Fermi Observations of GRB 090902B: Spectral and Temporal Complexity During the Prompt and Extended Emission Phases

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On behalf of the Fermi GBM and LAT Collaborations

The Second LAT Collaboration Burst

- GBM Trigger at 11:05:08.31 UT, 2 September 2009
- ARR initiated
- GBM loc: RA, Dec = 264.5, 26.5, 51° from LAT boresight
- 200 counts > 100 MeV, 39 > 1 GeV in 100 s
- LAT location: 265.00, 27.33
- Swift XRT afterglow/loc.
- GROND localization 3.3 arcmin from LAT location
- Gemini-N redshift: z = 1.822
Autonomous Repoint
Properties and Light Curves

More vitae:

- $T90 = 21.9$ s, 50-300 keV
- $\text{Fluence} = 4.4 \times 10^{-4}$ erg cm$^{-2}$ (10 keV – 10 GeV)
- $E_{\text{iso}} = 3.6 \times 10^{54}$ erg (cf. GRB 080916C, $9 \times 10^{54}$ erg)
- LAT emission extends well beyond GBM prompt phase
- Highest energy photon measured from a burst: $33.4 \pm 2.7^{-3.5}$ GeV, arriving 82 s after the GBM trigger

- Study correlated variability in various bands,
- Possible delayed onset of $>100$ MeV emission

J. Chiang
Time-integrated Spectrum

- Evidence for a hard power-law component, $\Gamma = -1.93$
- Band + PL $\Rightarrow \Delta CSTAT = 2000$ (2 dof)
- PL / (Band+PL) fluence ratio = 24%, 10 keV– 10 GeV
Low energy extension of PL component

Interval b, T0 + 4.6 to 9.6 s

$\Delta C_{\text{STAT}} = 3165$, ($\geq 1000$ for GBM only)

This is the first time a low energy extension of the power-law component has been definitively seen.
Time-resolved Spectral Fits

Table 1. Band function + power-law fit parameters for the time-resolved spectral fits.

<table>
<thead>
<tr>
<th>Interval</th>
<th>Time Range (s)</th>
<th>$E_{\text{peak}}$ (kev)</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\Gamma$</th>
<th>CSTAT/DOF</th>
<th>$\Delta$CSTAT</th>
<th>Energy fluence (erg cm$^{-2}$, 8 keV–30 GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>...</td>
<td>0.0–30.0</td>
<td>726 (±8)</td>
<td>-0.61 (±0.01)</td>
<td>-3.8 (±0.2)</td>
<td>-1.93 (±0.01)</td>
<td>2562/963</td>
<td>2005</td>
<td>(4.59 ± 0.05)×10$^{-4}$</td>
</tr>
<tr>
<td>a.</td>
<td>0.0–4.6</td>
<td>526 (±12)</td>
<td>-0.09 (±0.04)</td>
<td>-3.7 (±0.3)</td>
<td>-1.87 (±0.04)</td>
<td>901/963</td>
<td>43</td>
<td>(3.72 ± 0.13)×10$^{-5}$</td>
</tr>
<tr>
<td>b.</td>
<td>4.6–9.6</td>
<td>908 (±15)</td>
<td>0.07 (±0.03)</td>
<td>-3.9 (±0.2)</td>
<td>-1.94 (±0.02)</td>
<td>1250/963</td>
<td>3165</td>
<td>(1.44 ± 0.03)×10$^{-4}$</td>
</tr>
<tr>
<td>c.</td>
<td>9.6–13.0</td>
<td>821 (±16)</td>
<td>-0.26 (±0.03)</td>
<td>-5.0 (±0.8)</td>
<td>-1.98 (±0.02)</td>
<td>1310/963</td>
<td>2109</td>
<td>(9.42 ± 0.24)×10$^{-5}$</td>
</tr>
<tr>
<td>d.</td>
<td>13.0–19.2</td>
<td>529 (±9)</td>
<td>-0.65 (±0.02)</td>
<td>-3.2 (±0.1)</td>
<td>-1.86 (±0.02)</td>
<td>1418/963</td>
<td>199</td>
<td>(1.29 ± 0.03)×10$^{-4}$</td>
</tr>
<tr>
<td>e.</td>
<td>19.2–22.7</td>
<td>317 (±8)</td>
<td>-0.78 (±0.02)</td>
<td>-2.4 (±0.1)</td>
<td>...</td>
<td>1117/965</td>
<td>...</td>
<td>(4.8 ± 0.2)×10$^{-5}$</td>
</tr>
<tr>
<td>f.</td>
<td>22.7–25.0</td>
<td>236 (±25)</td>
<td>-1.30 (±0.04)</td>
<td>-2.2 (±0.1)</td>
<td>...</td>
<td>1077/965</td>
<td>...</td>
<td>(1.0 ± 0.1)×10$^{-5}$</td>
</tr>
<tr>
<td>e.+f.</td>
<td>19.2–25.0</td>
<td>327 (±8)</td>
<td>-0.91 (±0.02)</td>
<td>-2.6 (±0.1)</td>
<td>-1.59 (±0.20)</td>
<td>1219/963</td>
<td>16</td>
<td>(6.1 ± 0.4)×10$^{-5}$</td>
</tr>
<tr>
<td>g.</td>
<td>25.0–30.0</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>-1.93 (±0.25)</td>
<td>1209/967</td>
<td>...</td>
<td>(6.8 ± 0.8)×10$^{-6}$</td>
</tr>
</tbody>
</table>

