Photospheric emission models of GRBs and their detectability by GLAST

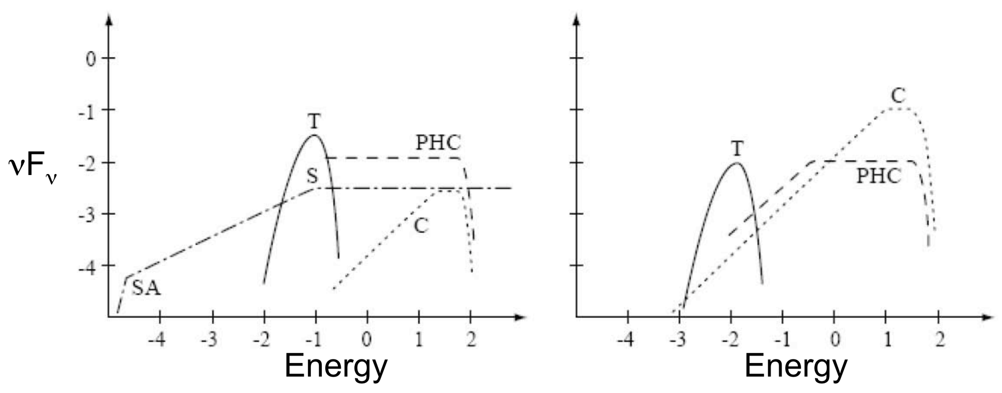
Milan Battelino (Stockholm University), Felix Ryde (Royal Institute of Technology, Stockholm), Nicola Omodei (INFN, Pisa) and David L. Band (CRESST/UMBC/GSFC) on behalf of the LAT GRB Science Working Group and of the GBM Team

Abstract

Thermal radiation in the prompt emission from gamma-ray bursts has been suggested by several authors. Indeed, observational data from BATSE on-board CGRO can be interpreted as containing a photospheric component in the sub-MeV range, that varies in strength within and between bursts, explaining the hardness of the sub-peak spectra. GLAST will, by including the energies in the MeV-GeV domain, give us the possibility to determine whether a thermal, photospheric component is the determining feature of the spectrum in the sub-MeV range. A study on this subject is presented in this poster.

Photospheric emission models and GLAST

The prompt emission in GRBs probably emanates from various emission sites in a collimated, relativistic outflow. A strong flash is expected in the MeV range when the thermal radiation flux, that is advected outwards, is released as the outflow becomes optically-thin. The defining opacity can stem from e^+e^- pairs or from the electrons associated with the baryon load of the outflow. The distance from the central engine to such a photosphere will depend on the (time-varying) leptonic density and the amount of energy injected into the outflow. The spectrum of this photosphere is expected to be blackbody.



Models predicting a thermal photospheric component has been suggested, or discussed, by several authors e.g. *Mészáros and Rees* (2000), *Daigne and Mochkovitch* (2002), *Drenkhahn and Spruit* (2002), *Ryde* (2004 and 2005), *Rees and Mészáros* (2005) and *Ryde et al* (2006). *Mészáros and Rees* (2000) show that the contribution of thermal radiation originating from the expanding fireball when it, at the photospheric radius, becomes optically-thin to Thomson scattering could explain the hard spectral slopes seen in a large fraction of the γ-ray bursts detected with BATSE. They show that by varying the dimensionless entropy, which is directly proportional to the maximum Lorentz-factor of the outflow, and the variability or dissipation time-scale, the strength of the non-thermal and the thermal spectra vary, e.g., as shown in the figure above. The figure is adapted from *Mészáros et al.* (2000) and shows a photospheric component, represented by a blackbody, and a non-thermal component in νF_ν-spectra.

