Joint spectral analysis of GRBs, a time-resolved systematic approach

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on behalf of the Fermi-LAT and Fermi-GBM collaboration

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Summary. — The *Fermi* mission is a space-based observatory designed to study the gamma-ray sky. It comprises two main instruments: the *Large Area Telescope* (LAT) and the *Gamma-ray Burst Monitor* (GBM), together covering a broad energy range from approximately 10 keV to over 300 GeV. One of the mission's key scientific goals is the detection and study of *Gamma-Ray Bursts* (GRBs), whose prompt emission mechanisms and emission sites remain not fully understood. In this work, we focus on bright GRBs observed jointly by *Fermi*-GBM and *Fermi*-LAT. Two fully operational pipelines, developed using the *Multi-Mission Maximum Likelihood* (3ML) framework, have been implemented to perform systematic joint spectral analyses—both time-integrated and time-resolved. These tools have been tested on a sample of approximately 50 GRBs; from these analyses, we obtained preliminary distributions of spectral parameters, such as photon indices, peak energy, and possible additional components. This work sets the stage for a broader systematic study leveraging *Fermi*'s broadband capabilities.

1. – Introduction

The *Fermi* Gamma-Ray Space Telescope is an international space mission dedicated to the study of the gamma-ray sky. It was launched over 17 years ago on June 11, 2008, on a Delta II rocket, placed in an almost circular orbit at an altitude of 565 km and an inclination of 25.6°.

The spacecraft hosts two scientific instruments: the Large Area Telescope (LAT) [1] and the Gamma-ray Burst Monitor (GBM)[2]. The *Fermi* observatory is a collaborative international effort, with support from NASA in the USA, and contributions from France, Germany, Japan, Italy, and Sweden. The *Fermi*-LAT and *Fermi*-GBM Collaborations count over 400 members from over 90 universities and laboratories.

The study and characterisation of Gamma-Ray Bursts (GRBs) is among the main scientific targets of *Fermi*. The combination of LAT and GBM enables observations of GRB emission over a broad energy range, from 10 keV up to hundreds of GeV, spanning more than seven decades in energy. Observing GRBs in the gamma-ray domain provides crucial information for understanding the underlying physics and emission mechanisms behind these extremely energetic phenomena.

2. – The *Fermi* mission

2˙1. *The Large Area Telescope*. – The LAT is a pair-conversion telescope sensitive to gamma rays in the energy range from approximately 20 MeV to more than 300 GeV. It consists of a tracker (TKR), made up of a 4 x 4 array of identical towers. Each tower contains 18 x-y pairs of single-sided silicon strip detectors with strip pitch of 228 μm, totaling 880.000 data channels. These detectors are responsible for converting incoming gamma rays and determining their arrival direction.

The energy of the incoming photons is measured by the calorimeter (CAL), which consists of 1.536 cesium iodide logs (CsI) corresponding to a total radiation length of 8.6 X_0. The calorimeter is arranged in the same 4 x 4 tower configuration as the tracker.

The described assembly is surrounded by a segmented Anti-Coincidence Detector (ACD) system, which consists of 89 individual plastic scintillator tiles with scintillating fibers covering seams. The ACD plays a critical role in rejecting the abundant charged-particle background in space.

With a field of view (FoV) of approximately 2.4 sr at 1 GeV that ensures a $\sim$ 20% coverage of the entire sky at any given time, a large effective area ($\sim$ 6500 cm^2 on-axis above 1 GeV), excellent background rejection capabilities, good angular resolution ($\sim$ 0.8° at 1 GeV), and high time accuracy (<10 μs relative to spacecraft time), the LAT is well suited for the detection and time-resolved characterization of GRBs.

2˙2. *The Gamma-ray Burst Monitor*. – The GBM is the secondary instrument on board of *Fermi.* It consists of 12 thallium-doped sodium iodide (NaI) scintillator detectors and 2 bismuth germanate (BGO) high-energy calorimeters. The NaI detectors are sensitive in the 8 keV-1 MeV range, while the BGOs cover the 150 keV-40 MeV range, bridging the energy gap below $\sim$ 1 MeV where most of the GRB emission typically occurs.

The 12 NaI detectors are placed in groups of three at the four corners of the spacecraft, providing a broad angular coverage. The two BGO calorimeters are positioned symmetrically on opposite sides of the spacecraft. This detector configuration provides a FoV of approximately 9.5 sr, essentially any part of the sky not occulted by the Earth.

GRB localization is achieved by comparing the relative signal amplitudes detected in the NaI detectors, which have different orientations with respect to the source. This method allows the GBM to determine the direction of transient events to within a few degrees [3].

3. – Gamma-ray Bursts (GRBs)

Gamma-Ray Bursts (GRBs) are among the most powerful and luminous phenomena in the observable Universe [4]. Their durations span from a few milliseconds up to several hours or, in some cases, up to days. Based on this duration, GRBs are classified into two main categories: Short GRBs, with durations below 2 seconds, and Long GRBs, lasting longer than 2 seconds. This empirical classification has been widely used in the literature, although recent observations suggest that the boundary between the two populations may not always be clear.

