OBSERVATIONS OF GRB HIGH-ENERGY PROPERTIES WITH *Fermi*

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The Large Area Telescope (LAT) on the *Fermi* Gamma-ray Space Telescope observatory is a pair conversion telescope sensitive to gamma rays over more than four energy decades, between 20 MeV and more than 300 GeV. Acting in synergy with the Gamma-ray Burst Monitor (GBM) - the other instrument onboard the mission - the LAT features unprecedented sensitivity for Gamma-Ray Bursts (GRB) in terms of spectral coverage and instrumental dead time. During the first six months of mission *Fermi* detected more than one hundred GRB. Four of them had a significant high-energy emission and could be studied with the Large Area Telescope. After reviewing *Fermi* performance for GRB studies, we present here these four GRB and their temporal and spectral characteristics.

1 Introduction

Before *Fermi*, two experiments have performed GRB observation above 20 MeV : the Energetic Gamma-Ray Experiment Telescope (EGRET) onboard the Compton Gamma-Ray Observatory (CGRO) from 1991 to 2000 and the Italian experiment Astro-rivelatore Gamma a Immagini LEggero (AGILE) operating since 2007.

Three types of emission have been observed :

- a prompt high-energy emission coincident with the keV-MeV emission ;
- a temporally extended high-energy emission in the case of GRB 940217, with a 18 GeV photon recorded ∼75 minutes after the prompt emission. The origin of this extended emission may require more than one emission mechanism [1] ;
- a high-energy extra spectral component has been observed for GRB 941017. Its temporal evolution is decorrelated from the low-energy emission, and the wide band spectrum is inconsistent with a pure synchrotron model [2].

Little is known so far about GRB emission above 100 MeV, and *Fermi* LAT observations should help to shed light on the underlying acceleration mechanisms. In section 2 we describe *Fermi* performance and operations for GRB studies. Section 3 presents the four *Fermi* LAT detections after six months of operations. Their temporal and spectral characteristics are detailed, in particular the very bright GRB 080916C.

2 GRB observations with *Fermi*

2.1 GRB detection and localization

The *Fermi* observatory consists of two instruments. The LAT is a pair conversion telescope which allows independent on-board and ground burst trigger and spectral analysis up to more

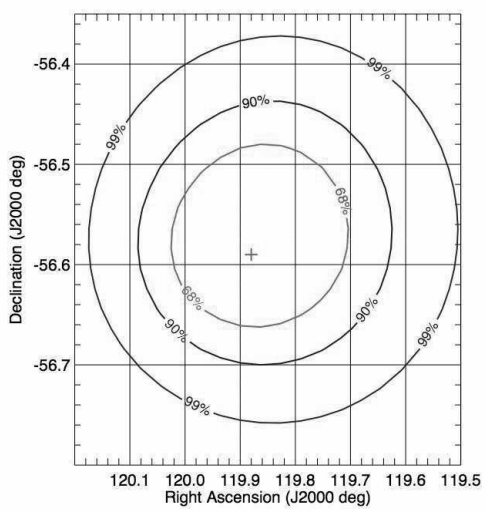

Figure 1: GRB 080916C LAT localization with 68%, 90% and 99% C.L. error contours.

than 300 GeV. The GBM is a set of 14 photomultipliers (12 NaI and two BGO) allowing burst trigger, localization over the entire unocculted sky and spectral analysis from 8 keV to 40 MeV.

The combined use of these two instruments allows a spectral coverage of seven energy decades that matches the typical spectrum of a GRB prompt emission. Besides, the GBM observations give the low-energy context without which the LAT data would be difficult to understand.

The wide field of view of both instruments (the LAT field of view is $\sim$2.4 sr) and their low deadtimes (2.6μs for the GBM, a minimum of 26.5μs for the LAT) confer them good detection capabilities for intense transient sources such as GRB. A study based on BATSE (Burst And Transient Sources Experiment, onboard CGRO) bursts characteristics yields a detection rate of $\sim$200 GRB per year for the GBM and $\sim$13 GRB per year for the LAT, which is consistent with the actual detections so far (the actual GBM detection rate is slightly higher, see section 3). LAT on-ground detection search is generally more sensitive than the onboard search, as it uses fully reconstructed events. As an example GRB 080916C could have triggered the onboard algorithm, whereas GRB 080825C was just above on-ground detectability threshold.