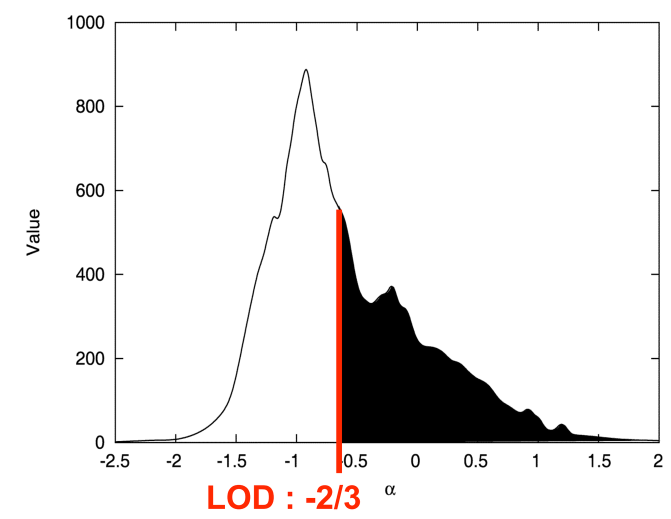
The strength of the thermal peak can be boosted by it being Comptonized through dissipative effects below the photosphere (magnetic reconnections or shocks). Much of the available energy will be in the kinetic energy of the associated baryons. This kinetic energy can naturally be dissipated into random energy, again through shocks or magnetic reconnections within the outflow. These will give rise to the broad, non-thermal radiation spectra, such as synchrotron emission. This picture leads to the expectation that the photospheric emission dominates in the GBM energy range, while the non-thermal emission from the dissipation sites in the optically-thin part of the outflow will dominate in the LAT energy range.

BATSE and hard spectral slopes

The **Band Model**, a softly broken power-law characterized by a sub-peak spectral index α, an energy peak E_p and a high energy spectral index β, models successfully the majority of γ-ray bursts that were detected with the Large Area Detector (**LAD**) of the Burst And Transient Source Experiment (**BATSE**) instrument onboard the Compton Gamma-Ray Observatory (**CGRO**).

This empirical model, with no claim to describe the physical processes behind the prompt emission, has properties that in many bursts could be described as the result of non-thermal radiation processes, such as *synchrotron* or *inverse Compton scattering*.

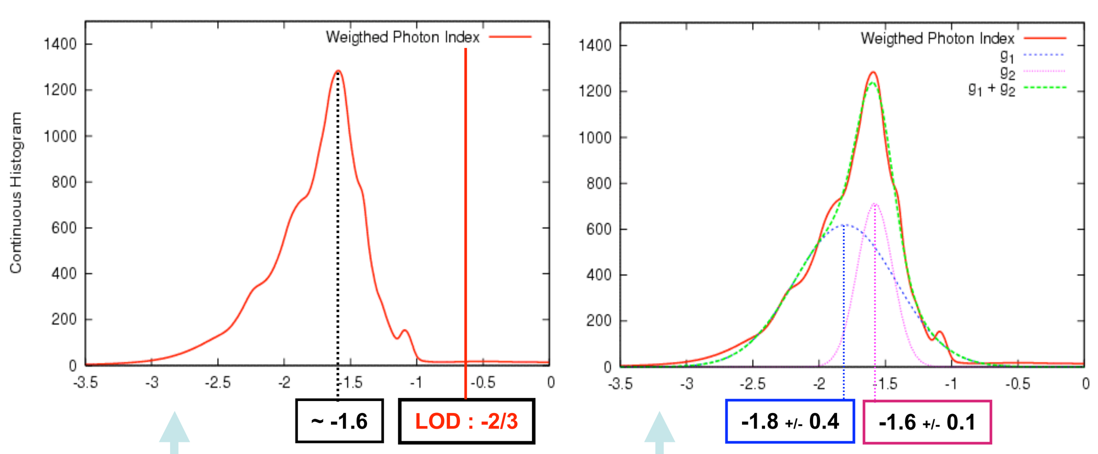
Several authors including *Crider et al.* (1997) and *Tavani, Band & Ghirlanda* (2000) show that some spectra, even though well-described by the Band model, can not be the result of plain *optically-thin synchrotron* (**OTS**) radiation processes, due to their hard sub-peak spectral slopes, with a Band model spectral index α larger than -2/3, the so called **OTS** *line-of-death* (**LOD**).



