Theoretical modeling and interpretation of a distinct hard spectral component in GRB 090902B detected with Fermi

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on behalf of the Fermi Large Area Telescope Collaboration

Summary: A hard spectral component is required to fit GRB 090902B data in addition to the canonical Band spectrum. The origin of such a component can be explained as the radiation from cosmic rays accelerated in the GRB jet or/and early afterglow emission from an ultra relativistic decelerating jet.

Abstract

GRB 090902B shows for the first time clear evidence of excess emission both at low energies (below 50 keV) and at high energies (above 100 MeV), which can not be fitted with a Band function alone. These excesses are well-fit by a single hard, photon index -1.9, power-law component suggesting a common origin for both. We present Gamma-ray Burst Monitor (GBM) and Large Area Telescope (LAT) data and discuss various theoretical models which may give rise to such a component and outline possible scenarios which also give rise to a delayed onset of >100 MeV emission.

Specs of the long GRB

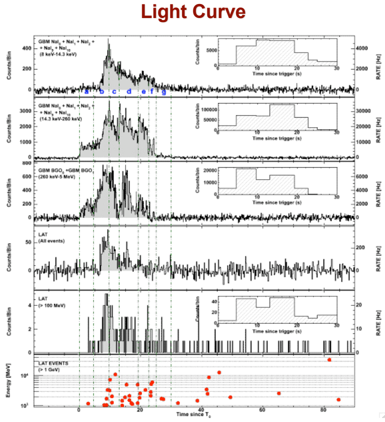
- GBM trigger: 11:05:15 UT on 2 September 2009
- Angle to the LAT bore-sight = 52.0 deg before the ARR
- (Autonomous re-pointing)
- 2 ks observation in the ARR mode before Earth occultation
- GBM location: RA, Dec = 264.5, 26.5 deg; Err = 1.0 deg
- Redshift, z = 1.822 (Gemini)

- 200 photons >100 MeV, 39 photons >1 GeV
- Onset of >100 MeV emission is delayed by ~3 sec.
- Highest energy photon $33.4^{+2.7}_{-3.5}$ GeV arrives at T_0+82 sec.

- T90 = 21.9 s (50-300 keV)
- Extended emission in LAT out to 1ks
- Fluence = 4.4×10^{-4} erg cm^{-2} (10 keV–10 GeV) in T_0+25 sec.
- Isotropic energy release, $E_{iso} = 3.6\times10^{54}$ erg

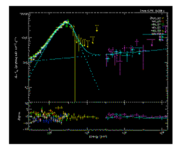
Many features – delayed onset of >100 MeV emission, isotropic energy, extended LAT emission – are similar to the long GRB 080916C (z = 4.35)

Light Curve

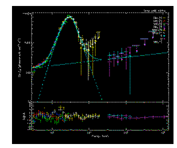


Spectroscopy

Clear evidence of a distinct hard component. Fits excess emission both below ~50 keV and above ~100 MeV



Time integrated spectra
hard component index Γ=-1.93



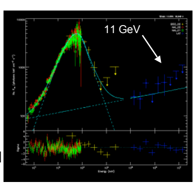
Time resolved spectra (4.6-9.6 s)
hard component index Γ=-1.94

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

Interval	Time Range (s)	E_{peak} (kev)	α	β	Γ	CSTAT/DOF	ΔCSTAT	Energy fluence (erg cm^{-2}, 8 keV–30 GeV)
···	0.0–30.0	726 (±8)	-0.61 (±0.01)	-3.8 ($^{+0.2}_{-0.3}$)	-1.93($^{+0.01}_{-0.01}$)	2562/963	2005	$(4.59 \pm 0.05)\times10^{-4}$
a.	0.0–4.6	526 (±12)	-0.09 (±0.04)	-3.7 ($^{+0.3}_{-0.6}$)	-1.87($^{+0.04}_{-0.05}$)	901/963	43	$(3.72 \pm 0.13)\times10^{-5}$
b.	4.6– 9.6	908 ($^{+15}_{-14}$)	0.07 (±0.03)	-3.9 ($^{+0.2}_{-0.3}$)	-1.94 (±0.02)	1250/963	3165	$(1.44 \pm 0.03)\times10^{-4}$
c.	9.6–13.0	821 (±16)	-0.26 (±0.03)	-5.0($^{+0.8}_{-\infty}$)	-1.98 (±0.02)	1310/963	2109	$(9.42 \pm 0.24)\times10^{-5}$
d.	13.0–19.2	529 (±9)	-0.65 (±-0.02)	-3.2 ($^{+0.1}_{-0.2}$)	-1.86 (± 0.02)	1418/963	199	$(1.29 \pm0.03)\times10^{-4}$
e.	19.2–22.7	317 (±8)	-0.78 (±-0.02)	-2.4 (±0.1)	···	1117/965	···	$(4.8 \pm 0.2) \times10^{-5}$
f.	22.7–25.0	236 ($^{+25}_{-33}$)	-1.30 ($^{+0.04}_{-0.03}$)	-2.2 (±0.1)	···	1077/965	···	$(1.0 \pm 0.1)\times10^{-5}$
e.+f.	19.2–25.0	327 (±8)	-0.91 (±0.02)	-2.6 (±0.1)	-1.59 (±0.20)	1219/963	16	$(6.1 \pm0.4)\times10^{-5}$
g.	25.0–30.0	···	···	···	-1.93 ($^{+0.25}_{-0.26}$)	1209/967	···	$(6.8 \pm 0.8)\times10^{-6}$

