Fermi
Gamma-ray Space Telescope

LAT Observations of Gamma-ray Bursts

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On behalf of the Fermi-LAT and Fermi-GBM collaborations
After the burst itself, afterglow emission in radio, optical and X-ray is observed for days (and sometimes months and years) which decays with time.
Duration distributions - two classes?

- Two distinct populations
  - Short $<\sim 2s$
  - Long $>2$ s
GRB Afterglows

GRB leave behind a faint declining echo at lower wavelengths. Important as it allows us to better measure the location of the source.

- Faint, fading X-ray, optical or radio afterglows.
- Identification of absorption or emission lines in afterglow or host galaxy allows determination of distance.

Implies that GRB are enormously energetic: $10^{48} - 10^{54}$ ergs. (c.f. Solar rest mass = $\sim 2 \times 10^{54}$ ergs)
Gamma-ray bursts

Huge flux of gamma-rays lasting from 0.1–1000’s seconds

**Compact Mergers:** Two neutron stars, or a neutron star and a black hole, collide and merge, producing a jet.

**Collapsars:** A rapidly spinning stellar core collapses and produces a supernova, along with relativistic jets.
Fireball model

FORMATION OF A GAMMA-RAY BURST could begin either with the merger of two neutron stars or with the collapse of a massive star. Both these events create a black hole with a disk of material around it. The hole-disk system, in turn, pumps out a jet of material at close to the speed of light. Shock waves within this material give off radiation.

MERGER SCENARIO

NEUTRON STARS

BLACK HOLE

NEUTRON STARS

CENTRAL ENGINE

MASSIVE STAR

HYPERNOVA SCENARIO

JUAN VELASCO

JET COLLIDES WITH AMBIENT MEDIUM (external shock wave)

BLOBs COLLIDE (internal shock wave)

GAMMA RAYS

X-RAYS, VISIBLE LIGHT, RADIO WAVES

PREBURST

GAMMA-RAY EMISSION

AFTERGLOW
Some History

- EGRET detected 4 GRB in its pair conversion telescope.
- In one GRB, EGRET observed emission above 30 MeV for more than an hour after the prompt emission.
- 18 GeV photon was observed (the highest ever seen by EGRET from a GRB).
- Due to Earth occultation/telemetry gap, it is unknown for how long the high energy emission lasted.

Unlike optical/X-ray afterglows, gamma-ray luminosity did not decrease with time -> additional processes contributing to high energy emission?
Joint EGRET-BATSE observations

Analysis using EGRET TASC data

- Classic sub-MeV component observed in BATSE data which decays by factor of 1000 and $E_{\text{peak}}$ moves to lower energies
- Higher Energy component observed within 14-47 seconds by EGRET and at later times by both BATSE and EGRET detectors
- Higher Energy Component has
  - $dN/dE = kE^{-1}$
  - lasts $\sim 200$ seconds
  - Increases total energy flux by factor of 3

(See also Granot and Guetta, 2003)
Some open questions

- How high in energy does the prompt GRB emission extend?
  - Measurements of high energy cutoffs in GRB provide information on:
    - particle acceleration
    - Bulk Lorentz factors for each pulse

- Is there a second emission component? What is its nature?

- How common are high energy afterglows such as that seen in EGRET?

- What is the density and spectrum of UV/optical intergalactic radiation fields?
  - Look for high energy cutoffs/spectral breaks as a function of redshift

- Test of Lorentz invariance at high energies (quantum gravity...)
  - Set a limit on the constant speed of light
Fermi and GRB

- LAT: <20 MeV to >300 GeV. With both onboard and ground burst triggers.
- GBM: 12 NaI detectors—8 keV to 1 MeV. Used for onboard trigger, onboard and ground localization, spectroscopy: 2 BGO detectors—150 keV to 40 MeV. Used for spectroscopy.
- Total of >7 energy decades!