GRB localization is performed onboard and on-ground. For GBM triggers, NaI data are used and a location is derived onboard within 2 s to better than 15°. An automatic refinement to better than 5° is done on-ground within a few minutes. Finally, a human-in-the loop localization is performed.

A LAT location is derived for LAT triggers using the GBM onboard location as seed. LAT localization studies based on simulations have shown that the position accuracy depends on the burst's characteristics (fluence, hardness, duration) and its position in the LAT field of view. The detection of events above 1 GeV strongly improves the localization. For example, GRB 080825C with no photon above 1 GeV was localized with an error radius of $\sim$1°, whereas GRB 080916C localization yielded an error radius of $\sim$0.1° (see figure 1).

2.2 Alerts and notices

For every detection, a GCN notice is sent to the ground within 10 s through the TDRSS network. Several update messages are issued within a few minutes. These automated messages contain the

following information : localization, significance of the detection, and for GBM triggers also the most probable nature of the source (e.g. GRB, Soft Gamma Repeater, Anomalous X-ray Pulsar, Terrestrial Gamma-ray Flash, solar flare, accidental event) according to a Bayesian classification scheme. GBM notices are publicly available since October 17th, 2008, and LAT notices since February 28th, 2009. A ground notice containing an improved localization is also sent for GBM triggers, that involves a more sophisticated software algorithm than for the onboard notices.

Circulars are sent by GBM and LAT team members. In the case of a common GBM/LAT detection, a first GBM circular is sent rapidly , it contains a refined manual localization and a preliminary lightcurve based on the so-called trigger data, sent to the ground along with the alert messages. A second circular is sent after the full science data have been sent to the ground, processed, and the studies have been performed.

LAT processed data are available to the Burst Advocate in average eight hours after their acquisition. The Automated Science Processing that is a part of the LAT data processing pipeline searches for a prompt emission or an afterglow in LAT data, for every *Fermi* or *Swift* detection. Counts maps and lightcurves are produced, a localization and a first spectral analysis are performed. After a detailed manual study a circular is issued, containing a localization, along with spectral and temporal analyses, and possible results of the search for a high-energy afterglow.

2.3 LAT follow-up observations

In case of a bright GBM trigger or a LAT detection, an Autonomous Repoint Recommendation (ARR) can be sent to the spacecraft 2 to 600 s after the trigger time. The spacecraft will slew so as to keep the burst location as close as possible to the LAT Z-axis, as long as it remains above the Earth horizon by at least 20° (i.e. the nominal Earth avoidance angle). During occultations of the target by the Earth the spacecraft will slew at a constant angle from the Earth limb until the target rises on the other side. If no interrupt occurs, this maneuver lasts five hours, then the LAT resumes normal data taking in survey mode.

Since this maneuver impacts other observation activities, the threshold on the brightness of the burst has been set so that roughly one ARR per week can be accepted for a burst occuring within the LAT field of view. Bursts occuring outside the LAT field of view require a larger slew and the threshold is higher : roughly one such ARR per month should be accepted.

Spacecraft response to ARR was enabled on October 8th, 2008. Since then five ARR were accepted, the latter two for real bursts occuring in late March, 2009. These two ARR allowed a follow-up of GRB extended emission by the LAT.

3 GRB observations with the LAT

As shown in figure 2 about 120 GRB have been detected by the *Fermi* Gamma-ray Burst Monitor between July 14th 2008 and February 1st 2009, along with two SGR, two AXP, a few TGF and a solar flare. Four GRB have been detected by the *Fermi* Large Area Telescope as well :

- GRB 080825C [3] [4] was the first significant detection (6.15 σ in the LAT) of a GRB in the LAT with 10 events seen above 100 MeV;
- GRB 080916C [5] [6] was the brightest LAT detection with 10 events above 1 GeV and more than 140 events used for the spectral analysis above 100 MeV. A follow-up observation by the ground optical telescope GROND allowed its redshift measurement : $z = 4.35 \pm 0.15$ [12]. We will discuss the consequences of this measure;
- GRB 081024B [7] [8] was the first short burst with emission above 1 GeV. It was a LAT detection with a significance of 8.4 σ;
- GRB 081215A [9] [10] was not in the field of view of the LAT, but it was bright enough to produce a significant increase of the raw count rate in the tracker (more than 8 σ).

