News from Fermi LAT on the observation of GRBs at high energies

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on behalf of the Fermi LAT collaboration

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The Fermi observatory

LAT: Pair conversion telescope
Trigger, localization, spectroscopy
20 MeV → 300 GeV

GBM 14 PMT
12 NaI
Trigger, localization, spectroscopy
8 keV → 1 MeV
2 BGO
Spectroscopy
150 keV → 40 MeV
GRB detection and localization

On-board LAT detection:
On-board track reconstruction
Search for clustered tracks
Modes: seeded by GBM trigger or blind
1 LAT-only detection so far: GRB 090510

On-board LAT localization:
0.1° to 0.5° few seconds after trigger
→ GCN notice
(see GCN circular 10777)

On-ground (>8 hours after trigger):
Automatic search, immediately following data processing
Modes: seeded with GBM and Swift GCN notices and blind
→ significance, localization

Burst Advocate performs likelihood analysis
→ detection significance, localization

Better accuracy if GeV events available (PSF smaller)
Small systematic error at large inclination angles

GRB follow-up

- GBM detection
  - Two thresholds: in and out LAT FoV
  - <10s: repoint request sent to S/C
  - <100s: slew (if accepted and observable)

- Up to 2.5 hours follow-up

Target 10° off-axis while 5° above horizon

- Long-lived high-energy emissions
- Increased statistics
- Better significance and localization
- Varying backgrounds in GBM and LAT
- Higher contamination by Earth limb

GRB 090323
- planned orbit
- actual orbit with repoint

![Graphs showing the angle of the source with the LAT boresight for GRB 090323 with planned and actual orbit with repoint.]
GRB data

GRB 090902B

GBM data

LAT Low Energy Event (LLE)
On-board photon selection
One track required

- High statistics
- Timing and spectral analyses (yet unpublished)
- High background rates
- (energetically) binned analyses of bkg-subtracted data

LAT standard data
Tight quality cuts > 100MeV in ROI
- (very) low background
- (published) likelihood analyses: spectra, localization

Even tighter cuts used for long-lived emissions (faint)
Detection criteria

**LLE Data**

- Two ways to look for detections:
  - LLE data, Transient events, >100 MeV significant excess over the background level
  - Background estimated fitting the off-pulse region TAKING INTO ACCOUNT VARIATION OF THE EXPOSURE.
- Criteria: fluctuation above 4 sigma

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**GRB090323 Lightcurve -- E>50MeV, ROI=20deg**

- **Correct**
- **Wrong**

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Nicola Omodei - Prompt 2011
Fermi detections as of 2011-01-20

530 GBM GRB (since Aug 2008)
22 LAT GRB (>100 MeV, TS > 16)
5 LAT LLE-only GRB

Circles:
In Field-of-view of LAT (<70°): 275
Out of the FOV

Squares:
LAT detections

11 months Fermi LAT count map

PRELIMINARY
First LAT GRB catalog

• First systematic study of GRB properties at high (E>50MeV) energies.
  – Covers bursts starting August 2008 – ~present (2+ yrs).
• Will include tabulated data describing important GRB parameters
  – Usual GRB properties:
    • Duration, average flux, peak flux, time of the peak flux, fluence
  – HE Extended Emission parameters:
    • Temporal decay slope, spectral evolution, start/end time
  – Prompt emission parameters:
    • Delayed onset of the LAT emission, spectral evolution & components
• Includes discussions on the unique properties of individual bursts (extra spectral components, HE spectral cut-offs, analysis caveats).
• Includes details on the tools and methods involved in the analysis.
Study of the extended emission

- We measure a systematically longer duration in the LAT
  - Emission at GeV energy lasts longer than the emission at MeV energy
    - Different component?
    - OR, better sensitivity of the LAT detector (low background) than the GBM detector (background dominated)

- We systematically measure an onset between the GBM and the LAT emission
The Fantastic 4!

