Signature of the Photosphere in the GRB Prompt Emission

Rupal Basak
Supervisor: A. R. Rao
TIFR, Mumbai, India

SN-GRB Workshop 4-8 November, 2013
Outline

- Background
- Thermal and non-thermal components
  - 2BBPL model: 090902B and 081221
  - Parametrized joint fit: 081221, 090618
  - A Spine-sheath Jet
  - Independent Detection
  - Predicting GeV emission
- Conclusions and future works
Goodman (1986), Paczynski (1986) gave standard model even before the BATSE was launched.

If a high energy density is created at a point of space it will drive e-p plasma and radiation.

The radiation will be thermalized before reaching the photosphere. Hence, the *spectrum* should be *blackbody* like. There will be boosting by Lorentz factor towards the observer, and the temperature should decrease due to adiabatic expansion.

The *light curve* is predicted as a simple *pulse*.

Rupal Basak

Photosphere in GRB prompt emission
Light Curve and Spectrum

The zoo of GRB Light curves

Blue: Blackbody (BB)
Green: Inverse Compton (IC)
Red: Data

Lazzati, GRB conference 2012, Munich

Credit: J.T. Bonnell (NASA/GSFC)
Internal-External Shock


Internal Shock

External Shock

The Flow decelerating into the surrounding medium

Collisions between different parts of the flow

Jet

collapse

GRB

\approx 10^{13} \text{ cm}

\text{Afterglow}

\text{XO}

\text{OR}

\text{> } 10^{16} \text{ cm}
The internal shock produces relativistic electrons, which in their rest frame produce \textbf{synchrotron} emission. This model is phenomenologically represented by Band model --- two smoothly joined power-laws.

\[
I(E) = \begin{cases} 
A_b \left[ \frac{E}{100} \right]^{\alpha} \exp \left[ \frac{-(2+\alpha)E}{E_{\text{peak}}} \right] & \text{if } E \leq \left[ (\alpha - \beta)/(2 + \alpha) \right] E_{\text{peak}} \\
A_b \left[ \frac{E}{100} \right]^\beta \exp[\beta - \alpha] \left[ \frac{(\alpha - \beta)E_{\text{peak}}}{100(2+\alpha)} \right]^{(\alpha - \beta)} & \text{otherwise}
\end{cases}
\]
Issues in the Synchrotron Model

- Band model is a phenomenological model.
- Low energy index crosses the "line of death".
- The actual spectrum can be more complicated.
- IS model have its own problems: (i) efficiency is at most 20%, (ii) the situation of inner shell moving faster than the outer one is unstable (Waxman & Piran 1994, ApJL, 433, 85)
**Good news:** There are provisions in the original fireball model. Once the photons go into the optically thin region, they are free to escape. With a reasonable guess work and assuming very high Lorentz factor, Goodman (1986) suggested broadening of the Planck spectrum. But, this is still far from the actual observation.
Rupal Basak

Photosphere in GRB prompt emission

Time-resolved Spectrum


BBPL = blackbody + powerlw
BBPL sometimes is even better than Band model.

The kT evolves with time. This can be explained by the standard fireball model.
BBPL sometimes is even better than Band model.

The $kT$ evolves with time. This can be explained by the standard fireball model.
Various Other Possibilities

Subphotospheric dissipation --- Multicolour BB+PL (mBBPL)

Time resolved spectra of GRB 090902B (Ryde + 2010). The light curve does not contain a smooth or separable pulses. For the same GRB Zhang et al. (2011) claim a BBPL fit for fine enough temporal bins.
Various Other Possibilities

Double hump structure --- Band+BB

**GRB 110721A**, fitted with Band+BB model (Axelsson et al. 2011). One notices the double hump in the spectrum (Also see Guiriec et al. 2011; Ryde et al. 2010, 2011; Burgess et al. 2011, McGlynn et al. 2012).
The Final Picture?

Lazzati, GRB conference 2012, Munich

Rupal Basak

Photosphere in GRB prompt emission
The Model

I. GRB 090902B and GRB 081221
Double hump is clearly visible in the residual of BBPL fit.

mBBPL, as done by Ryde + (2010), takes a continuous temperature distribution over a disk. In contrast 2BBPL model is truly double hump.
2BBPL Model: GRB 090902B

Rao, Basak, Bhattacharya et al. 2013
2BBPL Model: GRB 090902B

Rao, Basak, Bhattacharya et al. 2013

Band model

BBPL model

2BBPL model

2 BBs with a power-law

Rupal Basak

Photosphere in GRB prompt emission
2BBPL Model: GRB 090902B

Some interesting features of 2BBPL

Rupal Basak

Photosphere in GRB prompt emission
Case Study: GRB 081221


Light Curve

kT & peak energy evolution

Chi squares

Parameter evolution

2BBPL and BBPL fit

2BBPL and Band fit

Photosphere in GRB prompt emission
Conclusion I

Energy (keV)

Higher BB

Lower BB

Power-law

$E F(E)$

Energy (keV)
Conclusion I

Energy (keV)

Higher BB

Lower BB

\[ E_F(E) \]

Energy (keV)
At a later time:
Conclusion I
The Model

II. Parametrized Joint Fit

See poster P31 in the GRB conference
Choices of Spectral Models

- **Fully non-thermal**
  - Band model.