Good spectral observations of the prompt phase of lots of GRB
Large Area Telescope (LAT)

- Efficient observing mode (don’t look at Earth)
- Wide FoV (useful GRB observations out to 65 half angle, 3.6 sr)
- Low deadtime (27µs c.f. 100ms for EGRET)
- Large effective area
- Good angular resolution
- Increased energy coverage (to few hundred GeV)

Very major improvements in capabilities for GRB observations compared to previous missions in this energy range.

More photons - study high energy lightcurves, good detection sensitivity

Study the *population* of MeV-GeV bright bursts

Measure spectra out to hundreds of GeV - how common are the high energy components such as that seen in GRB 941017?
GRB090902B - Autonomous repoint

- LAT pointing in celestial coordinates from -120 s to 2000 s
  - Red cross = GRB 090902B
  - Dark region = occulted by Earth (\( qz > 113^\circ \))
  - Blue line = LAT FoV (\( \pm 66^\circ \))
  - White lines = 20° (Earth avoidance angle) / 50° above horizon
  - White points = LAT events (no cut on zenith angle)
Rapid increase in exposure as GRB location comes to the center of the FoV
~Constant exposure for 5 hours, with gaps for occultation and SAA passage
Swift observations of bright well-localized LAT bursts have been extremely successful in detecting X-ray afterglows. Follow-up optical obs provide redshift
Fermi-LAT Observations of GRB

• Prompt emission phase
  – Onset of >100 MeV delayed w.r.t. keV flux
  – Durations of high energy emission longer than keV emission
  – Hard power-law components seen in bright LAT GRB
  – Cutoffs -> fewer detected GRB than hoped

• Afterglows
  – Properties of MeV-GeV afterglows and connection to prompt phase
  – MeV-GeV counterparts to x-ray flares
Delayed Onset and Extended GeV Radiation of Fermi LAT GRBs

(long) GRB 090902B

8 – 14.3 keV

14.3 – 260 keV

260 keV – 5 MeV

LAT (all events)

> 100 MeV

> 1 GeV

(t(s)

(short) GRB 090510

8 - 260 keV

260 keV – 5 MeV

all LAT events

>100 MeV

> 1 GeV

(t(s)

16
• The LAT >100 MeV emission starts after the keV emission, sometimes by up to 80 seconds.
Duration Distributions

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)
Fluence Distributions

PRELIMINARY

GBM Fluences from 8 keV to 35 MeV (Nava et al.2011)
GRB 090902B: A Hard Component in Long GRB


Best fit spectrum to interval b
\((T_0 + 4.6 \text{ s to } T_0 + 9.6 \text{ s})\) is a band function (smoothly broken power-law) + power-law component.

Hadronic model providing additional hard component with excess at low and high energies?

Two non-thermal power-law + thermal component?
GRB 090510: A Short Hard GRB with an extra component

GRB090510. First bright short GRB
Clear detection of an extra component, inconsistent with the Band function.
Ackermann et al., ApJ

Early onset of afterglow?
• Sharp spike seen at all measured gamma-ray energies
  – Strongest below 15 keV and above 10 MeV
  – Clear correlation between keV and MeV/GeV lightcurves

Ackermann et al, 2011
Hard power-law component emerges during the bright spike, with cutoff at 1.4 GeV

Power-law index remains constant through the afterglow (~5000 seconds)
More on cutoffs and spectral breaks

- Sample of 36 bright BGO detected bursts
  - Extrapolate GBM spectrum to the LAT range
  - Compare LAT upper limit with that “expected” from extrapolation
  - Test that the data cannot be adequately fit by a softer spectrum when fitting LAT and GBM data together.