- Four bursts show an exceptionally high fluence
- These bursts are not the closest to us
GBM-LAT Fluence-Fluence correlation

- Correlation driven by super luminous GRBs

GBM Fluences from 8 keV to 35 MeV (Nava et al. 2011)
Time resolved spectral analysis

- Flux decays as a power law in time ($t^{-\alpha}$), $\alpha \sim 1 - 2$
- No clear breaks. Different type of spectral evolutions.
  - Early afterglow from a radiative fireball? (see Ghisellini’s talk)
LAT detection during X-ray flare activity

GRB100728A:

★ **Fermi/GBM:** Very bright burst:
  ∗ \( S (10\text{-}1000 \text{ keV}) \approx 1.3 \times 10^{-4} \text{ erg/cm}^2/\text{s} \rightarrow \text{Fermi ARR} \)

★ **Swift/BAT:** \( T_{90} \approx 200 \text{ s}, \) faint emission seen up to \( \approx 750 \text{ s} \)

★ **Swift/XRT:** 8 bright flares (from \( \approx 150 \text{ s} \) to \( \approx 850 \text{ s} \))

★ **Fermi LAT:**
  ∗ No detection during the prompt phase (large incident angle \( \approx 58^\circ \))
  ∗ Significant detection during the flaring activity (TS=32)
  ∗ No significant temporal correlation (which does not mean significant non correlation!)
Fermi LAT Spectral analysis

GRB 080916C

GBM $T_{90} \sim 70$ sec
LAT $T_{05} \sim 5$ sec
LAT $T_{90} \sim 205$ sec

- Is there any transition between the prompt GBM emission, and LAT extended emission?
- Do we see an “extra component”? 
Fermi LAT Spectral analysis

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Fermi LAT Spectral analysis

GRB 080916C

<table>
<thead>
<tr>
<th>GBM NaI + NaI (8 keV-260 keV)</th>
<th>Time since trigger (s)</th>
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<tbody>
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<td>1500</td>
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<table>
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<td>700</td>
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<th>LAT (&gt; 100 MeV)</th>
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<tr>
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<tbody>
<tr>
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<td>4</td>
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<tr>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
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</table>

| GBM T_{90} ~ 70 sec           |
| LAT T_{05} ~ 5 sec            |
| LAT T_{90} ~ 205 sec          |

- Is there any transition between the prompt GBM emission, and LAT extended emission?
- Do we see an “extra component”?

In some cases not...
In other cases, yes!

Evidence of the extra components

GRB 090510
Integrated counts spectrum

GRB 090902B
Integrated spectrum fit

Joint spectral fit (of binned data):
GBM<40MeV
standard LAT data>100MeV

• Constrains main keV-MeV component
• Spectral evolution during prompt phase
• Additional PL component seen at high and low energies

See also Binbin Zhang’s talk
Detection rate / Sensitivity

Pre-launch estimates:
Band function fits to bright BATSE GRB
- ~9.3 GRB/y w/ >10 photons >100 MeV
- ~2.7 GRB/y w/ >100 photons >100 MeV
- ~2.7 GRB/y w/ >10 photons >1 GeV

Compared with:
Number of “predicted” photons from likelihood fit, executed in different time windows

The comparison of the rates suggests that we are seeing fewer bursts (especially at high energy) than what we had anticipated, the cause could either be:
1. Extrapolating from BATSE/GBM to LAT is VERY dangerous (large lever arm, big uncertainties).
2. A suppression of the spectrum could effect the number of GRB detected.


If the additional component is a feature of LAT GRB, why do we see fewer bursts than expected extrapolating from a single powerlaw?
Do we see any cut-off in LAT data?
What about non-detected GRB in FoV?
Do we see any cut-off in LAT data?

- **GRB090926**
  - Bright LAT GRB, sharp feature in the light curve: time resolved spectroscopy

Significant detection of a Cut-off at LAT energy

- A significant detection of a cut off in both the time integrated spectrum and in the spectrum coincident with the bright spike.
- Cut-off in GRB could also explain the deficit of GRB we see.

What about non-detected GRB in FoV?