- **Thermal+non-thermal**
  - BBPL = Blackbody + powerlaw
  - mBBPL = Multicolor BB + PL
  - 2BBPL = 2BBs + PL

BBPL = Blackbody + powerlaw
mBBPL = Multicolor BB + PL
2BBPL = 2BBs + PL
Choices of Spectral Models

- Fully non-thermal Band model.
- Thermal+non-thermal
  - BBPL
  - mBBPL
  - 2BBPL

- A proper choice of time bins
- Re-binning of spectral channels
- Parametrization of spectral model
Parametrized Joint Fit

Fully non-thermal Band model.

See poster P31 in the GRB conference

Rupal Basak
Photosphere in GRB prompt emission
Parametrized Joint Fit

Fully non-thermal Band model.

Time binning according to the count per bin. Notice the unequal bin size.

If a 4 parameter model (Band) is fitted at each bin, total 72 (18x4) parameters are required.
**Fully non-thermal Band model.**

Peak energy of the Band model varies smoothly with time.

**Parametrized Joint Fit**

Count Rate vs. Time (s) with peak energy on the vertical axis.
Fully non-thermal Band model.

Peak energy of the Band model varies smoothly with time.

Photon indices remain more or less constant over a section.

Parametrized Joint Fit

Rupal Basak
Photosphere in GRB prompt emission
Perform a simultaneous fit, parametrizing the peak evolution and tying the photon indices.

From 72 parameters, this will reduce to 26 parameters

Similar treatment for other models

For example, BBPL will have same no. Of parameters as Band. MBBPL will have one extra and 2BBPL will have two extra free parameters,
Spectrum at different Regions

Comparison b/w Band, BBPL and mBBPL

Photosphere in GRB prompt emission
Values of Alpha

Rupal Basak

Photosphere in GRB prompt emission
Values of Alpha

$\alpha$ is within the "line of death" where Band Model is the best.
In all cases 2BBPL is superior than BBPL. In all cases 2BBPL is comparable or better than Band. mBBPL is inferior than Band and 2BBPL.

In summary, 2BBPL is the best model.

Same results are obtained for two pulses of GRB 090618. These are the two brightest GRBs having separable pulses. It is unlikely that we can find better result in any other GRBs.


<table>
<thead>
<tr>
<th>Region</th>
<th>Model2/Model1</th>
<th>p</th>
<th>σ</th>
<th>C.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse1, Rising</td>
<td>BBPL/Band</td>
<td>0.38</td>
<td>0.87</td>
<td>61.5%</td>
</tr>
<tr>
<td></td>
<td>mBBPL/Band</td>
<td>0.41</td>
<td>0.81</td>
<td>58.5%</td>
</tr>
<tr>
<td></td>
<td>2BBPL/Band</td>
<td>0.30</td>
<td>1.04</td>
<td>70.2%</td>
</tr>
<tr>
<td></td>
<td>2BBPL/BBPL</td>
<td>0.03</td>
<td>2.19</td>
<td>97.1%</td>
</tr>
<tr>
<td>Pulse1, Falling</td>
<td>Band/BBPL</td>
<td>0.30</td>
<td>1.03</td>
<td>69.9%</td>
</tr>
<tr>
<td></td>
<td>mBBPL/BBPL</td>
<td>0.33</td>
<td>0.97</td>
<td>66.6%</td>
</tr>
<tr>
<td></td>
<td>2BBPL/BBPL</td>
<td>1E-5</td>
<td>4.4</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>Band/2BBPL</td>
<td>0.48</td>
<td>0.70</td>
<td>51.9%</td>
</tr>
<tr>
<td>Pulse2, Rising</td>
<td>Band/BBPL</td>
<td>0.02</td>
<td>2.37</td>
<td>98.2%</td>
</tr>
<tr>
<td></td>
<td>mBBPL/BBPL</td>
<td>0.01</td>
<td>2.55</td>
<td>98.9%</td>
</tr>
<tr>
<td></td>
<td>2BBPL/BBPL</td>
<td>1E-20</td>
<td>9.29</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>2BBPL/BBPL</td>
<td>0.39</td>
<td>0.86</td>
<td>60.9%</td>
</tr>
<tr>
<td>Pulse2, Falling</td>
<td>Band/BBPL</td>
<td>1E-5</td>
<td>4.41</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>mBBPL/BBPL</td>
<td>8E-5</td>
<td>3.95</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>2BBPL/BBPL</td>
<td>2E-66</td>
<td>17.2</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>2BBPL/BBPL</td>
<td>0.30</td>
<td>1.03</td>
<td>69.7%</td>
</tr>
<tr>
<td></td>
<td>2BBPL/mBBPL</td>
<td>0.16</td>
<td>1.39</td>
<td>83.5%</td>
</tr>
</tbody>
</table>
The Model