Our analysis of 847 time-resolved spectra from 57 bright BATSE bursts shows that a significant fraction of the spectra has a spectral index α that lies beyond this *line-of-death* for the *optically-thin synchrotron* (**OTS**) spectra. The prompt emission for these bright bursts hence demands another explanation than pure **OTS** processes.

Simulations of a photospheric component as detected by the instruments onboard GLAST

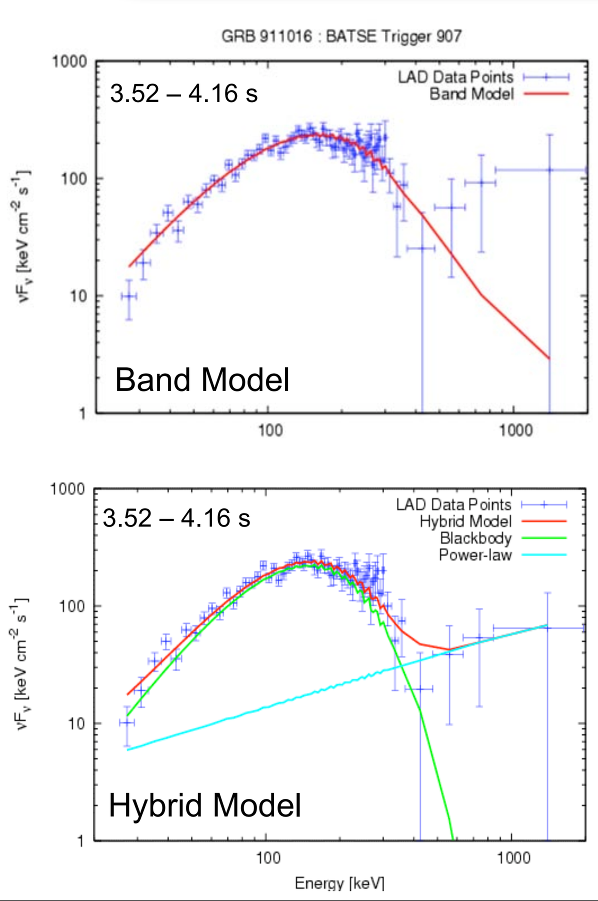
847 spectra from 57 bright BATSE bursts



OBSERVATIONAL DATA

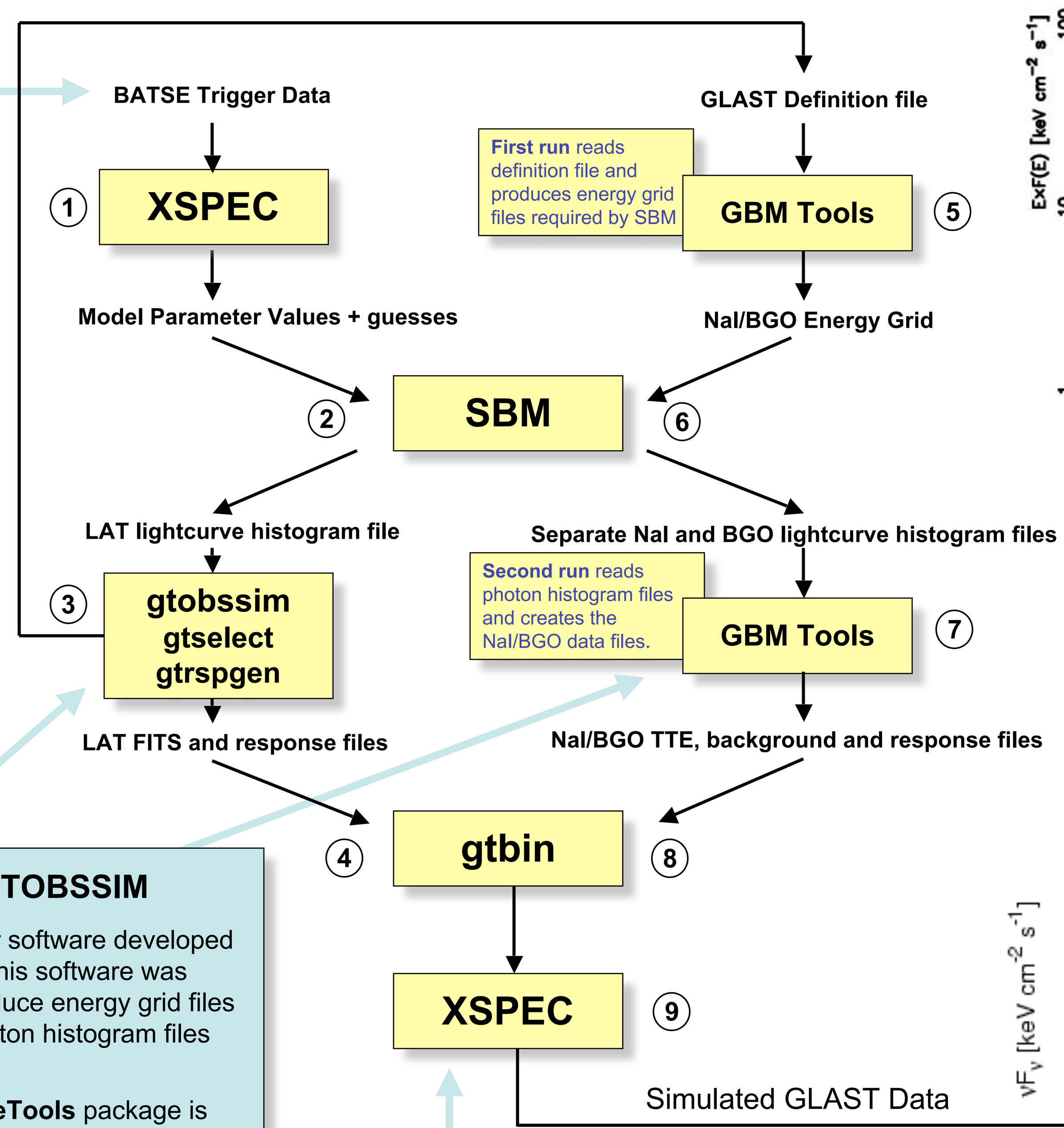
We imposed a **Hybrid Model**, consisting of a **blackbody** and a **single power-law component**, on the set of 57 bright bursts detected with the Large Area Detector (**LAD**) of the Burst And Transient Source Experiment (**BATSE**) instrument onboard **CGRO**. The resulting continuous histogram from the parameter estimates of the power-law spectral index is well-fitted with two Gaussians centered around the spectral indices *-1.6+/-0.1* and *-1.8+/-0.4*. Both values are consistent with *optically-thin synchrotron* (**OTS**) spectrum resulting from a distribution of *1st order Fermi shock-accelerated electrons*. The **OTS** *line-of-death* (**LOD**), characterized by spectral index *-2/3*, is hence avoided as can be seen in the figures above.

Input parameters for this model were deduced from Hybrid Model **XSPEC** fits on three actual observed single-pulsed bursts **GRB 911016**, **GRB 941026** and **GRB 960530** in the **keV-MeV** range. The figure below shows two XSPEC model fit spectra for the Band model and the Hybrid model respectively.



SOFTWARE AND MODEL IN SIMULATIONS

The simulations were performed using **Simple Burst Modeler** (**SBM**), ***GBM Tools*** and ***gtobssim***. **SBM** is a framework used to implement radiative models, in this case a **Hybrid Model** consisting of a **broken power-law** with a **high-energy cut-off** and a **thermal emission component** represented by a **blackbody function**. The thermal component is in the model described by a peak temperature and flux that evolves over time. The photon histogram files produced by **SBM** are input to ***GBM Tools*** and ***gtobssim*** to produce the event data. The simulation procedure is summarized in the figure below.