3˙1. *Prompt emission.* – GRBs exhibit two main emission phases. An initial phase known as the *prompt* emission, a highly variable and intense phase occurring mainly in the energy range from 10 keV to tens of MeV. It typically lasts from fractions of seconds up to a few minutes. The duration of this phase is usually quantified by the T_{90}, which is defined as the time interval during which the integrated photon counts increase, in the 50-300 keV energy range for GBM, from 5% to 95%.

The prompt emission is followed by the *afterglow*, a long-lasting multi-wavelength component that can last up to several days after the initial burst.

The prompt phase is characterized by a non-thermal, continuum spectrum. Its spectral shape typically follows a broken power law, with a peak in the νF_ν representation denoted as E_{peak}. The spectral indices below and above E_{peak} are referred to as α and β. This shape of the spectra is usually well fitted by a phenomenological function known as the Band function [5].

A major challenge in understanding prompt emission of GRBs lies in its high variability and the diversity in behavior from burst to burst. This makes it difficult to establish a universal model. Therefore, population studies based on statistically large GRB samples are crucial to identify common properties and constrain the typical spectral parameters.

3˙2. *State of the art.* – Several previous population studies using *Fermi* data can be found in the literature. However, most are limited in scope: they either rely on time-integrated analyses of GBM-only events [6, 7, 8, 9, 10], or focus on LAT-only data [11]. Only one joint GBM-LAT time-integrated catalog covering the first four years of the mission has been published, and it includes just a handful of cases [12]. On the time-resolved side, only one GBM catalog of same period exists [13].

As of now, a systematic, joint, time-integrated and time-resolved spectral analysis covering the full period of *Fermi*'s operation is still lacking. This is the gap that this project aims to address.

4. – Towards a joint systematic analysis

4˙1. *Sample selection and data preparation.* – The sample selection was carried out using the first 16 years of *Fermi* data, spanning from August 2008 to September 2024. Within this period, a total of 257 GRBs were detected by the LAT, although not all of them were simultaneously observed by GBM. To ensure the feasibility of a joint spectral analysis, a further selection criterion was applied: the arrival time of the first LAT-detected significant photon (more than 90% probability of belonging to the event) must fall within the T_{90} interval as defined by the GBM team. This criterion yielded a refined sample of 167 GRBs suitable for both time-integrated and time-resolved joint analysis.

For each event in the refined sample, standard channel selections were applied to the GBM detectors. For the NaI scintillators, energy channels below 10 keV and overflow channels above 900 keV were excluded. For the BGO detectors, only channels in the range of 250 keV to 40 MeV were retained.

The energy range of the LAT is divided into two sub-energy ranges, the LAT standard energy range starting from 100 MeV up to 1 TeV and the LAT Low-Energy (LLE) range spanning from 30 MeV to 100 MeV energy range [14].

4˙2. *Analysis tools*. – Both the time-integrated and time-resolved pipelines were developed using the Multi-Mission Maximum Likelihood (3ML) Python-based framework [15]. 3ML provides a high-level, unified interface for performing maximum likelihood and Bayesian analyses across data from multiple instruments and/or missions.

For the GBM data, 3ML is capable of directly interfacing with NASA's HEASARC archive to automatically download the relevant files required for spectral analysis. For LAT data, the pipeline relies on the `gtburst` software, which integrates with 3ML (version 2.4.2) to download and prepare LAT data. The necessary response and event files are generated using the `Fermitools` software (version 2.2.0), which is also fully compatible with 3ML.

4˙3. *Workflow of the systematic analysis*. – After the data are downloaded, the time intervals for spectral analysis are defined. Depending on the duration of the event, the time window varies accordingly: for long GRBs ($T_{90} > 2$ s), we select a time window of $T_{90} \pm 20\%$; for short GRBs ($T_{90} < 2$ s), a window of $T_{90} \pm 1$ s is adopted. This choice is made to ensure that the analysis captures the main low-energy emission, along with potential late-time photons or possible precursor emission.

Once the time interval is defined, the event is divided into smaller time bins using the Bayesian block algorithm [16], with the brightest NaI detector as the reference light curve. Time bins with a signal-to-noise ratio (SNR) below 5 are classified as background-dominated and are excluded from the analysis, and no spectral fitting is performed on those. An example of the re-binned light curves of GRB 090510A can be seen in Figure 1, where the light curve of the brightest NaI detector is shown (top panel), together with the re-binning obtained using the Bayesian blocks algorithm. The light curves from the BGO (middle panel) and the LLE data with overlaid LAT photons (bottom panel) are also shown.