III. A Spine-sheath Jet
Origin of 2BBPL: Spine-sheath Jet

Ito, Nagataki, Ono et al. 2013
(Talk by H. Ito in GRB conf.)

Peak of the spectrum,
\[ E_p = r_i^{1/6} \eta^{8/3} L^{-5/12} \]

Peak luminosity,
\[ L_p = r_i^{2/3} \eta^{8/3} L^{1/3} \]
Origin of 2BBPL: Spine-sheath Jet

\[ E_p = r_i^{1/6} \eta^{8/3} L^{-5/12} \]

\[ L_p = r_i^{2/3} \eta^{8/3} L^{1/3} \]

Peak of the spectrum,

Peak luminosity,

Ito, Nagataki, Ono et al. 2013
(Talk by H. Ito in GRB conf.)

Lazzati & Begelman (2008)

Rupal Basak

Photosphere in GRB prompt emission
The Model

IV. Independent Observation

- XRT: 0.3-10 keV
- BAT: 15-150 keV
- GBM: 8keV- 30 MeV
- LAT >30MeV
- Fermi
- Swift
XRT Observation of the Second BB

Page et al. (2011)

081221


Rupal Basak

Photosphere in GRB prompt emission
XRT Observation of the Second BB

BB temperatures in the XRT time-resolved spectrum

Note that temperature falls as a power-law with time.
XRT Observation of the Second BB

BB temperature in the BAT/ GBM spectrum in 118-125 s

Preliminary
XRT Observation of the Second BB

Rupal Basak

Photosphere in GRB prompt emission
XRT Observation of the Second BB

BB Temperature (keV)

Time since trigger (s)

Preliminary

BB temp. In BAT

Rupal Basak

Photosphere in GRB prompt emission
XRT Observation of the Second BB

To emphasize, these are independently detected and falls perfectly in our predicted line.
The Model

V. Predicting GeV emission
First detection: GRB 940217 (Hurley et al. 1994), observed by CGRO/EGRET, 90 minutes after the CGRO/BATSE detection.

Features: (a) Delayed onset, (b) longer lasting, (c) late time power-law temporal evolution, (d) spectrum: either an extrapolation of Band or significantly different component (most notable for bright cases)

Problems: (1) No unified spectral model found for MeV-GeV data (e.g., Zhang et al. 2011 found five combinations) (2) Very weak MeV-GeV correlation to draw inferences

Solution? Try multi-component spectral model. We select two pair of GRBs with comparable GBM fluence, but widely different LAT fluence.
Morphological Difference

High LAT count:
(A) 090902B,
(B) 090926A

Low LAT count:
(A) 100724B,
(B) 091003


Rupal Basak

Photosphere in GRB prompt emission
MeV-GeV Correlation


Correlations between the LAT fluence with the GBM fluence and GBM PL fluence

<table>
<thead>
<tr>
<th>Correlation</th>
<th>Pearson r</th>
<th>Pearson P</th>
<th>Spearman r</th>
<th>Spearman P</th>
<th>D-parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total GBM-LAT fluence</td>
<td>0.87</td>
<td>5.66E-6</td>
<td>0.75</td>
<td>5.61E-4</td>
<td>-1.4</td>
</tr>
<tr>
<td>Non-thermal GBM-LAT</td>
<td>0.88</td>
<td>3.21E-6</td>
<td>0.81</td>
<td>9.23E-5</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Rupal Basak
Photosphere in GRB prompt emission
Conclusions and Future Works

**Conclusions:**

1. The peak of the prompt emission spectrum of GRB has a photospheric origin. However, in most general case it has another weaker peak due to the structure of the jet itself (Rao, Basak, Bhattacharya et al. 2013 arxiv: 1308.2506; Basak & Rao et al. 2013 ApJ 768, 187)

2. The 2BBPL model is always statistically better than other models. The PL component might be a combination of Fermi acceleration within the jet and synchrotron radiation in the IS regions


**Future work:**

1. Production of PL component along with very high GeV emission has to be investigated with greater detail

2. A full simulation of the prompt emission with varying jet profile as well as optically thin synchrotron emission to be performed
XRT Observation of the Second BB

At later times, looks like two BBs and hence, the last three points can split.