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Fermi-GBM Analysis of GRB 221009A

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At 13:16:59.99 UT on October 9th, 2022, the Fermi Gamma-ray Burst Monitor (GBM) triggered on gamma-ray burst (GRB) 221009A. This GRB has the highest fluence value GBM has ever detected. The light curve consists of two distinct emission episodes, a single isolated peak with a thermal spectra followed by a longer, extremely bright, multi-pulsed event with a non-thermal spectra. The two main peaks of the second event, from t_0+218 to t_0+276 seconds and t_0+508 to t_0+513 s, had such high photon rates they caused pulse-pile up effects in the GBM detectors. Afterglow emission is detectable in the GBM energy range out to t_0+1467 seconds when the field of view was occulted by Earth. Here we present the key parts of our spectrotemporal analysis for the triggering pulse, prompt emission, and afterglow and the pulse pile-up corrected energetics for the this historically bright event.

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1. Introduction

On 2022 October 9 at 13:16:59.99 UTC (t_0), the *Fermi*-GBM flight software triggered on GRB 221009A. A burst that would later be known as "The BOAT" (brightest of all time). The *Fermi*-GBM is a wide-field (>8 sr) survey instrument made up of twelve sodium iodide (NaI) detectors oriented around the spacecraft and two bismuth germanate (BGO) detectors on opposite sides of the spacecraft. These detectors cover energy ranges from 8 keV to 1000 keV and 200 keV to 40 MeV, respectively [1]. The other scientific instrument on-board *Fermi* is the *Fermi*-LAT, a pair-conversion telescope covering an energy range from 20 MeV to more than 300 GeV [2].

Due to the excessively high photon rate produced by GRB 221009A, both *Fermi*-GBM and *Fermi*-LAT experienced bad time intervals (BTIs) with data issues[1] [6–8]. The details of these data issues, including the valid detectors and time intervals for each *Fermi*-GBM and *Fermi*-LAT data type, can be found in [4] and [5]. For this analysis we use the *Fermi*-GBM Continuous Spectroscopy (CSPEC) and Time-Tagged Event (TTE) data types and the *Fermi*-LAT Low Energy (LLE) data type during the intervals when each data type is valid. CSPEC and TTE data both have 128 channels of spectral resolution, but the CSPEC data are binned to a temporal resolution of 1.024 s in the interval following the trigger. LLE data are time-tagged photons like TTE, but span an energy range from 30 MeV to 10 GeV [3]. Both *Fermi*-GBM and *Fermi*-LAT data types are available for download via the public archive at the Fermi Science Support Center (FSSC) website[2,3].

For the majority of the burst duration the TTE data are unrecoverable due to the summed count rate between the detectors exceeding a data rate of 375 kHz [1]. For this reason TTE data is only used when analyzing the triggering pulse. For CSPEC data, a binned data type, there was no data loss. However, the input count rates seen by individual detectors exceeded ~50k counts per second which caused complex deadtime and pulse pile-up (PPU) effects in the *Fermi*-GBM BTIs. PPU occurs when electronic pulses overlap in the data causing distortions in both intensity and the observed spectra [9, 10]. Although this cannot be corrected automatically via any standard method, details for correcting these data issues are presented in [4]. Here we will ony present the results of the correction technique.

2. Triggering Pulse

Using the well-documented *Fermi*-GBM Targeted Search [11, 12] we searched for GRB 221009A source emission prior to the *Fermi*-GBM trigger time and found no such emission. This points to the triggering pulse (Figure 1, region I of [4]) being the true first emission from GRB 221009A. Upon analyzing this section of the lightcurve we found that the high-energy LLE photons arrived ∼ 1.5 s prior to the *Fermi*-GBM photons possibly pointing to a distinct physical origin. This pulse, from t_0-1.3 s to t_0+42.9 s, was best fit by either a multicolor blackbody (mBB) [13] model or a power-law with an exponential cutoff (COMP), the parameters of which can be found in Table 1. Although discussed in more detail in [4], the key thing to note is that both functions point to a thermal spectral origin.

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[1] `https://fermi.gsfc.nasa.gov/ssc/data/analysis/grb221009a.html`

[2] `https://fermi.gsfc.nasa.gov/ssc/data/`

[3] `https://heasarc.gsfc.nasa.gov/FTP/fermi/`

3. Prompt Emission

All regions and sub-regions shown in Figure 1 of [4] were best fit by a Band function [14], the parameters of which can be found in [4]. Because of this, the two *Fermi*-GBM BTI regions were corrected with the underlying function assumed to be a Band function. As was worth noting with the triggering pulse, the Band function is a non-thermal function, pointing to a transition from thermal to non-thermal from triggering pulse to the bulk of the prompt emission. Only one region, region IVc, just after the first *Fermi*-GBM section with data issues, is best fit by a Band function with an additional power-law (PL) component which extends out to higher energies. The parameters of this fit can be found in Table 1. The additional PL component has a photon index of ∼-1.9, which is consistent with the canonical PL value of Γ= -2 expected with the emergence of the early afterglow [15]. The prompt emission being superimposed with the afterglow emission is similar to observations of GRB 190114C [16].

