GRB in the High Energy and Very High Energy regime

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On behalf of the Fermi GBM and LAT teams and of the MAGIC team
Gravitational potential energy → “Fireball” (Mészáros 2006)

\[ \Gamma \approx \text{few } \times 100 \]
\[ (\Gamma \equiv [1 - \beta^2]^{-1/2}, \beta \equiv v/c) \]

* connection with GW
GRBs: general properties

- The spectra instead are very similar
- The general kind of spectrum is not thermal
- There are some exception that show a thermal spectrum

Wide energy range needed for GRB observations!

Kaneko et al. (2006)
Non thermal emission (from internal shocks)

Shock accelerated electron distribution

Synchrotron Emission Spectrum

Shock acceleration

1st and 2nd order Fermi

\[ E_{pk} \propto \gamma_{\text{min}}^2 \left( B \Gamma \right) \]

\[ \alpha = -\frac{3}{2} \]

\[ \beta = -(p+2)/2 \]
1986: Thermal emission from the fireball


Broadening due to geometrical effects

Blackbody

Paczyński 1986,

Fireball model, high optical depths

Strong thermal component expected ~1 MeV and at $10^{12}$ cm
Potential prompt emission mechanisms

Simple photospheric model: Blackbody
\[ \alpha = 1 \]

Simple synchrotron model
\[ \alpha = -3/2 \]
\[ \beta = -(p+2)/2 \]
Optically thin synchrotron emission in internal shocks; jitter radiation, IC

- Line of death
- Shock acceleration
- Efficiency of internal shocks

The emission from the photosphere is not Planckian

- Geometrical effects (Pe’er 2008, Lundman et al. 2012)

Multiple spectral components (e.g. Mészáros et al. 2002)

Thermal Photosphere, T
Shock Synchrotron, S

\[ \eta_{\star} = 1.07 \times 10^3 \]
\[ \xi = \frac{1}{21.7} \]
\[ \ell' < 1 \]

Slope of cooling spectrum \( \alpha = -1.5 \)

\( \text{SA} \)
\( \text{PHC} \)

\( \text{PHC} \)
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)
5 EGRET bursts with >50 MeV observation 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 @ $\sim T_0$
18 GeV $\gamma$ @ $\sim T_0 + 75$ 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
Si Tracker
pitch = 228 μm
8.8 \times 10^5 channels
18 planes

ACD
segmented scintillator tiles

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

The Large Area Telescope
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

<table>
<thead>
<tr>
<th>Table 1</th>
<th>BEST GRB Models</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PL</td>
</tr>
<tr>
<td>Fluence spectra</td>
<td>112 (23%)</td>
</tr>
<tr>
<td>Peak flux spectra</td>
<td>123 (44%)</td>
</tr>
</tbody>
</table>
GRB 110721A

Time resolved spectra consist of two peaks, one at 100 keV and one at ~ MeV

Time resolved spectrum: (Axelsson et al. 2012)

Best fit model: Band function + Planck function
GRB 110721A

Exceptionally high peak energy 15 MeV during initial time bin

Peak energy evolution as a function of time

\[ E_p = A p^1 (t - t_0)^p \]

\[ t_0 = -0.8 \pm 0.3 \text{ s} \]

\[ p = 1.89 \pm 0.35 \]

\[ \alpha = -0.81^{+0.07}_{-0.06} \]

\[ \beta = -4.1^{+0.4}_{-0.7} \]

\[ E_{pk} = 15.2^{+1.3}_{-1.2} \text{ MeV} \]

Importance of BGO and LLE data!

cf. Lloyd & Petrosian (1998)
GRB 110721A

Significant temperature evolution

Filled points: >5σ detection of an extra (blackbody) component

Open points: ~3σ detection of an extra (blackbody) component

Grey points: higher time resolution gives lower significance in each bin. However the characteristic trend is confirmed.

Evolution different from $E_p$ and normalization!