The spectra of each individual time bin are fitted using several model configurations. The four main empirical models employed are: the Band function, a smoothly broken power law (SBPL) [17], a cutoff power law also known as the Comptonized model, and a simple power law, following the approach of previous time-resolved analyses [13]. In addition, the Internal Shock Synchrotron Model (ISSM) [18] is being tested. Unlike the aforementioned empirical models, ISSM provides a physically motivated framework based on synchrotron radiation from electrons accelerated in internal shocks, offering the possibility to constrain physical parameters directly from the fit. For the Band, SBPL, and ISSM models, the addition of an extra component such as a blackbody is also evaluated.

This multi-model approach is essential given the diversity of GRB spectral shapes. For each time bin, the best-fitting models are selected based on the Bayesian Information Criterion (BIC) [19]. The model with the lowest BIC is initially considered the best. Then, the ΔBIC values for the other models are computed relative to this minimum. If any alternative model has a ΔBIC lower than 6, it is considered statistically indistinguishable from the best model, and thus multiple models may be deemed equally consistent with the data; in such cases, preference is usually given to the simpler model.

A refinement of this model selection procedure is currently under consideration. Consequently, the results obtained so far should be regarded as preliminary.

4˙4. *An insight on very preliminary results*. – The analysis has so far been performed on a sub-sample of 30 GRBs, selected among the brightest events observed by GBM. The time binning procedure applied to this set produced a total of 546 bins, each of which

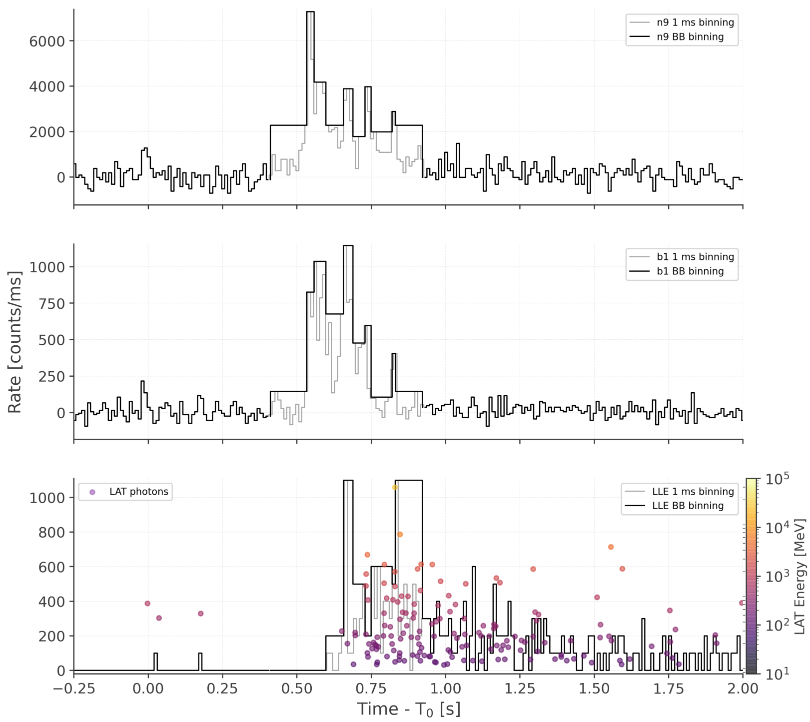

Fig. 1. – Light curves as observed by the *Fermi*-GBM and *Fermi*-LAT for GRB 090510A. The top panel shows in gray the light curve of the brightest NaI detector (n9 in this case), with the Bayesian block re-binning overlaid in black. The same format is applied to the BGO b0 detector in the middle panel. In the bottom panel, the LLE light curve is shown in gray, with the Bayesian block segmentation in black. LAT photons are overplotted as colored dotted poionts, where the color encodes the energy of each photon.

was subjected to spectral analysis. As expected from previous literature reports, the Comptonized function generally results in the largest number of successful fits, followed closely by the Band function and the SBPL.

Distributions of the main spectral parameters, α, β, and E_{peak}, were obtained. Although the analysis is still in progress and requires further refinement, these first results appear consistent with the characteristic values reported in earlier works. This provides a promising validation of the pipeline and model selection approach, and sets the groundwork for the upcoming systematic analysis of the full GRB sample.

5. – Conclusions

A systematic time-resolved analysis of GRBs jointly detected by *Fermi*-LAT and *Fermi*-GBM is essential to improve our understanding of these extreme transients and the physical mechanisms driving their prompt emission. To this end, a dedicated analysis pipeline has been developed using the 3ML framework, capable of performing time-resolved spectral fits across the broad energy range covered by the *Fermi* mission.

Although some refinements are still required, preliminary tests performed on a subsample of 30 of the brightest GRBs show results consistent with previous studies, validating the approach and establishing a solid starting point for the full-sample analysis.

Future developments will include the identification and characterization of additional spectral components beyond standard empirical models, the comparison between GBM-only and joint GBM–LAT results, and the study of the spectral evolution of GRBs, among others.

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