4. Afterglow

In this work we choose to highlight only the most important results from our afterglow analysis and defer the reader to [4] for the full description. As was mentioned in the previous section, there is evidence of the afterglow flux overlapping with the prompt emission. Although observing GRB afterglow in the *Fermi*-GBM energy band is rare, it has also been observed in other extremely bright GRBs [17] [18]. The long, smooth decay period after t_0+575 s is consistent with observations of typical afterglow emission and the dip at t_0+1460 s is due to the GRB source location being is occulted by the Earth for *Fermi*.

We temporally bin the GRB lightcurve from the end of the second *Fermi*-GBM BTI ($\hat{0}$+510 s) to the time of Earth occultation, fit the spectrum with a Band function, and extrapolate down to 10 keV in order to compare with *Swift*-XRT [19]. In order to constrain the peak of the afterglow amongst the prompt emission, we first fit the two pulses of the 10 keV lightcurve with Norris pulse models [20] and the long, smooth emission with a broken power-law (BPL). Knowing that the afterglow lightcurve will rise as a power law with an index of 3 (ISM) or 1/2 (wind), we are able to see isolate when the BPL peaks for each medium. This is at $t^{\mathrm{ag,ISM}}_{peak} \gtrsim t_{\mathrm{ref}} + (140 \pm 2)$ s and $t^{\mathrm{ag,wind}}_{peak} \gtrsim t_{\mathrm{ref}} + (120 \pm 6)$ s with a temporal decay slope of $\alpha^{\mathrm{ag}}_{decay} = -0.82 \pm 0.03$ ($t_{ref} = 510$ s). We tentatively identify t^{ag}_{peak} as the time when the prompt emission shuts off and the emission is solely from the afterglow emission.

Assuming the true afterglow peaks amongst the prompt emission, we fix the temporal decay index of our BPL function to our measured $\alpha^{\mathrm{ag}}_{decay}$ value, set our reference time to the start of the bulk of the prompt emission ($t_{\mathrm{ref}} = t_0 + 175$ s), and fixed our temporal rise index ($\alpha^{\mathrm{ag}}_{rise}$) to be either 3 or 1/2 for the ISM or wind-type external media respectively. By requiring that the afterglow flux not exceed the prompt emission flux, we place a limit of $t^{\mathrm{ag,start,ISM}}_{peak} \gtrsim t_{\mathrm{ref}} + 105$ s. Unfortunately we could not obtain a similar value for the wind-type external medium because the resulting fit was unconstrained.

5. Energetics

After correcting the *Fermi*-GBM BTIs for PPU effects, we were able to derive values for the total energetics if GRB 221009A. The total isotropic equivalent energy ($E_{\gamma,\rm iso}$) in the 1-10,000 keV range derived from the fluences in the individual time intervals from t_0-2.7 s to t_0+1449.5 s, and after performing k-corrections is $E_{\gamma,\rm iso} = (1.01 \pm 0.007) \times 10^{55}\ erg$. The fluence for GRB 221009A is $(9.47 \pm 0.07) \times 10^{-2}$ erg cm^{-2}. The beaming corrected energy is $E_\gamma = 6.1 \times 10^{51} \left(\theta_j/2\right)^2\ erg$, assuming an opening angle of 2 degrees [21]. The 1 s isotropic-equivalent peak luminosity obtained by integrating the spectrum from t_0+230.8 s to t_0+231.8 s interval and performing k-corrections is $L_{\gamma,\rm iso} = (9.91 \pm 0.06) \times 10^{53}$ erg s^{-1}. The energy flux here is $F = (8.48 \pm 0.06) \times 10^{-2}$ erg s^{-1} cm^{-2}. These PPU-corrected energetics values are consistent with those independently produced by [22], [23], and [24]. For a more detailed analysis including Lorentz factor calculations, central engine properties, and shock breakout interpretations, please see [4]. This is the main paper this talk was based off of.

Model (region)	**Time Range**	**Model Components**				**C$_{stat}$/DoF**
COMP	-1.343	α	E$_{peak}$			497/340
(I)	42.881	-1.73 ± 0.02	10440 ± 1900			
mBB	-1.343	K	kT$_{min}$	m	kT$_{max}$	487/379
(I)	42.881	$14.5^{+0.5}_{-0.6}$	$1.62^{+0.20}_{-0.34}$	$-0.854^{+0.009}_{-0.011}$	5000^{+600}_{-400}	
Band+PL	277.894	α	E$_{peak}$	β	Index	5707/336
(IVc)	323.975	-1.583 ± 0.001	1387 ± 9	-3.77 ± 0.01	-1.916 ± 0.009	

Table 1: The best fitting spectral functions for selected portions of the GRB 221009A lightcurve. A full version of this table including spectral fits over all intervals and explanations of each variable's units can be found in [4].

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