- We look at the sample of bright GBM/BGO GRBs, non detected in the LAT.
  - Extrapolate the GBM spectrum into the LAT energy range
  - Evaluate the flux “expected” in the LAT energy range
  - Test the significance:
    - Comparing the fit without the LAT data with the fit with the LAT data (UL) added to the fit

LAT "dark bursts", i.e. bright GRB in the GBM BGO but undetected by the LAT.

To explain their non-detection:
- either an intrinsic spectral break/cut-off
- or simply that we have not adequately estimated the errors on their high energy power law indices.

See also:
- Beniamini et al. (2011) arXiv:1103.0745
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  ★ or simply that we have not adequately estimated the errors on their high energy power law indices.

See also:
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What can we say about the Extra Component?

- **Leptonic models**: Inverse Compton, SSC
  - Low-energy excess and delay -> variability not explained
  - Couple internal shocks to photospheric emission? (Ryde 2010, Toma 2010)

- **Hadronic models**: p synchrotron, hadronic cascades (Asano 2009, Razzaque 2009)
  - Low-energy excess (from secondary pairs)
  - Late onset (p acceleration and cascade development)
  - Require large B field and larger energy than observed
  - What about GRB 090926A spike? (variability at all energies)

- **External shock synchrotron models**: (Early afterglow) (Ghisellini 2010, Kumar & Barniol Duran 2009), but also Piran 2010
  - Delayed onset, smooth afterglow
  - High variability of prompt emission not reproduced
Time correlation

- **GRB 090926**
  
  **Significant** correlation between the <15 keV and high energy component;

  **Weak correlation** between the bulk of the Band model and the high energy emission;

  **Variability at all energies**;

  **Preliminary**

  - GRB 090926
  - Time lag
  - p-value
  - > 5 sigma
  - ~ 3 sigma
  - Preliminary
Time correlation

- GRB 090510 - No significant correlation found between low and high energy.
  - Emission coming from different regions?
  - Afterglow origin of high energy gamma-rays?
Highest energy events...

<table>
<thead>
<tr>
<th>GRB</th>
<th>Angle from LAT</th>
<th>Duration (or class)</th>
<th># of events &gt;100 MeV</th>
<th># of events &gt;1 GeV</th>
<th>Delayed HE onset</th>
<th>Long-lived HE emission</th>
<th>Additional spectral component</th>
<th>Highest photon energy</th>
<th>Redshift</th>
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<tbody>
<tr>
<td>080825C</td>
<td>~ 60°</td>
<td>long</td>
<td>~ 10</td>
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<td>✓</td>
<td>X</td>
<td>~ 560 MeV</td>
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<td>long</td>
<td>145</td>
<td>14</td>
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<td>✓</td>
<td>?</td>
<td>~ 13 GeV</td>
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<tr>
<td>081024B</td>
<td>21°</td>
<td>short</td>
<td>~ 10</td>
<td>2</td>
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<td>✓</td>
<td>?</td>
<td>~ 3 GeV</td>
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<td>-</td>
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<tr>
<td>090217</td>
<td>~ 34°</td>
<td>long</td>
<td>~ 10</td>
<td>0</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>~ 1 GeV</td>
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<tr>
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<td>?</td>
<td>?</td>
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<td>?</td>
<td>?</td>
<td>0.736</td>
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<td>&gt; 150</td>
<td>&gt; 20</td>
<td>✓</td>
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<td>~ 31 GeV</td>
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<td>long</td>
<td>~ 20</td>
<td>&gt; 0</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
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<tr>
<td>090902B</td>
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<td>&gt; 200</td>
<td>&gt; 30</td>
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<td>✓</td>
<td>✓</td>
<td>~ 33 GeV</td>
<td>1.822</td>
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<tr>
<td>090926A</td>
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<td>&gt; 150</td>
<td>&gt; 50</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>~ 20 GeV</td>
<td>2.106</td>
</tr>
</tbody>
</table>

Last bright GRB: Sept 2009!
Update table with all the LAT detection on its way
**Jet's bulk Lorentz factor**

