\text{min}} < \gamma < \gamma_{\text{max}})$$

- $\nu_a$: self-absorption frequency
- $\nu_c$: cooling frequency
- $\nu_m$: synchrotron frequency of the minimum-energy electrons

$E_{\text{peak}} \sim \nu_m$
Bimodal Distribution

- bimodal distribution of durations: short and long GRBs
- short GRBs tend to be spectrally harder than long GRBs
An Example Long-Duration BURST

GRB 021206
ULYSSES
25-150 keV
Breakthrough
(\textbf{GRB970228})

\begin{itemize}
  \item \textbf{1997 Feb 28}: 8hrs
  \item \textbf{1997 Mar 3}: 3days
\end{itemize}
Optical transient
Fading afterglow

Index $= -1.6 \sim -1.2$

Index $= -2.1 \sim -1.1$
Radiations from GRB: “prompt” and “afterglow emission”

Adapted from Maiorano et al., A&A, 2005
FIREBALL MODEL

$\Gamma_R$  
$\Gamma_S$  

1-6 AU  
20 km  
1000-2000 AU

$\gamma$-RAYS

INTERNAL SHOCK  
EXTERNAL SHOCK

X-RAYS

ISM

OPTICAL  
RADIO
GRB970508:
large redshift determined first in the history of GRBs

\[ z = 0.835 \]
HOST GALAXIES OF THE LONG GRBS

• Are faint ($m_R \sim 26$); ~10 m-class telescopes required
• Aren’t pretty
• But they are normal (i.e. not active) galaxies with high star-formation rates
THE GRB REDSHIFT DISTRIBUTION

Number of bursts

Redshift

HIGHEST: 6.3;
HUGE ENERGY REQUIRED?

GRB990123

“The largest explosion in the Universe after the big bang”

Z = 1.60

Fluence(γ) = 5.1x10^{-4} erg/cm^{2}

E_{\text{ISO}}(\gamma) = 2x10^{54} \text{erg}
• Taking everything at face value, the isotropic energies in gamma-rays alone range from $>10^{51}$ to $>10^{54}$ erg for the long GRBS!!

• Where does it all come from?

• Collapse of a massive star ($30 \, M_\odot$) to a black hole fed by an accretion torus
Collimation is also required

- Collimation into a cone of 5–10° (jet!) decreases the gamma-ray energies by two orders of magnitude, to $\sim 10^{51}$ erg

- It also increases the total burst rate by the same factor, but this does not contradict anything we know about star formation and evolution
Jet & relativistic beaming
sideway expansion

$\Gamma^{-1} < \theta_o$

$\Gamma^{-1} > \theta_o$

Break of the slope
Evidence of jet

$\alpha = -0.82$

$\alpha = -2.18$

GRB990510
Optical/IR
Light Curve

Harrison et al. 99
“Standard energy”
Frail’s relation

\[ E_\gamma \propto E_{\text{iso}} \theta_{\text{jet}}^2 \]

\[ E_\gamma = (1.33 \pm 0.07) \times 10^{51} \text{ erg} \]

(Frail et al. 2001)
(Bloom et al. 2003)
GRB & SN
GRB980425/SN1998bw

- Optical Afterglow
  - Neither power-law temporal decay nor power-law spectra.
  - Not explained by the standard fire-ball model.

Supernova (SN 1998bw)

- Chance Probability $\sim 10^{-4}$
- $z = 0.0085$ (36Mpc)
  (the nearest GRB)
(Galama et al. 1998; Iwamoto et al. 1998)
GRB980425: A peculiar (?) GRB

Burst Fluence

\[ f_{GRB} \sim 4 \times 10^{-6} \text{ erg cm}^{-2} \]

Duration

\[ T_{90} \sim 23 \text{ sec} \]

No emission above 300 keV

1/4 in BATSE catalogue

“Normal” long duration GRB with \( z = 0.0085 \)

\[ E_{iso,\gamma} \sim 10^{48} \text{ ergs} \ll 10^{52} \text{ ergs} \]

Very weak GRB

Pian et al. 1999

Galama et al. 1998
SN1998bw: A peculiar SN Ic

Featureless

Broad Features

Bright & Broad light curve
Association with Supernova?

