The high energy GRBs: lessons learned from Fermi

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On behalf of the Fermi GBM and LAT teams
Photospheric emission in BATSE bursts

CGRO BATSE ERA (1994-2000)

Spectra from temporally resolved pulses observed by BATSE over the energy range 20-2000 keV.

Spectral fit: Black body combined with a power law

\[ N_E(E, t) = A(t) \frac{E^2}{\exp[E/kT(t)] - 1} + B(t) E^s \]

Photosphere (Planck function)

Additional non-thermal emission

Band only

BB+pl

EGRET TASC peak at \( E_p = 1600 \) keV

Ryde 2004 (see also Ghirlanda et al. 2003

Ryde 2005
High-Energy Emissions from GRB (Past)

- 5 EGRET bursts with >50 MeV observations in 7 years
- EGRET observed:
  - delayed HE gamma-ray emissions;
  - spectral extra component;

Gonzalez, Nature 2003 424, 749

Hurley et al. 1994

Two $\gamma >$GeV @~$T_0$
18 GeV $\gamma$ @~$T_0+75$ min
... and the X-ray Afterglow

- Discovered by BeppoSax (‘97)
  - Measurements of the distance
- Swift (2004-*):
  - Connection to the “Prompt” emission
  - X-Ray Flashes in the afterglow
  - Steep-Shallow-Steep decay
  - Also short bursts have an afterglow!
  - Fading to lower frequencies
The GBM detects ~250 GRBs/year
~18% short
~50% in the LAT FoV
The LAT detects ~10 GRBs/year

**NaI**: 8 keV - 1 MeV
**BGO**: 200 keV - 40 MeV
**LAT**: 30 MeV – 300 GeV

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**Typical** Prompt GRB Spectrum

\[ E^{-2} N(E) \text{ (erg cm}^{-2} \text{ s}^{-1}) \]

- **GBM**
- **LAT**

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Photon Energy (MeV)
Si Tracker
pitch = 228 μm
8.8 \times 10^5 channels
18 planes

CsI Calorimeter
hodoscopic array (8 layers)
6.1 \times 10^3 channels

LAT: 4 x 4 modular array
3000 kg, 650 W
20 MeV – 300 GeV

ACD
segmented scintillator tiles
GBM GRBs

Fermi GRBs as of 120921

1000 GBM GRBs
In Field-of-view of LAT (514)
Out of Field-of-view of LAT (486)
The prompt spectrum

- Band model is favorite only for a subset of bursts, while COMPT and PL are the most favorite;

Additional “Black Body” component over a Band function improves the residuals of the fit.


Goldstein et al., 2012

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Table 1

<table>
<thead>
<tr>
<th></th>
<th>PL</th>
<th>SBPL</th>
<th>BAND</th>
<th>COMP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluence spectra</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>112 (23%)</td>
<td>68 (14%)</td>
<td>75 (15%)</td>
<td>232 (48%)</td>
<td></td>
</tr>
<tr>
<td>Peak flux spectra</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>213 (44%)</td>
<td>51 (10%)</td>
<td>69 (14%)</td>
<td>154 (32%)</td>
<td></td>
</tr>
</tbody>
</table>
Extra HE spectral component

**GRB 090510 (short)**


First extra component by Fermi At > 5 sigma level

**GRB 090902B (long)**


T0+4.6s to T0+9.6s

First time a low-energy extension of the PL component has been seen

6 LAT GRBs show clear extra PL component
Cut-off on HE spectral component

GRB 090926A (long)


- Extra component shows at $>5\,\sigma$
- Spectral break at $\sim1.4\,\text{GeV}$
- First direct measurement of $\Gamma \sim 630$ (if cutoff due to $\gamma$-$\gamma$ absorption)
Joint LAT GBM spectral analysis

- GRB spectrum in several cases is NOT a simple “Band” function
- Deviation from the Band function at low energy;
- Additional power-law observed at high energy;
- High energy cut-off measured in the spectrum;