**gamma–gamma opacity constraint**
Maximum photon energy from relativistically moving source is related to its:
- Size: variability timescale
- Bulk Lorentz factor: allowed energy higher than for source at rest
- Target photon field spectrum: Band or Band+PL depending on cases

_Caveat:_ target photon field assumed uniform, isotropic, time-independent
- More realistic modeling (e.g. Granot 2008) yields significantly (~3 times) lower values

Maximum photon energy in LAT
Variability timescale from GBM light curve (more statistics)
- Robust (modulo caveat) constraints for most GRB

Cutoff energy for GRB 090926A
- Measurement Lorentz Factor~ 200-700

**Preliminary**

Romain Hascoët’s talk
Lorentz invariance violation

**Method 1:** assuming a high-energy photon is not emitted before the onset of the relevant low-energy emission episode

**Method 2:** associating a high-energy photon with a spike in the low-energy light curve that it coincides with

**Method 3:** DisCan (dispersion cancelation; very robust) – lack of smearing of narrow spikes in high-energy light curve

<table>
<thead>
<tr>
<th>GRB</th>
<th>Duration (or class)</th>
<th># of events &gt; 0.1 GeV</th>
<th># of events &gt; 1 GeV</th>
<th>Method</th>
<th>Lower Limit on $M_{QG,1}/M_{\text{Planck}}$</th>
<th>Valid for $s_n = 1$</th>
<th>Highest photon energy</th>
<th>Redshift</th>
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<tr>
<td>080916C</td>
<td>long</td>
<td>145</td>
<td>14</td>
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<td>0.11</td>
<td>1</td>
<td>~13 GeV</td>
<td>~4.35</td>
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<td>090510</td>
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<td>&gt;20</td>
<td>1,2,3</td>
<td>1.2, 3.4, 5.1, 10</td>
<td>1</td>
<td>~31 GeV</td>
<td>0.903</td>
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<tr>
<td>090902B</td>
<td>long</td>
<td>&gt;200</td>
<td>&gt;30</td>
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<td>1</td>
<td>~33 GeV</td>
<td>1.822</td>
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<tr>
<td>090926A</td>
<td>long</td>
<td>&gt;150</td>
<td>&gt;50</td>
<td>1,3</td>
<td>0.066, 0.082</td>
<td>1,1</td>
<td>~20 GeV</td>
<td>2.106</td>
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</table>

All lower limits $M_{QG,1} > M_{\text{Planck}}$

QG models with linear LIV disfavored
Extragalactic Background Light

Extrinsic gamma–gamma absorption by UV background light
Combined study of AGN and GRB of known redshift

Highest photon energies consistent w/ sources

- « baseline » model from Stecker et al. ruled out at ~3.6σ, using only GRBs

Conclusions

Fermi is doing well in providing new valuable information about GRBs

More than 20 GRBs detected at high energy by the Fermi LAT

Common properties

- Temporal extended emission
- Time onset between the LAT and GBM
- Existence of an extra spectral component
- Measured a cut-off in the spectrum
  - This could explain why we are seeing fewer bursts than we expected

New techniques to extend the energy range to the LAT at lower energy (<100 MeV)

- Study of the cut-offs
- Filling the gap with the GBM
Autonomous Repoint Requests (ARRs) typically cause large fluctuations in the off-axis angles of GRBs, complicating analyses:

- Pre-fit backgrounds become invalid
- Large exposure variations have to be properly taken into account → can't fit lightcurves in detected-count space.
Background Estimation

- A common method for estimating the background is by
  - fitting the background before and after the burst and interpolating or by
  - fitting the background before the burst and extrapolating.

× Does not work if an ARR causes rapid off-axis angle variations in the fit or burst intervals.

GRB090323 Lightcurve -- E>50MeV, ROI=20deg

N.B. same effect in GBM data
We have developed a background-estimation tool that uses a model of the LAT backgrounds. (described in Fermi's GRB080825c paper).

- 10-15% accuracy. Works for any observational conditions.
- Extensively used in the catalog's analyses: likelihoods, duration estimates, event probabilities, etc.

N.B. same effect in GBM data.