Fermi observations of the jet photosphere in gamma-ray bursts

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On behalf of the Fermi GBM and LAT teams
GRBs: general properties

- Very bright sources
- Occurs $\sim$1 per day
- Non-repeatable
- Isotropically distributed in the sky
- Cosmological distances ($z \sim 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;
GRBs: general properties

- The lightcurves can be very different from one to another
- The variability is \(~ 10\) ms
- The lightcurve variability carries the information on the size of the emitter
GRBs: general properties

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

Wide energy range needed for GRB observations!

Kaneko et al. (2006)
Gravitational potential energy → “Fireball”

(Mészáros 2006)

$\Gamma \approx \text{few } \times 100$

($\Gamma \equiv [1 - \beta^2]^{-1/2}$, $\beta \equiv v/c$)
Non thermal emission (from internal shocks)

Shock accelerated electron distribution

Synchrotron Emission Spectrum

\[ I_\nu \propto \gamma^{2\min} B \Gamma \]

\[ E_{pk} \propto \gamma_{\min}^{2} \]

\[ \alpha = -3/2 \]

\[ \beta = -(p+2)/2 \]

Fast Cooling

Shock acceleration

1st and 2nd order Fermi
1986: Thermal emission from the fireball

Fireball model, high optical depths

Strong thermal component expected $\sim 1$ MeV and at $10^{12}$ cm

Thermal emission in GRBs?

Broadening due to geometrical effects

Blackbody

Potential prompt emission mechanisms

Simple photospheric model:
- Blackbody

\[ \alpha = 1 \]

Simple synchrotron model:
- \[ \alpha = -\frac{3}{2} \]
- \[ \beta = \frac{-(p+2)}{2} \]
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 Photopere, T
- Shock Synchrotron, S
- Photospheric Comptonization, PHC
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)

Ryde 2005
Behavior of the thermal component

The spectral peak is due to a peaked thermal component.

Temperature Evolution $kT$

Evolution of the normalization, $A(t)$

$$F(t) = A(t) [kT]^4 \frac{\pi^4}{15}$$

CGRO BATSE ERA (1994-2000)

Ryde & Pe'er 2009
The spectral peak is due to a peaked thermal component.

\[ F(t) = A(t) [kT]^4 \pi^4 / 15 \]

**Behavior of the thermal component**

- Temperature Evolution \( kT \)
- Evolution of the normalization, \( A(t) \)

Distinct recurring behavior!
Simulations using prelaunch models of the response: gtobsim

BATSE energy range

Battelino, Ryde, Omodei, & Longo (2007)
Predictions for Fermi based on BATSE results

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Two components needed; a Band function and a BB (see Guiriec+10, Ryde+10, 11, Burgess+11, McGlynn+12)

(Guiriec et al. 2011)
Photosphere in GRB100724B

Limiting the band width to 8 keV - 1500 keV
(Comparing the BATSE fits)

(Guiriec et al. 2011)

CGRO BATSE fits of GRB981021
(Ryde & Pe’er 2009)

Band model

BB+pl model

EGRET TASC data available
for this burst; peak energy = 1600 keV
Photosphere in GRB100724B

Limiting the band width to 8 keV - 1500 keV (Comparing the BATSE fits)

- **Band model**
- **BB+pl model**

CGRO BATSE fits of GRB981021
(Guiric et al. 2011)

EGRET TASC data available for this burst; peak energy = 1600 keV

(Ryde & Pe’er 2009)
Two components needed; a Band function and a BB (see Guiriec+10, Ryde+10, 11, Burgess+11, McGlynn+12)
Having identified the photospheric emission allows the determination of the physical properties of the outflow and its photosphere Pe’er+07, Daigne+07.

In this case we find that the bulk Lorentz factor

\[ \Gamma \sim 325 \text{ and photospheric radius } R_{\text{ph}} \simeq 5.6 \times 10^{11} \text{ cm} \]
Time resolved spectra consist of two peaks, one at 30 keV and one at ~ MeV.

