Observations of the Jet Photosphere in GRBs: Interpretations and Consequences

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On behalf of the Fermi GBM and LAT teams
Bottom Line

1. Band function is not a universal form of GRB spectra

2. GRB spectra are not always optically-thin, but the photosphere need not emit a Planck function

3. GRB jet properties are variable. Lorentz factor decreases over individual pulses

- A small fraction of burst have a dominant photospheric component.

- A common type of spectrum is a doubly-peaked spectrum.
Basic framework: the fireball model

Nonthermal emission:
Synchrotron emission, inverse Compton emission

If below the saturation radius - strong black body
If above saturation radius - adiabatic cooling

\[
\frac{F_{BB}}{F_{NT}} = \left( \frac{r_{ph}}{r_s} \right)^{-2/3}
\]
Basic framework: the fireball model

Nonthermal emission:
Synchrotron emission, inverse Compton emission

\[ \eta = \frac{L}{\dot{M} c^2} \]

\[ T = 1.0 \times 10^7 \] \[ \xi = \frac{1}{2}, \sqrt{1} \]
\[ \xi < 1 \]
\[ \xi > 1 \]

\[ \eta = 10^7 \] \[ \xi = 1 \] \[ \xi < 1 \]
\[ \xi > 1 \]

\[ \eta = 10^5 \] \[ \xi = 1 \] \[ \xi < 1 \]
\[ \xi > 1 \]

\[ \eta = 594 \] \[ \xi = \frac{1}{2}, 17 \]
\[ \xi > 1 \]

\[ \eta = 321 \] \[ \xi = 1 \] \[ \xi < 1 \]
\[ \xi > 1 \]

\[ \eta = 80.6 \] \[ \xi = 1 \] \[ \xi < 1 \]
\[ \xi > 1 \]

\[ \eta = 36 \] \[ \xi = 1 \] \[ \xi < 1 \]
\[ \xi > 1 \]

Photospheric emission:
Blackbody emission from turbulent, relativistic outflow

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\[ \frac{F_{BB}}{F_{NT}} = \left( \frac{r_{ph}}{r_s} \right)^{-2/3} \]

Fermi

Meszaros et al. (2000)

Multi zone emission
Basic framework: the fireball model

Nonthermal emission:
Synchrotron emission, inverse Compton emission

Anatomy of a Burst
When a black hole forms from a collapsed stellar core, it generates an explosive flash called a γ-ray burst. Contrary to earlier thinking, evidence now suggests that the glowing fireball produces more γ-rays than do the shock waves from the blast.

1. Fireball is opaque. Electron-photon interactions prevent light from escaping.
2. Fireball is transparent. Thermal radiation includes γ-rays emitted by accelerated electrons and boosted to high-temperature plasma.
3. Shock waves accelerate electrons. γ-rays are emitted by accelerated electrons and boosted to high energies through scattering.
4. Electrons hit interstellar medium. They rapidly decelerate, emitting optical light and X-rays.

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Do we observe these components?
Pure photosphere?

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We need:
Broad energy band
High time resolution
High energy resolution

Multi zone emission

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Pure photosphere?

GRB090902B  Abdo et al. (2009), Ryde et al. (2010) Zhang et al. (2010)

Time resolved spectrum (11.608-11.880 s)

\[ \alpha = 0.55 \pm 0.16 \]

FWHM < 1 dex

Synchrotron emission excluded. likely photospheric emission
Pure photosphere?

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Wednesday, 24 April 13
Pure photosphere?
Spectra from temporally resolved pulses observed by BATSE over the energy range 20-2000 keV.
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Line of death

Ghirlanda et al. (2003): Black body in initial phase of burst
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**Ryde (2004): Blackbody throughout the pulse.**

**Photosphere (Planck function)**

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Rayleigh Jeans’ slope

Void of photons
Pure photosphere?

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6 bursts in the BATSE catalogue
Pure photosphere?

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Modification of Planck spectrum

- *Heating mechanism* below the photosphere modifies the Planck spectrum.
  - Magnetic reconnection: (Giannions 2006, 2008)
  - Weak / oblique shocks: (Lazzati, Morsonoi & Begelman 2011, Ryde & Peer 2011)
  - Collisional dissipation: (Beloborodov 2010, Vurm, Beloborodov & Poutanen 2011)

- *Geometrical broadening*: ‘photosphere’ is NOT a single radius, but is 3-dimensional. ‘Limb darkening’ in relativistically expanding plasma. (Lundman, Peer & Ryde 2012)

Emission from the photosphere does NOT necessarily appear as a Planck function.
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\[ r_{ph} \]
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Do we observe these components? Multi-peaked spectra?
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Do we observe these components?
Multi-peaked spectra?
Examples of multi-peaked spectra observed by *Fermi*:

The photospheric component is modelled by a Planck function.
Is expected to be broadened to some extent.