- Significant evidence for a spectral break in ~10% of the sample.
  - Intrinsic break
  - Or, incorrectly measured spectral parameters

See also Beniamini et al 2011, Guetta et al, 2011
Fermi-LAT bursts are bright!
X-ray observations typically start ~12 hours after the prompt emission.
Early Afterglows

Large flares/rebrightening often seen during the early afterglow (within an hour or so)

LAT afterglows seen for several GRB with durations lasting up to an hour or so
Long-lived Emission with power-law temporal decays

LAT Detection during X-ray Flare Activity

• GRB100728A
  – Bright GBM burst->ARR
  – No prompt LAT detection (but was at edge of FoV, 58 deg)
  – Hard spectrum (1.4+-0.2)
  – Gamma-ray fluence consistent with extrapolation of the X-ray flare spectrum
  – Unable to distinguish between afterglow or flare emission due to weak LAT detection

• Sample of 140 Swift GRB
  – 49 (35%) show flares at early times
  – 12 with good LAT observations (in FoV and away from Earth limb)
  – 29 flares with simultaneous Fermi/Swift observations, 1 detection!
Afterglow in bulk

- We have only one joint Swift/LAT trigger
- Swift routinely observes x-ray and optical afterglows
- LAT observes the entire sky every two hours
  - Guaranteed to have LAT observations for every Swift afterglow.
  - Remove the two known detections (GRB090510 and GRB0100728A) and combine the rest of the GRB to search for a weak signal
- 155 BAT GRBs from Aug 2008 - Dec 2010 with XRT detections
- For each burst, perform likelihood analysis between 0.1-300 GeV, 0.1-1 GeV and 1-300 GeV
  - Calculate test statistic (TS) as a function of flux (peak indicates best fit value for each GRB)
  - Sum the TS curves for all GRB, the peak in the summed curve is the most probable value for the population
Combining to get a marginally significant detection

- Signal becomes more significant if we select UVOT detected bursts, or select bursts with high fluence in prompt phase
Comparing X-ray and Gamma-ray SED

- Evidence for an SSC component?
# Summary Table & Highest Energy Events compatible with the GRB position

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<th>GRB Name</th>
<th>Likelihood Detection &gt;100 MeV</th>
<th>LLE Detection</th>
<th>LAT off axis angle at T₀ (degrees)</th>
<th>QBM T₉₀</th>
<th>N Pred. Events (&gt;100MeV, Trans.)</th>
<th>HE Delayed Onset?</th>
<th>Long Lived HE Emission?</th>
<th>Maximum Energy (GeV) meas. during the LAT detection</th>
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**PRELIMINARY**
Some comments on the extra spectral 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
Lorentz Invariance Violation

- There is a fundamental scale (Planck scale $\lambda_{Pl} \approx 10^{-35} \text{ m}$) at which quantum gravity (QG) effects are expected to strongly affect the nature of space-time.

- Lorentz symmetry implies a scale-free space-time

- QG effects might cause violations of Lorentz Invariance (LIV) $\rightarrow \nu(E_\gamma) \neq c$

- LIV terms are typically described using a Taylor series:

\[
c^2 p^2 = E^2 \gamma \left[ 1 + \sum_{k=1}^{\infty} s_k \left( \frac{E_\gamma}{M_{QG,k}c^2} \right)^k \right]
\]

\[M_{QG} \lesssim M_{Planck} \equiv \sqrt{\hbar c/G} \approx 1.22 \times 10^{19} \text{ GeV/c}^2\]
QG effects might cause violations of Lorentz Invariance (LIV) → $u_\gamma(E_\gamma)$≠c

The now energy-dependent speed of light can be expressed as:

$$u_\gamma = \frac{\partial E_\gamma}{\partial p_\gamma} \simeq c \left[ 1 - \frac{1}{2} s_n \frac{1+n}{M_{QG,n} c^2} \left( \frac{E_\gamma}{M_{QG,n} c^2} \right)^n \right]$$

$s_n$ = +1 or -1 for speed retardation or acceleration with an increasing photon energy.

LIV perturbation term we would like to constrain

Usually $n=1$ or 2 (linear and quadratic LIV respectively).

There are many models that allow such Lorentz-Invariance violations, and some others that actually predict them (e.g. stringy-foam model J. Ellis et al. 2008).

