Fermi observations of the jet photosphere in GRBs: interpretations and consequences

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Bottom line:

- The emission mechanisms for GRBs are still unclear, but Fermi observations show that the photosphere plays an important role.

- The inclusion of the thermal component is the first step towards an understanding the physical origin of the prompt emission.

- Fermi provides evidence of subphotospheric heating (Photosphere ↔ Planck function)

We need time resolved spectroscopy!
GRBs: general properties

• Transient
• Very bright sources
• Observe ~1 per day
• Isotropically distributed on sky
• Cosmological distance (highest z~9)
Two phases:
- The PROMPT phase: lasting ~ 100s mainly in the kev-MeV band;
- The AFTERGLOW phase lasting >3000s;
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• The PROMPT phase: lasting ~ 100s mainly in the kev-MeV band;
• The AFTERGLOW phase lasting >3000s;

Very different light curves...

...but spectra quite similar.
Gravitational potential energy → “Fireball”

(Mészáros 2006)

\[ \Gamma \approx \text{few } \times 100 \]
\( (\Gamma \equiv [1 - \beta^2]^{-1/2}, \beta \equiv v/c) \)
**Should there be thermal emission in GRBs?**

1986: Thermal emission from the fireball

- Variability $>\sim 10$ ms
- Cosmological distances
- Observed Flux: $\sim 10^{-7} - 10^{-4}$ erg cm$^{-2}$ s$^{-1}$
- Typical observed energy: $<\sim$ MeV

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

Fireball model, high optical depths

Broadening due to geometrical effects


**Fig. 1.** — *Solid line*: energy distribution of the flux received by a distant observer at rest with respect to the center of mass of the fluid. The vertical scale in arbitrary units. (*Dashed line*): corresponding distribution for a blackbody at the initial temperature of the fluid.
Observed spectra are *not* Planck spectra
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Optically thin **synchrotron emission** in internal shocks; jitter radiation, IC

- Line of death
- Shock acceleration
- Efficiency of internal shocks
Observed spectra are not Planck spectra

Solution?

Optically thin synchrotron emission in internal shocks; jitter radiation, IC
- Line of death
- Shock acceleration
- Efficiency of internal shocks

Multiple spectral components (e.g. Mészáros et al. 2002)

Thermal Photophere, T
Photospheric Comptonization, PHC
Shock Synchrotron, S
Optically thin **synchrotron emission** in internal shocks; jitter radiation, IC

- Line of death
- Shock acceleration
- Efficiency of internal shocks

**Multiple spectral components** (e.g. Mészáros et al. 2002)


- Geometrical effects (Pe’er 2008, Lundman et al. 2012)

The emission from the photosphere is **not Planckian**

The observed spectra are **not** Planck spectra.

Photospheric emission in BATSE bursts

Spectra from temporally resolved pulses observed by BATSE over the energy range 20-2000 keV. Spectral fit: Black body combined with a power law: \[ N_E(E, t) = A(t) \frac{E^2}{\exp[E/kT(t)] - 1} + B(t) E^8 \]

**Photosphere (Planck function)**

**Additional non-thermal emission**

**Ryde 2004**
(see also Ghirlanda et al. 2003)

EGRET TASC peak at \( E_p = 1600 \) keV

Ryde 2005
The spectral peak is due to a peaked thermal component. Behavior of the thermal component:

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

Temperature Evolution \( kT \)

Evolution of the normalization, \( A(t) \)
The spectral peak is due to a peaked thermal component. *Behavior of the thermal component:*

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**Temperature Evolution** $kT$

**Evolution of the normalization, $A(t)$**

Distinct recurring behavior

Ryde & Pe‘er 2009
Predictions for *Fermi* based on BATSE results
Simulations using prelaunch models of the response: \texttt{gtobsim}

Battelino, Ryde, Omodei, & Longo (2007)
Predictions for Fermi based on BATSE results
Simulations using prelaunch models of the response: gtobsim

GRB100724B

Two components needed; a Band function and a BB Guiriec et al. 2010

also seen in e.g. GRB090820A (Burgess et al. 2011)
Limiting the band width to 8 keV - 1500 keV (Comparing the BATSE fits)

