Varying faces of photospheric emission in gamma-ray bursts

Magnus Axelsson
Stockholm University and OKC

On behalf of the *Fermi* GBM and LAT teams

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Basic framework: the fireball model

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 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.
Paczyński 1986:

ANATOMY OF A BURST

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Black hole

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 protons to high energies through scattering.

3 SHOCK WAVES
Accelerate electrons.

4 ELECTRONS HIT INTERSTELLAR MEDIUM
They rapidly decelerate, emitting optical light and X-rays.

Broadening due to geometrical effects

Blackbody

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 is in arbitrary units. (Dashed line): corresponding distribution for a blackbody at the initial temperature of the fluid.

Single Planck function bursts

Compton Gamma-Ray Observatory
GRB930214

Spectra from temporally resolved pulses observed by BATSE over the energy range 20-2000 keV.

Rayleigh Jeans’ slope

Void of photons

Ryde (2004): Blackbody throughout the pulse
Ghirlanda et al. (2003): Blackbody in initial phase of burst
Spectra from temporally resolved pulses observed by BATSE over the energy range 20-2000 keV.

CGRO BATSE: 6 observed bursts out of 2200

- Ryde (2004): Blackbody throughout the pulse
- Ghirlanda et al. (2003): Blackbody in initial phase of burst
Single Planck function bursts

Fermi Gamma Ray Space Telescope

GRB100507

Rayleigh Jeans’ slope

Void of photons

Ghirlanda et al. 2013
Single Planck function bursts

Fermi Gamma Ray Space Telescope

GRB100507

Fermi GST: 2 observed bursts out of 1400

Rayleigh Jeans’ slope

Abbreviation: GST

Ghirlanda et al. 2013

Void of photons
Narrow “BB-like” components

Ryde et al. 2011
Narrow “BB-like” components

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

Ryde et al. 2011
What do these bursts tell us?

1. Jet photosphere is detected! Photosphere has an effect on the formation of the GRB spectra.

2. Some spectra are pure blackbodies $\rightarrow$ strong theoretical implications!

3. Some spectra are slightly broader than a BB $\rightarrow$ broadening mechanisms

4. Typical spectra are not this kind

5. Motivation to search for blackbodies in the 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 much higher some cases.
Two component spectra

Fermi

Fregate

CGRO

GRB 960530

Gamma-ray Space Telescope
Changes the interpretations!

1. Change in $E_{\text{peak}}$
2. Change in alpha (synchrotron?)
3. Change in emission zones

GRB120323A
Conditional 1: Multiple Emission Zones

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Afterglow

- Synchrotron radiation
- X-ray
Two emission zones - model

Photosphere
(No dissipation below)

Above photosphere
(Optically thin)

Thermal component - Planck function (BB)
Non-thermal component - Band function
synchrotron, ICMART...

2 zone emission, various realisations

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

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

Magnetisation of the jet allows the ratio to vary (Daigne et al. 2013)
GRB110920
Two component fit

Band + BB

Synchrotron + BB

McGlynn et al. 2012

Burgess et al. 2014

Not a general solution!
Talk and poster by Michael Burgess
Interpretation 2: Photospheric emission
Modification of Planck spectrum

*Heating mechanism* below the photosphere modifies the Planck spectrum

- **Internal shocks**
  (Peer, Meszaros, Rees 06, Ryde+10, 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!
Modeling with subphotospheric dissipation

- Our code (by Pe’er & Waxman 2004) solves the kinetic equations for internal shocks
- Includes cyclo/synchrotron emission, SSA, Compton scattering (direct/inverse), pair production, pair annihilation

Dissipation at optical depth $\tau = 10$

Emerging photon spectrum

Planck function

Comptonization

Synchrotron emission

$\Gamma = 100, \tau = 10, L_{sd} = 1, \epsilon_{pl} = 0, \epsilon_s = 0.2, \epsilon_e = 0.3, \epsilon_B = 0.3$
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Dissipation at optical depth $\tau = 10$

See poster by Björn Ahlgren
**Modification of Planck spectrum**

*Geometrical broadening:* ‘photosphere’ is NOT a single radius, but is 3-dimensional

\[ \beta \equiv \frac{v}{c} \]

Pe’er 2008; Pe’er & Ryde 2011

Lundman, Peer, Ryde 2012

‘Limb darkening’ in relativistically expanding plasma: emission from photosphere is NOT seen as Planck!
Modification of Planck spectrum

*Geometrical broadening:* ‘photosphere’ is NOT a single radius, but is 3-dimensional

But we do see spectra well fit by a single blackbody! → strong constraints on models

‘Limb darkening’ in relativistically expanding plasma: emission from photosphere is NOT seen as Planck!
Possible observable to discriminate between interpretations: **Polarisation**

- Synchrotron emission is easily polarised.
- Is the photosphere polarised?
Polarisation from the photosphere

- Polarized emission in range **0-40% expected** (depending on viewing angle and jet structure)

- **Only** a change in pol. angle of **90°** is possible (due to jet axisymmetry)

- If jet is wide, most obs. see low polarization (few percent)

- Correlations expected between spectrum and polarization

Lundman, Pe’er, & Ryde 2014
Conclusions

The jet photosphere is important for the understanding of GRB emission.

Most GRB spectra do not look thermal (i.e., Planckian).

Many GRBs have multiple components.

Interpretations: 1. Multi zone emission
2. Pure photospheric emission

Polarisation measurements are important!