If the speed of light depends on its energy → then two photons of different energies emitted together will arrive at different times.
GRB090510 as seen by Fermi

- **Top**: Energy versus Time plot for the events detected by the LAT.
- **Light curves**: GRB's emission at different energies.
- The GRB started with a precursor event, that caused the GBM trigger.
- After about half a second the bulk of the main emission started.
- How was this GRB used to constrain LV?
  - Using the 31GeV photon and an assumption for its maximum time delay.
  - Based on its tens-of-ms narrow pulses and searching for spectral lags.
Fermi-LAT Constraints from GRB090510

- Extract dispersion information from all the detected LAT photons (detected energy range 35MeV – 31GeV).
  - Performed multiple trials, in which it moved each photon time according to a *trial spectral lag coefficient* (in ms/GeV), find the lag that maximises the sharpness of the lightcurve.
  - The spectral lag coefficient was found to be consistent with zero.
- Perform a bootstrap analysis to gauge the statistical errors of that measurement, which produced our final result:
  - a symmetric upper limit on the spectral lag coefficient
  - $|\Delta t/\Delta E|<30\text{ms/GeV} \leftrightarrow M_{QG,1}>1.22M_{Pl}$
  - (99% CL) on possible linear ($n=1$) dispersion of either sign ($s_n=\pm 1$).

![Diagram showing constraints on various astrophysical objects with their corresponding energies and masses.](image)
How fast is the emission region moving?

• Relativistic motion of the emitting shell:
  – A relativistic motion of the shell allows higher energy events in dense region to escape.
  – Observing high-energy events correlated with the fast variability allows us to constrain to the speed ($\Gamma_{\text{min}}$) of the emitting shell.

• For target photon spectrum assume band function, or power-law.
  • Caveat: target photon field assumed uniform, isotropic, time-independent
    – More realistic modeling yields significantly (~3 times) lower values
Summary

- 250 GRB/year detected by GBM
- 27 GRBs detected at high energy by the Fermi LAT
- Common properties at high energies
  - Temporal extended emission
  - Flux decreases as a power-law with time, with no breaks
  - 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
- Waiting for more MW early afterglow observations (joint Lat-BAT trigger, or LAT onboard trigger + rapid TOO)
GBM Observations of GRB

- GBM detects ~250 GRB/year (c.f. 100 with Swift)
  - Exceed pre-launch expectations of ~200/year due to flexible trigger algorithm
- Broad spectral coverage, relatively poor localization
GBM Spectra - Thermal Components?

- Black body components have been fit in several GRB - GRB080916C, GRB090902, GRB100724B...

  Guiriec et al, 2011, Ryde et al 2011

**GRB100724B - brightest GBM burst**

- Non-thermal

- Thermal ($kT \approx 38$ keV)

Expect thermal/blackbody component from photosphere
The Fermi Observatory

Large Area Telescope (LAT)
Observes 20% of the sky at any instant, views entire sky every 3 hrs
20 MeV - 300 GeV - includes unexplored region between 10 - 100 GeV

Gamma-ray Burst Monitor (GBM)
Observes entire unocculted sky
Detects transients from 8 keV - 40 MeV

• Huge improvement over previous missions in this waveband
  – Increased effective area
  – Improved angular resolution
  – Broader energy range
  – Wide field of view
Nov 9, 2009 - add new TGF trigger
  - TGF trigger rate increased by factor of ~10 to 1 per 3.7 days
Feb/March 2011, solar activity
Joint EGRET-BATSE observations

- High energy component not always present in EGRET TASC observations.

- Above 100 MeV, spark chamber observations were much more sensitive than TASC observations (albeit with smaller FoV)
Fermi Observatory

Large Area Telescope (LAT):
- 20 MeV - >300 GeV
- 2.4 sr FoV (scans entire sky every ~3hrs)

Gamma-ray Burst Monitor (GBM)
- 8 keV - 40 MeV
- views entire unocculted sky

Launched on June 11, 2008
• In survey mode, the LAT observes the entire sky every two orbits (~3 hours).
• Multiwavelength observations in coordination with the LAT are limited only by the ability to coordinate to other observations in other wavebands.
• Can also perform pointed observations of particularly interesting regions of the sky.