<table>
<thead>
<tr>
<th>GRB ID</th>
<th>Fluence (10^{-7} erg/cm^2)</th>
<th>Best model</th>
</tr>
</thead>
<tbody>
<tr>
<td>100724B</td>
<td>4665^{+76}_{-78}</td>
<td>Band with exponential cutoff 48.9</td>
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<tr>
<td>000902B</td>
<td>4058^{+24}_{-25}</td>
<td>Comptonized + Power law 50.8</td>
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<tr>
<td>000926A</td>
<td>2225^{+50}_{-48}</td>
<td>Band + Power law with exponential cutoff 48.1</td>
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<tr>
<td>000916C</td>
<td>1795^{+39}_{-41}</td>
<td>Band + Power law 48.8</td>
</tr>
<tr>
<td>000323</td>
<td>1528^{+44}_{-44}</td>
<td>Band 57.2</td>
</tr>
<tr>
<td>100728A</td>
<td>1293^{+26}_{-28}</td>
<td>Comptonized 59.9</td>
</tr>
<tr>
<td>100414A</td>
<td>1098^{+35}_{-36}</td>
<td>Comptonized + Power law 69.0</td>
</tr>
<tr>
<td>000628</td>
<td>927^{+13}_{-16}</td>
<td>Logarithmic parabola 18.3</td>
</tr>
<tr>
<td>110721A</td>
<td>876^{+28}_{-33}</td>
<td>Logarithmic parabola 40.3</td>
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<td>000328</td>
<td>817^{+34}_{-34}</td>
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<td>100116A</td>
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<tr>
<td>000510</td>
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<tr>
<td>091031</td>
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<tr>
<td>110428A</td>
<td>255^{+10}_{-11}</td>
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<tr>
<td>090720B</td>
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<td>100225A</td>
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<td>091208B</td>
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<td>100620A</td>
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<td>090631B</td>
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<tr>
<td>081024B</td>
<td>30^{+5}_{-5}</td>
<td>Band 18.7</td>
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</table>

Note: We exclude from this table all GRBs outside the nominal LAT FOV (with $\theta > 70^\circ$) and GRB 101014A, which was detected too close to the Earth limb.
Non-detected LAT GRB

Bright GBM/BGO GRBs, non detected in the LAT:

⇒ the flux “expected” (extrapolated) exceeds the LAT flux UL;

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- an intrinsic spectral cut off is required to reconcile the GBM and LAT data.
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Non-detected LAT GRB

Bright GBM/BGO GRBs, non detected in the LAT:

➔ It is possible to estimate the bulk Lorentz factor if the cut off is due to $\gamma\gamma$ absorption.

Delayed Onset

Almost all GRBs show a delayed onset of the HE component!!!
Prompt and temporally extended emission

GRB 090926A (long)

- Clear onset of the high energy
- Spectral evolution in the prompt phase
  - Spectral index stable at later times
- Highest event not coincident with lower energy pulses
- Time extended emission clearly visible

Ackermann et. al. 2013, ApJS 209, 11A
Prompt and temporally extended emission

- The Spectral index is stable at later times and has very similar value in many GRBs of ~ -2.

Three time windows:
- GBM;
- LAT;
- EXT;

Ackermann et. al. 2013, ApJS 209, 11A
High-energy emission (observed by the LAT) starts later and lasts longer than the low-energy emission (observed by the GBM).

- “Delayed onset” and “Temporally extended” emission
- In three cases a significant ($3\sigma$) break is measured in the Light curve

\[ \alpha \sim 1.7-2.7 \]
Ground telescope possible catches

<table>
<thead>
<tr>
<th>GRB NAME</th>
<th>Number of events (P&gt;0.9)</th>
<th>Energy GeV</th>
<th>Arrival time s</th>
<th>Probability</th>
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<td>GRB081006</td>
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<td>0.79</td>
<td>12.08</td>
<td>0.955</td>
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<td>GRB081024B</td>
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<td>3.07</td>
<td>0.49</td>
<td>1.000</td>
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<td>GRB090217</td>
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<td>179.08</td>
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<td>5461.08</td>
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<td>GRB110721A</td>
<td>22</td>
<td>1.73</td>
<td>0.74</td>
<td>0.998</td>
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<td>GRB110731A</td>
<td>64</td>
<td>3.39</td>
<td>435.96</td>
<td>0.998</td>
</tr>
</tbody>
</table>

Ackermann et. al. 2013, ApJS 209, 11A
Long lived HE component

GRB 090510 (short GRB)


LAT emission until 200 s
No spectral evolution (photon index $-2.1 \pm 0.1$)

Simultaneous fit of the SED at 5 different times

$E_{-1.38\pm0.07}$

• Forward shock model can reproduce the spectrum from the optical up to GeV energies
• Extensions needed to arrange the temporal properties

Several GRBs have been detected simultaneously from Fermi and Swift
Hyper luminous GRBs

- Brightest GBM bursts, are also the Brightest LAT bursts
- Large dispersion
Class of hyper luminous bursts
- statistical fluctuation?