**light curves of GRB 970228**

![Graph showing light curves of GRB 970228 in V, R_c, and I_c bands]

**Fig. 3.** — The V-, R_c-, and I_c-band lightcurves of GRB 970228 (fluxes versus time). The dotted curves indicate power-law decays with $\alpha = -1.73$, and redshifted SN 1998bw light curves. The thick line is the resulting sum of SN and power-law decay light curves.
The brightest GRB localized by HETE-2

- Duration in the 30-400 keV band was > 25 s.
- The fluence of the burst was ~1 x 10^-4 ergs cm^-2
- peak flux over 1.2 s was > 7 x 10^-6 ergs cm^-2 s^-1 (i.e., > 100 x Crab flux)
- X-ray afterglow: 7 mCrab (RXTE, +5 hr)
Light curve by ROTSE

Object 571 of 18022, Designation: ROTSE3 J104450.01+213117.7

GRB 030329 +
GRB 990123 ×

GRB990123

GRB030329
Red shift determined by VLT unit Kueyen
(GCN 2020, Greiner et al.)

\[ Z = 0.1685 \]
GRB030329
The “POSTER CHILD”
for the long GRB–Supernova connection

• GRB030329 was a bright (top 1%) nearby (z=0.17) burst, discovered by HETE

• It is the best-studied GRB to date (>>100 observations, ~50 publications)

• Its optical afterglow light curve and spectrum point clearly to an underlying supernova Ic component (SN2003dh)

• **GRB030329 is the most convincing case** among those having showed possible SN signatures (including GRB980425/SN1998bw).
• Optical afterglow spectrum resembles that of SN1998bw/
• 1997ef
• Broad, shallow absorption lines imply large expansion velocities

⇒ Some long GRB’s are associated with the deaths of massive stars (>30M☉)

• Afterglow light curve can be decomposed into two components: power law decay + supernova bump (SN1998bw redshifted)
Another smoking gun?
GRB 031203

INTEGRAL detection of GR031203 shows
- $E_p \gtrsim 190\text{keV}$
- $0.36 < S_x/S_g < 0.53$
  - X-ray Rich GRB

Sazonov et al. 2004

$z = 0.106$ (host gal.)
(2nd nearest GRB)

$E_{iso} = 4 \times 10^{49} \text{erg}$
Faint afterglow
Possible SN counterpart of GRB031203

comparison with that of SN1998bw

Melesani et al. 2004
X-ray flashes
X-ray flash

X-ray rich GRB

WFC/BeppoSAX
**Ginga** (Strohmayer et al. 1998)  

- $\alpha$  

$\log E_p \text{ [keV]}$  

- Number of events  

**WFC / BATSE** (Kippen et al. 2002)  

- Peak Flux $P_{1024}$ (ph cm$^{-2}$ s$^{-1}$)  

$E_p \text{ (keV)}$  

(22 GRBs)
GRB020903

Trigger time: 10:05:37.96 on 2002 September 3

Burst properties:
- Duration (2-10 keV): 4.9 s (T50), 9.8 s (T90)
- X-ray / γ-ray fluence ratio: \( S(2-30 \text{ keV}) / S(30-400 \text{ keV}) = 7.3 \)
GRB020903

Trigger time: 10:05:37.96 on 2002 September 3

Burst properties:
- Duration (2-10 keV): 4.9 s (T50), 9.8 s (T90)
- X-ray / γ-ray fluence ratio: $S(2-30 \text{ keV}) / S(30-400 \text{ keV}) = 5.6$

Afterglow candidate:
- Optical transient (Palomar 200-inch, Soderberg et al.)
- Redshift of underlying galaxy $z = 0.25 \pm 0.01$ (Soderberg et al., Chornock & Filippenko)
- Host galaxy is an irregular galaxy (HST, Levan et al.)

Palomar 200' A.L.C.
Question:

Does XRF really belong to the GRB family?
Event rates of XRF/XRR/GRB

- February 2001 - September 2003
  - XRF: 15, XRR: 20, GRB: 10
- WXM HV on time
  - 1.1 years
- Field of view of WXM
  - 60° x 60°

BeppoSAX XRFs: ~ 100 yr⁻¹ (Heise et al. 2002)

Underestimation? …. HETE has better sensitivity for detecting XRFs

Event rates of each GRBs

XRF ~ XRR ~ GRB

XRF ~ GRB ~ 1/3 All GRBs
T90

![Graph showing the distribution of XRFs, XRRs, GRBs, and BATSE GRBs over log(T90) [s].]
α distribution
Fluence ratio distribution

![Graph showing the distribution of fluence ratios for Hard GRB, XRR, and XRF events. The x-axis represents \( \log(S(2-30 \text{ keV})/S(30-400 \text{ keV})) \), and the y-axis shows the number of events. The graph indicates different distributions for each category, with Hard GRB having the lowest counts, XRR having the highest counts, and XRF in between.]
$$E_{\text{peak}} \text{ vs. fluence ratio}$$

$$\alpha = -1$$
$E_{\text{peak}}$ distribution

![Graph showing $E_{\text{peak}}$ distribution for different categories such as XRF, X-ray-rich GRB, and Hard GRB.](image)
Peak F (50–300 keV) vs $E_{\text{peak}}$

comparison with SAX & BATSE
“Extended” Amati’s relation

$E_{\text{peak}}^{\text{src}} \propto E_{\text{iso}}^{0.5}$
• No boundaries seen between XRFs, XRRs, and hard GRBs.