A Highly Relativistic Outflow

- Time-resolved nuFnu spectrum of Band+PL fit in interval "e" [9.6-13] s
- Similar variability time scale in GBM (~50 ms) and LAT (~100 ms) may suggest a common physical origin of the both components.
- Calculate opacity of $\gamma\gamma \rightarrow e^+e^-$ pair production by the 11 GeV photon with soft photons using Band+PL fit
- Keep variability fixed "53 ms" [BGO] vary Γ, opacity = 1 → Γ_{min} the minimum bulk Lorentz factor



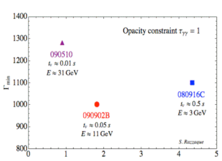
Large Γ_{min}~1000 implies Large emission radius $R \sim 10^{15}$ cm

Similar to GRBs 080916C and 090510

Some caveats

- The PL component may Originate from physically Separate region
- Radiation transport effect

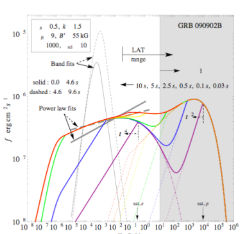
Both may lead to lower Γ



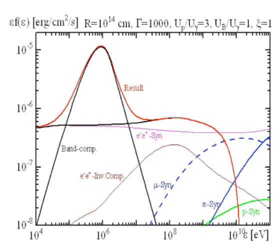
The Distinct Hard Spectral Component

Poses challenge to theoretical models

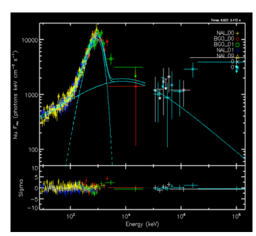
Synchrotron self-Compton (SSC) model is inadequate -- Compton peak at very high energy, can not produce excess emission observed below ~50 keV, may require large power.
Proton synchrotron radiation + cascade -- can produce hard component, delayed onset of >100 MeV emission, requires high magnetic field, requires large power.
Photopion production + cascade -- can produce hard component, poor efficiency, requires large power.
Early afterglow synchrotron -- can produce hard component though excess emission below ~50 keV maybe challenging to produce, delayed onset of >100 MeV emission
Photospheric emission + power-law -- requires non-thermal (power-laws) in addition to thermal emission to explain the hard component, does not fit data better than Band+PL.



Proton synchrotron radiation+cascade



Photopion production+cascade



Photospheric emission + power-law

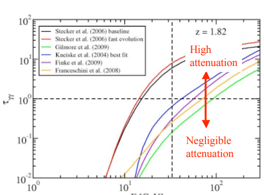
Constraint on the EBL Models

Opacity of $\gamma\gamma \rightarrow e^+e^-$ pair production by the 33.4 GeV (highest from a GRB!) photon with photons of the extragalactic background light (EBL)

For Stecer et al. 2006 Models, the opacity
$\tau_{\gamma\gamma}$ ~ 7.7 (fast evolution)
$\tau_{\gamma\gamma}$ ~ 5.8 (baseline)

Both Stecker et al. models can be ruled out with >3σ significance

Other models: OK

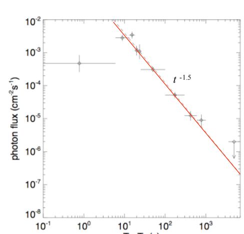


Extended Emission

An ultra-relativistic jet, Γ >1000, and large energy will slow down in a few seconds and this can cause extended emission from synchrotron radiation.

The power-law flux decay indicates afterglow behavior.

The origin of the 33.4 GeV photon at T_0+82 s from afterglow electron synchrotron radiation may be challenging.



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