**Band model**

**NaI Band**

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

**BB+pl model**

**NaI**  
**BB+pl**

- EGRET TASC data available for this burst; peak energy = 1600 keV
Limiting the band width to 8 keV - 1500 keV (Comparing the BATSE fits)

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

EGRET TASC data available for this burst; peak energy = 1600 keV
Two components needed; a Band function and a BB (see Guiriec+10, Ryde+10, 11, Burgess+11, McGlynn+12)
GRB 120323A

Time resolved spectra consist of two peaks, one at 30 keV and one at ~ MeV

Best fit model: Band function + Planck function

(Guirie et al. 2012)
Time resolved spectra consist of two peaks, one at 100 keV and one at ~ MeV.

Best fit model: Band function + Planck function.
GRB 110721A

Exceptionally high peak energy 15 MeV during initial time bin [-0.32: 0 s]

Peak energy evolution as a function of time

\[ E_p = A_p(t - t_0)^p \]

\[ p = 1.89 \pm 0.35 \]
\[ t_0 = -0.8 \pm 0.3 \text{ s} \]

\[ \alpha = -0.81^{+0.07}_{-0.06} \]
\[ \beta = -4.1^{+0.4}_{-0.7} \]

\[ E_{pk} = 15.2^{+1.3}_{-1.2} \text{ MeV} \]

Importance of BGO and LLE data!

cf. Lloyd & Petrosian (1998)
Evolution different from $E_p$ and normalization!

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**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.

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Evolution different from $E_p$ and normalization!
Comparison to BATSE analysis:

**Fermi:**

[Graph showing temperature vs. energy for Fermi data, with a comparison to prior works by Ryde & Pe'er (2009) and Axelsson et al. (2012).]

**CGRO BATSE:**

[Graph showing energy spectrum and temperature decay for CGRO BATSE data, with a comparison to Ryde & Pe’er (2009).]
Observables give physical parameters of outflow

Blackbody normalisation, \( \mathcal{R} \)

\[
\mathcal{R} \equiv \left( \frac{F_{BB}}{\sigma_{SB} T_{ob}^4} \right)^{1/2} = \xi \frac{(1+z)^2 r_{ph}}{d_L} \frac{\Gamma}{\Gamma}
\]

Luminosity, \( L_0 \)

\[
L_0 = 4\pi d_L^2 Y F
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Lorentz Factor

\[
\Gamma \propto \frac{L_0 \sigma_T}{8\pi \Gamma^3 m_p c^3}
\]

Photospheric radius \( r_{ph} \)

\[
\frac{r_{ph}}{10^{14} \text{ cm}} = \frac{L_0 \sigma_T}{8\pi \Gamma^3 m_p c^3}
\]
Changing the shape of the thermal component

Photosphere in GRB090902B

\[ \Gamma = 750 \quad R_{ph} = (1.1 \pm 0.3) \times 10^{12} Y^{1/4} \text{ cm} \]

Ryde et al. 2010
Photosphere in GRB090902B

\[ \alpha = 0.31, \quad \beta = -4 \]

\[ \text{Energy} \ [\text{keV}] \]

\[ 8.1 - 8.5 \text{ s} \]

Ryde et al. 2011
Photosphere in GRB090902B

Energy [keV]

8.1-8.5 s

\( \alpha = 0.31 \)

\( \beta = -4 \)

15.9-16.4 s

Ryde et al. 2011
Possible explanation I

Idea: a heating mechanism below the photosphere modifies the Planck spectrum

Rees & Meszaros 2005

- **Internal shocks**
  (Peer, 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)

Emission from the photosphere is NOT seen as Planck!

Lazzati et al. 09 numerical simulation of jet propagation.
See also Mizuta 11, Toma11

Nymark et al. 2011, Pe’er et al. 2006
Possible explanation 2

Geometrical broadening

Angle dependent photosphere
Photosphere in a relativistic explosion
Simulations show:

- 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

- For **wider** jets, broadening when observed at $\theta_v \approx \theta_j$

Lundman et al. 2012
Conclusions

- The emission mechanisms for GRBs are still unclear, but Fermi observations show that the photosphere plays an important role.

- 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.

- 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.
Thank you!
Analytical and Monte Carlo study of geometrical effects (Lundman et al. 2012)

**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