Fermi LAT GRB Catalog (arXiv:1303.2908v1)
Intrinsic energetic

- The brightest GRBs are also the most energetic GRBs (not the closest)
- In the tail of the $E_{\text{iso}}$ distribution

Ackermann et. al. 2013, ApJS 209, 11A
Conclusions

- Fermi has made new interesting observations on GRB:
  - Prompt emission observed over a wider energy range:
    - Band model is no longer the best phenomenological model.
    - More complex spectral shapes are needed to reproduce the spectrum
  - High-energy emission not common in GRBs
  - Long lasting-delayed high-energy emission common in LAT detected GRB
Thank you!
LAT detection during X-ray flare activity

GRB100728A:

★ Fermi/GBM: Very bright burst:
  ✴ S (10-1000 keV) \( \sim \) 1.3 x 10\(^{-4}\) erg/cm\(^2\)/s \( \rightarrow \) Fermi ARR

★ Swift/BAT: T90\(\sim\)200 s, faint emission seen up to \(\sim\)750 s

★ Swift/XRT: 8 bright flares (from \(\sim\)150 s to \(\sim\)850 s)

★ Fermi LAT:
  ✴ No detection during the prompt phase (large incident angle \(\sim\) 58\(^\circ\))
  ✴ Significant detection during the flaring activity (TS=32)
  ✴ No significant temporal correlation (which does not mean significant non correlation!)
Simultaneous Swift detections

- 6 GRBs have been simultaneously detected by LAT and Fermi
  - GRB090510 [de Pasquale et al 2010 +...]
  - GRB110731A [Fermi Collaboration (Ackermann et al 2013)]
  - GRB 120624B [GCN]
The “fireball” model

Alternatives exists (electromagnetic model,...)

particles get accelerated as they bounce back and forth across the shock wave
compactness problem: large luminosity + small emitting region = large optical depth (\(\gamma-\gamma \rightarrow e^+e^-\) large)

Possible solution: relativistic motion (\(\Gamma \gg 1\))

\[
\tau_{\gamma\gamma}(E) = \frac{3}{4} \frac{\sigma_T d_L^2}{t_v \Gamma} \frac{m_e^4 c^6}{E^2(1+z)^3} \int_0^\infty \frac{d\epsilon'}{\epsilon'^2} n \left( \frac{\epsilon' \Gamma}{1+z} \right) \sqrt{\epsilon' E(1+z)} \frac{e^{-\epsilon' E(1+z)}}{\Gamma}
\]

\(\Gamma_{\text{min}}\) calculation from highest energy photon

\[
\Gamma_{\text{min}}(E_{\text{max}}) = \left[ \frac{4d_L^2 A}{c^2 t_v (1+z)^2 E_{\text{max}}} \frac{m_e^2 c^4}{g \sigma_T} \left[ \frac{(\alpha - \beta) E_{\text{pk}}}{(2 + \alpha) 100 \text{ keV}} \right] \right]^{\frac{2}{2-2\beta}} \times \exp \left( \frac{\beta - \alpha}{2 - 2\beta} \right) \left[ \frac{2m_e^2 c^4}{E_{\text{max}}(1+z)^2 100 \text{ keV}} \right]^{\frac{2}{2-2\beta}}
\]

for \(\Gamma_{\text{min}} > \sqrt{(1+z)^2 E_{\text{max}} E_{\text{pk}}(\alpha - \beta) / 2m_e^2 c^4 (2 + \alpha)}\)

\(\Gamma_{\text{min}}\sim 1000\) for short and long GRBs
A constraint on the quantum gravity mass ($M_{QG}$) can be derived by direct measurement of photon arrival time (assuming the emitted time is the same for all photons):

$$\frac{M_{QG,1}}{M_{\text{plank}}} > 1.19$$

This value disfavors quantum gravity models which linearly alters the speed of light ($n=1$).
And then GRB130427A happen...

- The brightest GRB in the LAT ever detected;
- More than 80 circulars delivered to the archive from several observatories:
  - GCN from the “usual suspects” + HAWC + IceCube
- Concept proven! Discoveries rely on the fast delivery of informations (GCN) quick look analysis and possible data sharing.
Extremely bright GRB (close)

- One of the brightest GRBs in gamma rays ever detected!
  - Redshift: $z = 0.34$, Energy released in gamma rays $\sim 10^{54}$ erg
  - The emission saturated GBM detectors!
  - The brightest burst ever detected by the LAT
- LAT detected emission for $\sim 20$ hours!

95 GeV