GBM TOOLS AND GTOBSSIM

GBM Tools is a GBM fast simulator software developed by the **GBM collaboration team**. This software was updated with the capabilities to produce energy grid files required by **SBM** and to read in photon histogram files produced by **SBM**.

gtobssim from the **GLAST ScienceTools** package is used to perform fast simulation of LAT spectra for a wide range of celestial sources. **gtobssim** was also modified to read in photon histogram files produced by **SBM**.

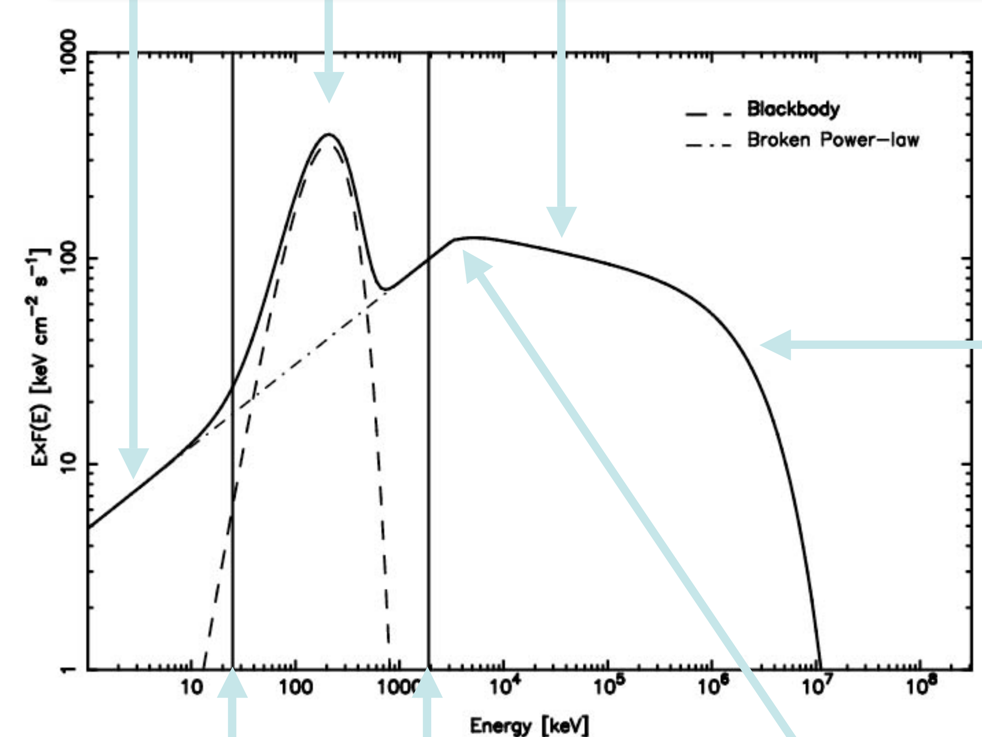
The response functions for **Data Challenge 2** (**DC2**) were used in the simulations and the three bursts were positioned at θ=27.1° and ϕ=95.3°.

XSPEC MODEL FIT

The same **Hybrid Model** that was used for the SBM simulations - consisting of a thermal photospheric component, represented by a blackbody, and a broken power-law with an exponential high-energy cut-off - was fitted to the resulting simulated GBM and LAT data.

MODEL COMPONENTS

Synchrotron spectra resulting from **slow cooling electrons** are expected to have two characteristic power-law indices: α = *-2/3* and β = *-1.6* while **fast cooling electrons** exhibit α = *-1.5* and β = *-2.1* which has been seen in, e.g., **GRB 941026**. The photospheric component is in the **Hybrid Model** represented by a **blackbody** and the non-thermal by a **broken power-law** with a **high-energy cut-off**.