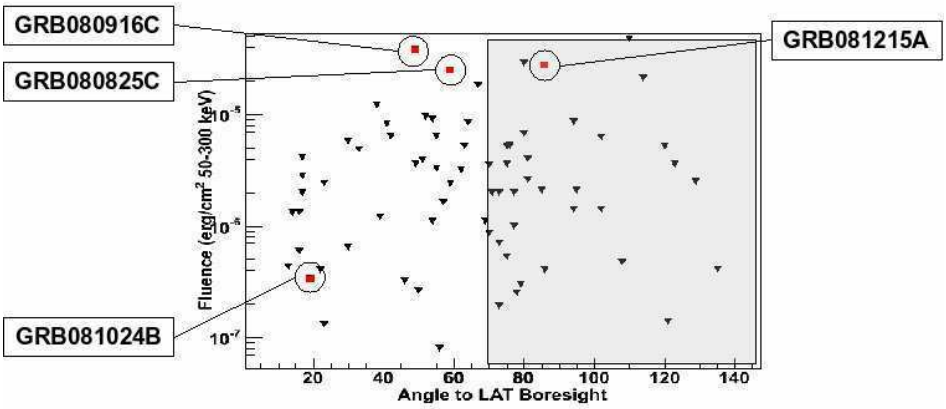

Figure 2: GRB detected by *Fermi*-GBM from July 14th, 2008, to February 1st, 2009. Fluence in range [50 – 300] keV is shown vs angle to LAT boresight. Four out of these ∼120 GRBs were detected in the LAT as well.

3.1 Temporal Characteristics

The multiwaveband lightcurve of GRB 080916C is shown in figure 3. The emission in the GBM energy range shows two peaks, the first of these is not observed in the LAT. This 4.5 s delay between high-energy and low-energy emissions is a hint of spectral evolution.

The emission in the LAT energy range was also temporally extended with respect to the emission in the GBM.While the GBM emission drops off 55 s after trigger time, the LAT emission remains significant for 1400 s. The analysis of this extended emission has been performed using tight cuts adapted to weak sources studies. A likelihood ratio test performed at the location given by GROND observation yielded a significance of 5.6 σ in the last time interval from T_0+200 s to T_0+1400 s. The flux above 100 MeV decays continuously from the main peak to these late times, and also the spectrum is consistent with the trend from the prompt emission : a power-law shape of similar slope.

GRB 080825C emission in the GBM energy range shows multiple peaks, with two main peaks in the first 5 s, and lasts 35 s. The emission above 100 MeV shows one main peak, coincident with the second main GBM peak, although the significance of this delay is poor because of the low statistics. Some events are detected when the signal in the GBM is already very weak, with a reasonable evidence (more than 3 σ) for an extended emission [3] [4] .

GRB 081024B is a short burst. The emission in the GBM lasts only 0.8 s and shows two main peaks. The LAT lightcurve above 100 MeV shows one main peak in this interval, and a few events arrive after the end of the emission in the GBM energy range [7] [8] .

The common feature to these three bursts is an extended emission in the LAT above 100 MeV with respect to the emission in the GBM. The delay observed in GRB 080916C does not significantly appear in the latter two bursts, but this effect might be a common property of GRB high-energy emission that future observations will confirm.

GRB 081215A is almost transverse and thus the LAT emission is studied from the raw tracker trigger rate. It shows one single pulse, simultaneous to the single pulse observed in the GBM. Although we have no accurate energy information on the corresponding LAT events, they are likely below 150 MeV according to a LAT simulation of this burst based on the extrapolation of the GBM spectral measurement [9] [10] .