- Band component has an initial hardening then softens over course of prompt phase
- Power-law component index is roughly constant ($\Gamma$~1.9) through T0+19.2s, then hardens in last 6 s ($\Gamma$~1.6)
Extended emission in LAT band

Photon index essentially constant after T0 + 25 s with $\Gamma = -2.1$
Implications for Models

- Conventional synchrotron-SSC models have difficulties producing <50 MeV power-law excess
- Syn-SSC blazar example: Mrk 421

See P1-53, D. Paneque
Implications for Models

• Alternatives to syn-SSC:
  – Hadronic models:
    • Proton synchrotron radiation (requires large B-fields)
    • Synchrotron by secondary pairs produced via photohadron interactions
    • Both scenarios require substantially more energy (1—2 orders of magnitude) than observed $E_{\text{iso}} (=3.6 \times 10^{54}$ erg).
    • Possible source of UHE cosmic rays
  – Early Afterglow (e⁺e⁻ synchrotron from external shock)
    • Can also account for possible delayed (~9s) onset of power-law component
    • Variability time scale of 90 ms in LAT data argues against external shock

*See P3-152 by Soeb Razzaque for more details
Implications for Models

- **Extended Emission (after $T_0 + 30s$):**
  - Afterglow synchrotron interpretation has difficulty explaining 33.4 GeV photon at $T_0 + 82s$
  - Photon index of -2.1 may pose difficulties for afterglow SSC emission

- **Constraints on $\Gamma_{\text{min}}$:**
  - $E_{\text{max}} = 11.16$ GeV, $t_{\text{var}} = 51$ ms (during prompt phase)
• EBL constraints: most models optically thin except “baseline” and “fast-evolution” models of Stecker et al 2006

• From analyses of MC sims, extrapolating the lower energy power-law, with and without absorption, these models are disfavored at >3σ level
LAT Fluence vs GBM Fluence

- Suggests that short and long could have different efficiencies for emitting gamma rays
Summary

- One of the most luminous bursts seen by the LAT: \( E_{\text{iso}} = 3.6 \times 10^{54} \text{ erg} \)
- Hard additional power-law component in the LAT band that extrapolates down to < 50 keV
  - Poses serious challenges for syn-SSC models
- PL/(Band + PL) fluence ratio: 24%
- Highest photon energy from a GRB: 33.4 GeV
- Extended emission out to 1 ks, \( \sim t^{-1.5} \) decline
- \( \Gamma_{\text{min}} = 1000 \)
- \( z = 1.822 \) and \( E_{\text{max}} = 33.4 \text{ GeV} \) constrains EBL models