In this case: $\Gamma \sim 210$ and $R_{ph} = (5.7 \pm 0.8) \times 10^{11} \text{cm}$
Comparison to BATSE analysis:

**Fermi:**

**GRB110721**

Axelsson et al. (2012)

**CGRO**

Ryde & Pe’er (2009)
\[ \alpha = 0.31 \pm 0.08 \]

\[ \beta = -4 \]

Photosphere in GRB090902B

\[ \Gamma = 750 \]

\[ R_{ph} = (1.1 \pm 0.3) \times 10^{12} \ Y^{1/4} \ \text{cm} \]

Ryde et al. 2010
Photosphere in GRB090902B

\[ \alpha = 0.3 \]

\[ \beta = -4 \]

Ryde et al. 2011
**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
- Extra component shows at $>5\sigma$
- spectral break at $\sim 1.4$ GeV
- First direct measurement of $\Gamma \sim 630$ (if cutoff due to $\gamma$-$\gamma$ absorption)
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>Fluoence 10 keV - 10 GeV (10^{-7}\text{ erg/cm}^2)</th>
<th>Best model</th>
<th>θ (deg)</th>
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<td>100724B 4665.76 +78 -68</td>
<td>Band with exponential cutoff</td>
<td>48.9</td>
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<tr>
<td>090902B 4058.24 +24 -25</td>
<td>Comptonized + Power law</td>
<td>50.8</td>
</tr>
<tr>
<td>090926A 2225.48 +48 -30</td>
<td>Band + Power law with exponential cutoff</td>
<td>48.1</td>
</tr>
<tr>
<td>080916C 1795.41 +44 -44</td>
<td>Band + Power law</td>
<td>48.8</td>
</tr>
<tr>
<td>090323 1525.29 +44 -44</td>
<td>Band</td>
<td>57.2</td>
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<td>100728A 1293.27 +27 -27</td>
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<td>090626 927.16 +17 -17</td>
<td>Logarithmic parabola</td>
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<td>090328 817.26 +26 -26</td>
<td>Band</td>
<td>64.6</td>
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<td>081024B 30.8 +4 -4</td>
<td>Band</td>
<td>18.7</td>
</tr>
</tbody>
</table>

NOTE.—We exclude from this table all GRBs outside the nominal LAT FOV (with θ > 70°) 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) exceedes the LAT flux UL;
- an intrinsic spectral cut off is required to reconcile the GBM and LAT data.

Non-detected LAT GRB

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

→ the flux “expected” (extrapolated) exceeds the LAT flux UL;
→ an intrinsic spectral cut off is required to reconcile the GBM and LAT data.
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

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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 (3σ) break is measured in the Light curve
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
The Fermi-LAT collaboration is preparing a new catalogue with more than 8 years of data and a new way to reconstruct photons (Pass8).

Thanks to a new GRB detection algorithm the rate of detected GRB/year moved from 10/year to 15/year!!!
Hyper luminous GRBs

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

HE fluence

Fermi LAT GRB Catalog
(arXiv:1303.2908v1)
Hyper luminous GRBs - Brightest GBM bursts, are also the Brightest LAT bursts - Large dispersion - Statistical fluctuation? HE fluence: new catalogue

Fermi LAT II GRB Catalog
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
Ground telescope possible catches

<table>
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<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>12.08</td>
<td>0.955</td>
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<td>0.49</td>
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<td>1.23</td>
<td>179.08</td>
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<td>GRB090323</td>
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<td>7.50</td>
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<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
Extreme GRB130427A

The brightest burst ever detected by the LAT

Redshift: $z = 0.34$, Energy released in gamma rays $\sim 10^{54}$ erg

The emission saturated GBM detectors!

LAT detected emission for $\sim 20$ hours!

95 GeV

Ackermann et al. Science 2013
The high energy LAT-detected photons challenge synchrotron origin from shock accelerated electrons.
A model for the GeV emission


From Vurm presentation at Ioffe GRB workshop 2014
A model for the GeV emission

Pair-enrichment of the external medium

1. ISM particle scatters a prompt photon
2. Scattered photon pair-produces with another prompt photon
3. New pairs scatter further photons etc.

Prompt radiation pair-loads and pre-accelerates the ambient medium ahead of the FS

Loading and pre-acceleration controlled by the column density of prompt radiation

From Vurm presentation at Ioffe GRB workshop 2014
Emission at VHE (>30 GeV) is possible through IC processes at the forward shock: es. Mezaros & Rees 1994 Bosnjak et al. 2009 Toma et al. 2011 etc.
MAGIC

Imaging Air Cherenkov Telescope (IACT) → VHE Gamma-ray astrophysics (~50 GeV to ~50 TeV)

Two 17m telescopes

236 m² mirror surface

Carbon fiber structure

Fast movement (180° in ~20s)

Aleksić et al. 2016
Imaging Air Cherenkov Telescope (IATC)

Use a “pair conversion telescope” in which the atmosphere acts as tracker & calorimeter.