• The $E_{\text{peak}}$ energy seems to be distributed in much lower energy, unlike the BATSE $E_{\text{peak}}$ distribution.

• $E_{\text{peak}} \propto$ time-average flux (50-300keV)
  $\propto$ peak flux (50-300keV)

• “Extended” Amati’s relation
  $E_{\text{peak,src}} \propto E_{\text{iso}}^{0.5}$ (from XRF to GRB)
redshift

XRF    z
• 020903  0.25
• 030429  2.65
• 030528  0.782
• 040701  0.215
• 050408  0.124
• 050416A 0.653

XRF? by Swift
Amati relation with jet-correction

High Energy Gamma-rays from GRB

~GeV gamma-rays detected in a few GRBs by EGRET. Mostly ~GeV photons were delayed.
GRB 940217: Delayed GeV emission up to 18 GeV
Distinct high energy component
GRB941017

\[ \sim 200 \text{MeV} \]

Gonzalez et al. 2003
• **GRB970417a**
  - Weak
  - $F \sim 1.5 \times 10^{-7} \text{erg/cm}^2$ (BATSE)

• **BATSE**
  - $(295.7, 55.8)$
  - $6.2^\circ$ (1σ)

• **Milagrito**
  - $(289.9, 54.0)$
  - $E > \sim$ a few 100 GeV
  - $F \sim 10^{-3} - 10^{-6} \text{erg/cm}^2$ (>$50 \text{GeV}$)
  - Chance P = 2.8 x 10$^{-5}$

Atkins et al. a-ph/0001111
SHORT GRBS
TYPICAL SHORT-DURATION BURST

ULYSSES
GRB000607
25-150 keV

COUNTS/0.064 s
TIME, s
SHORT BURSTS

• The preceding is based on 8 years of analysis of ~150 long duration bursts with optical, radio, and/or X-ray counterparts.

• What we know today about the short bursts is based on 3 months of analysis of ~3½ events.

• In some cases, the burst durations are > 2 s.

• In other cases, the error boxes are large and contain many possible host galaxies, but probability arguments favor one particular galaxy.

• So the picture is not as clear yet as for the long bursts.
# SHORT BURSTS

<table>
<thead>
<tr>
<th>GRB</th>
<th>X-RAY?</th>
<th>OPTICAL?</th>
<th>RADIO?</th>
<th>REDSHIFT</th>
<th>GALAXY</th>
<th>ENERGY erg</th>
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<tr>
<td>050509</td>
<td>YES</td>
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<td>NO</td>
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<td>1.1x10^{48}?</td>
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<td>NO</td>
<td>0.03?</td>
<td>BLUE, SPIRAL</td>
<td>1.2x10^{47}?</td>
</tr>
</tbody>
</table>
HOST GALAXIES OF SHORT BURSTS

GRB050509

GRB050709

GRB050724

GRB050813

GRB050906
WHAT ARE THE MECHANISMS FOR THE SHORT BURSTS?

- Merger of a compact binary system, such as two neutron stars, or a neutron star and a black hole

Lack of optical and radio afterglows is explained by tenuous ISM, if merger takes place outside host
Giant magnetar flares begin with \( \sim 0.2 \) s long, hard spectrum spikes with \( E \sim 10^{46} - 10^{47} \) erg.

The spike is followed by a pulsating tail with \( \sim 1/1000^{th} \) of the energy.

Viewed from a large distance, only the initial spike would be visible.

It would resemble a short GRB.

It could be detected out to 100 Mpc.

GRB050906 at \( z=0.03 \) could be a magnetar flare.
Short GRB
GRB050709
Short burst 050709

Duration: ~70 ms (30-400 keV)

Spectrum (during first 0.2s)

Model: power law × exponential

Photon index: \(0.53^{+0.12}_{-0.13}\)

Peak energy: \(83.9^{+11}_{-8.3} \text{ keV}\)
HST image

5.6 day
HST image
HST image

In the outskirt of the late-type galaxy.

No SN comp found.

May suggest a merger scenario.

Fox (2005)
A long soft pulse followed by a short/hard pulse and then by a long/soft pulse. Its spectrum is represented by a power-law with a photon index of 2, not consistent with the Amati relation. Villasenor et al. 2005
GRB050408 (long GRB)

Soft Hump!

Not on Amati relation

Early X-ray afterglow
by Swift/XRT
Nousek 2005 (Astro-ph/0508332)