Two component spectra: Blackbody component typically 5-10% of total flux.
But many cases with 40-60%.
Multi-peaked spectra

Fermi

Axelsson et al. 2012

Guiriec et al. 2013
Multi-peaked spectra

**Fermi**

Axelsson et al. 2012

**PHEBUS/Fregate**

Guiriec et al. 2013

Barat et al. 2000
Multi-peaked spectra

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**CGRO BATSE**

Ryde 2005

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Recurring, characteristic behaviors

The thermal component of GRB pulses have typical behaviors:

**Temperature**

**Normalization**

*CGRO*  
*BATSE*  

*Fermi*

Ryde & Pe'er 2009

Axelsson et al. 2012

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Recurring, characteristic behaviors

The thermal component of GRB pulses have typical behaviors:

**CGRO**

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**Fermi**

**Temperature**

**Normalization**

Ryde & Pe’er 2009

Burgess et al. 2013

Wednesday, 24 April 13
Jet properties in GRB 110721A  

(Iyyani et al. 2013)

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

Best fit model: Band function + Planck function

\[
\frac{F_{BB}}{F_{NT}} = \left( \frac{r_{ph}}{r_s} \right)^{-2/3}
\]
Translation of the observables to jet quantities
Pe’er, Ryde et al. (2007)

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

See also e.g.
Fan et al. (2011)
Guiriec et al. (2012)
Hascoet et al. (2013)

\[ r_{ph} \gg r_s \quad \mathcal{R} \approx \frac{(1+z)^2}{d_L} \frac{r_{ph}}{\Gamma} \]

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

(Unknowns efficiencies, magnetisation, distance)

Daigne’s talk
Typically: $R_{\text{ph}} \sim 10^{12} \text{ cm}$

$\Gamma \sim \text{few } 100$

$R_0 \sim 10^{6-9} \text{ cm}$

Translation of the observables to jet quantities

Pe’er, Ryde et al. (2007)

$$R \equiv \left( \frac{F_{BB}}{\sigma_{SB} T^4} \right)^{1/2}$$

$$r_{\text{ph}} > r_s \quad R \approx \frac{(1+z)^2 r_{\text{ph}}}{d_L} \frac{1}{\Gamma}$$

$$r_{\text{ph}} = \frac{L_0 \sigma_T}{8\pi \Gamma^3 m_p c^3}$$

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Ryde et al. 2010, ApJL, 709,
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\( F_{BB} \quad \Gamma \quad r_{\text{ph}} \quad r_o \quad (r_s) \)

(Unknowns efficiencies, magnetisation, distance)

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GRB 110721A

Photosphere radius
\( R_{\text{ph}} \approx \text{few} \times 10^{12} \text{ cm} \)

Lorentz factor of the flow

Increased baryon pollution.

Accretion disk stabilizes -> stronger neutrino-driven wind
Interacts with the jet -> pollute it with baryons
Characteristic behaviors of the thermal component in GRB pulses

Temperature

Normalized blackbody

\[ R \approx \frac{(1 + z)^2 r_{ph}}{d_L} \frac{1}{\Gamma} \]

\[ R \equiv \left( \frac{F_{BB}}{\sigma_{SB} T^4} \right)^{1/2} \]
Assuming fireball, adiabatic acceleration

Interpretation:
- Oblique shocks more easily develop for lower $\Gamma$?
- Magnetic content of the flow?
- Change in emission efficiency?
- Change in amount of dissipation?

Values of $r_o$ within the size of the progenitor Wolf-Rayet star

More internal dissipation in the jet at later times
Assuming fireball, adiabatic acceleration

### Nozzel radius

\[ r_o \]

### Saturation radius

\[ r_s \]

Values of \( r_o \) within the size of the progenitor Wolf-Rayet star

More internal dissipation in the jet at later times

Lead to a decrease in adiabatic cooling

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\frac{F_{BB}}{F_{NT}} = \left( \frac{r_{ph}}{r_s} \right)^{-2/3}
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- Magnetic content of the flow?
- Change in emission efficiency?
- Change in amount of dissipation?

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**References:**

- Guiriec et al. (2012)
- Daigne et al. (2012)
- Iyyani et al. (2013)
Summary

1. A small fraction of burst have a dominant photospheric component. Can be blackbody or Band like.

2. A common type of spectrum is a double peaked spectrum. The low energy peak can be modelled by a blackbody. *Gives recurring behaviour!* The flow properties can be determined: Lorentz factor, jet composition, multiple emission zones.

3. The GRB jet is variable. Lorentz factor decreases over GRB pulses

4. Weak bursts are only fit with a Band function. Can give erroneous physical interpretation!