Huge effective area \( \approx 300 \text{ m} \)
IATC array

Multiple views of the same shower → stereoscopic reconstruction
Dedicated alert system for GCN com.
- Zenith < 60°
- Moon distance > 30°
- Sun zenith > 103°
+ Fermi-GBM filters

GRB Alert rate
- 7/8 GRB follow-up/year
- + 1/2 GRB (GBM)
- Duty cycle 10%
- + Late Time Observations

- New auto-procedure implemented in 2013
- 90 GRBs observed so far (since 2005)
- No detection until now

Many GRBs observed within 100 s
## MAGIC GRB follow-up

<table>
<thead>
<tr>
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<td>-</td>
<td>01:14:02</td>
<td>03:17:15</td>
<td>25-37</td>
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<td>-</td>
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Ahnen et al. (MAGIC Collaboration) 2017, in preparation

### MAIN LIMITS:
- Low duty cycle
- Thr. Energy (EBL)
- Reaction time (important but not critical)
GRB090102 limits from VHE observation

$E_{n_{52}} = 4.5;$
$T = T_0 + 4 \text{ ks}$
$\epsilon_e = 0.1;$
$\epsilon_B = 0.01$
$z = 1.547;$
$n = 1 \text{ cm}^{-3}$

*MAGIC upper limits on GRB090102*

The next IACT generation: CTA

- Low energy threshold (down to 20 GeV)
- Large effective area at multi-GeV range ($10^4 \times$ Fermi-LAT)
- Fast slewing capabilities

First prototype: end 2017 in LP
The next IACT generation: CTA

GRBs are KSP of CTA:
→ Emission mechanism
→ EBL at high redshift
→ UHECR, neutrini
→ Lorentz invariance

Expected detection rate < ~0.5 GRB yr\(^{-1}\)
(dependig on the assumed GRB model and array layout and performance)

Inoue et al., 2013
Lombardi, Carosi, Antonelli, 2013
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.

- MAGIC is following about 10 GRB/year but no detection so far!
  - Improved follow-up algorithm in 2013.
  - Best low energy threshold among the operating IATCs.
  - Low duty cycle :(

- CTA will come soon with an improved energy threshold and effective area!!!
Thank you!
GRBs: general properties

- Very bright sources
- Occurs ~1 per day
- Non-repeatable
- Isotropically distributed in the sky
- Cosmological distances (z~9 highest redshift)
- Observed Flux: $\sim 10^{-7} - 10^{-4}$ erg cm$^{-2}$ s$^{-1}$
- Typical observed energy: $\sim$ MeV
GRBs: general properties

Two phases:
● The PROMPT phase: lasting ~ 100s main in the kev-MeV band;
● The AFTERGLOW phase lasting >3000s;

Two populations in time duration:
● SHORT: duration of the prompt phase <2s;
● LONG: duration of the prompt phase >2s;
The lightcurves can be very different from one to another.
The variability is \(\sim 10\) ms.
The lightcurve variability carries the information on the size of the emitter.

From nasa.gov, BATSE catalog
Photosphere in GRB090902B

Derived jet properties

Non-detected LAT GRB

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

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

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.

Long lived HE component

GRB 090510 (short GRB)

*De Pasquale et al., ApJL 709, 146 (2010)*

- 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
LAT detection during X-ray flare activity

GRB100728A:

- **Fermi/GBM:** Very bright burst:
  - S (10-1000 keV) $\sim 1.3 \times 10^{-4}$ erg/cm$^2$/s
  - $\rightarrow$ Fermi ARR
- **Swift/BAT:** T$_{90}$~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]
  - GRB 130427A [GCN, Fan et al. arXiv:]
- Picture consistent with afterglow model...
compactness problem: large luminosity + small emitting region = large optical depth ($\gamma-\gamma \rightarrow e^+e^-$ large)

Possible solution: relativistic motion

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

$\Gamma_{\text{min}}$ calculation from highest energy photon

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

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

$\Gamma_{\text{min}} \sim 1000$ for short and long GRBs
The “fireball” model

Alternatives exists (electromagnetic model,...)
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).
• 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.