Best fit model: Band function + Planck function

GRB 120323A

(Guiriec et al. 2012)
GRB 110721A

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

Best fit model:
Band function + Planck function

(Axelsson et al. 2012)
GRB 110721A

Exceptionally high peak energy 15 MeV during initial time bin

Peak energy evolution as a function of time

\[ E_p = A_p (t - t_0)^p \]
\[ p = 1.89 \pm 0.35 \]
\[ t_0 = -0.8 \pm 0.3 \text{ s} \]

Importance of BGO and LLE data!

\[ \alpha = -0.81^{+0.07}_{-0.06} \]
\[ \beta = -4.1^{+0.4}_{-0.7} \]
\[ E_{pk} = 15.2^{+1.3}_{-1.2} \text{ MeV} \]

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 $R_{ph} = (5.7 \pm 0.8) \times 10^{11}$ cm
Comparison to BATSE analysis:

**Fermi:**
GRB110721
Axelsson et al. (2012)

**Temperature**

**Normalization**

**CGRO BATSE:**

Ryde & Pe’er (2009)
Photosphere in GRB090902B

\[ \alpha = 0.31 \pm 0.08 \]

\[ \beta = -4 \]

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

Ryde et al. 2010
Photosphere in GRB090902B

Derived jet properties

Photosphere in GRB090902B

\[ \alpha = 0.3 \]

\[ \beta = -4 \]

Ryde et al. 2011
Photosphere in GRB090902B

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Ryde et al. 2011
Idea: a heating mechanism below the photosphere modifies the Planck spectrum

- Internal shocks
  (Pe’er, Meszaros, Rees 06, Toma+10, Ioka10)

- Magnetic reconnection
  (Giannions 06, 08)

- Weak / oblique shocks
  (Lazzati, Morsonoi & Begelman 11, Ryde & Peer 11)

- Collisional dissipation
  (Beloborodov 10, Vurm, Beloborodov & Poutanen 11)

Idea: the spectrum changes with the angle of sight

Lundman et al. 2012
Modification of Planck spectrum

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Nynmark et al. 2011, Pe’er et al. 2006

Idea: the spectrum changes with the angle of sight

Emission from the photosphere is NOT seen as Planck!

Lundman et al. 2012
Conclusions

✓ Fermi confirms BATSE results on thermal emission in GRBs

✓ Many GRBs have ‘double humped’ spectra and the Band function cannot model their shapes. (Guiriec+10,12, Ryde+10, 11, Burgess +11, McGlynn+12, Axelsson+12)

✓ The addition of a photospheric component improves the fit in many cases, and follows well-defined characteristics.

✓ The spectrum emerging from the photosphere does not need to be a Planckian. Several broadening mechanisms, e.g. subphotospheric dissipation or geometrical.

✓ The inclusion of the blackbody is the first step towards an understanding the physical origin of the prompt emission: The Band function does not provide it.
Parameters of the Photosphere

\[ R \sim \frac{L_0}{\Gamma^4} \]

\[ r_{ph} = \frac{L_0 \sigma_T}{8\pi \Gamma^3 \rho_p c^3} \]

\[ R \equiv \left( \frac{F_{BB}}{\sigma_{SB} T_{ob}^4} \right)^{1/2} \]

\[ L_0 = 4\pi d_L^2 Y F \]
Geometrical broadening

Angle dependent photosphere $\rightarrow$ Limb darkening
Photosphere in a relativistic explosion
Analytical and Monte Carlo study of geometrical effects

Analytic model

- Considers last scattering positions of photons
- Local emissivity is given by the 'scattering density' attenuated by the optical depth

Monte Carlo simulation

- Tracks photon propagation within regions of varying electron density and Lorentz factor
- Full photon propagation below the photosphere, including Comptonization of photons

Lundman et al. 2012
Results
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• Geometrical effects can produce broadening of the spectrum without introducing synchrotron photons

• For narrow jets ($\Theta_j \leq \text{few}/\Gamma_0$) broadening observed at any viewing angle
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- For narrow jets ($\theta_j \leq \text{few}/\Gamma_0$) broadening observed at any viewing angle.
- For wider jets, broadening when observed at $\theta_v \approx \theta_j$.

Lundman et al. 2012
Idea: a heating mechanism below the photosphere modifies the Planck spectrum

Modification of Planck spectrum

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