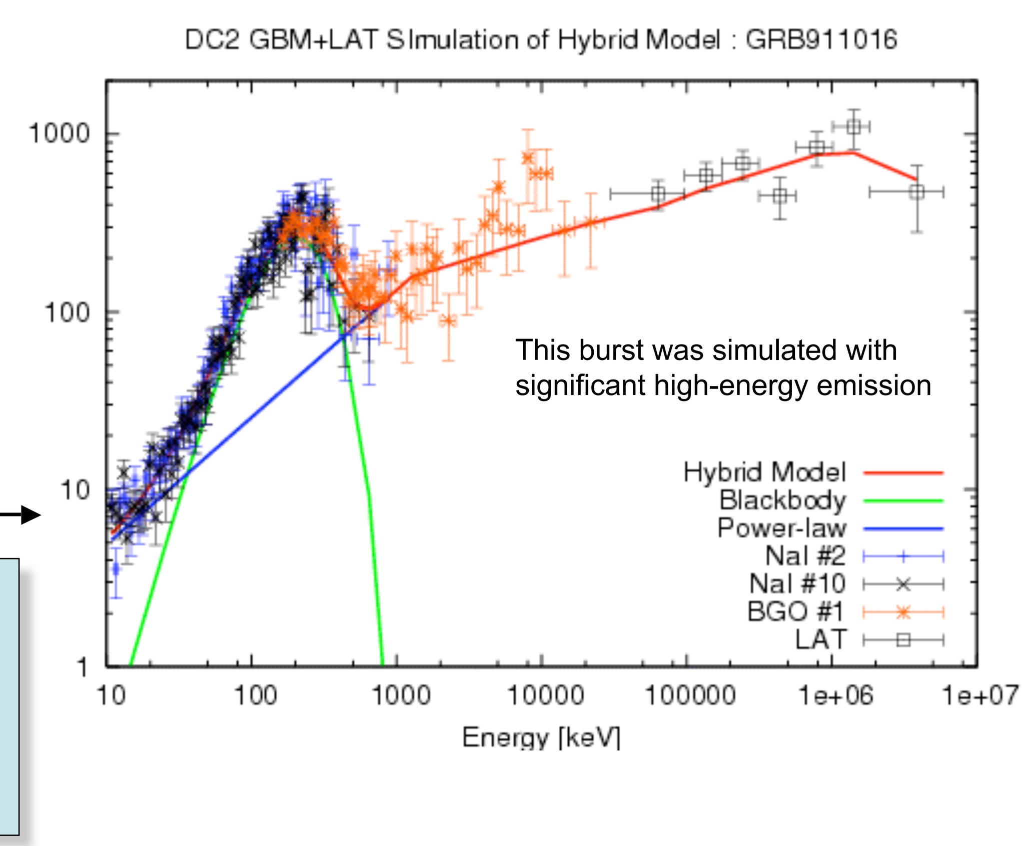


HIGH-ENERGY CUT-OFF

At very high energies attenuation is expected, either from – as in this simulation - the competition between the acceleration of the electrons and radiative cooling leading to an exponential, high-energy cut-off or due to the **extra-galactic background light** (**EBL**). The e-folding energy for the synchrotron cooling cut-off is predicted to lie close to ~3 GeV (de Jager et al, 1996, *ApJ* **457**, 253).

The BATSE energy window

The position of the break within the BATSE window and its evolution may explain the values of the power-law index in the Hybrid Model fits (a blackbody and a single power-law component) to the BATSE data.



RESULTS

The simulated bursts show consistency with a model described by a **broken power-law** with a **high-energy cut-off** and a thermal **blackbody component** in the GBM energy range. **χ2 statistic** was used for model testing and for parameter estimates on both ungrouped and grouped (>9 photons per bin) data. The table below shows results from the model tests on grouped data.

Burst	χ^2	*P-value*
GRB911016	**0.98**	**0.55**
GRB941026	**0.82**	**0.98**
GRB960530	**1.03**	**0.36**