3.2 GRB080916C spectral characteristics

On-going analyses of all LAT detected GRB show that their spectra are well fit with a Band function [13]. In the case of the bright GRB 080916C, a detailed time-resolved spectroscopy could

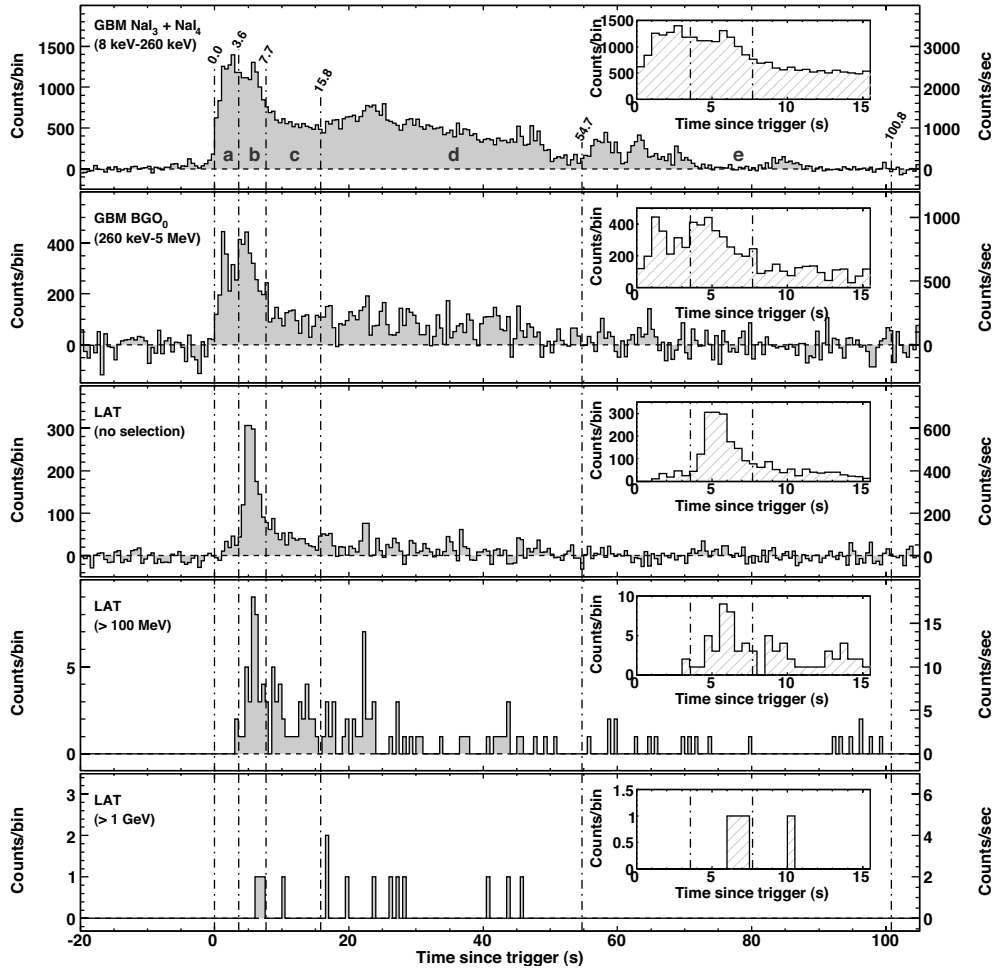

Figure 3: GRB 080916C multiwaveband lightcurve. From top to bottom : NaI (low-energy detectors of the GBM), BGO (intermediate energies), LAT raw counts (no quality cuts or spatial selection have been applied), LAT events used for spectroscopy above 100 MeV, and LAT events above 1 GeV. The first three lightcurves are background subtracted. More than 3000 LAT raw counts were observed, most of them are likely to be below 100 MeV. More than 140 events could be used for spectroscopy above 100 MeV, 14 of them above 1 GeV. The most energetic event has an energy of 13.2 GeV and was detected 16.5 s after the trigger time.

be performed.

The combined GBM-LAT spectrum for the interval containing the main LAT peak is shown in figure 4. Its best fit has a reduced chi-square of 0.96 and good residuals, and the Band parameters are given in table 1. This spectrum shows no evidence for any additional component as could be seen for GRB 941017. Neither does it show any roll-off.

The lightcurve of GRB 080916C was divided in five time bins, and a GBM/LAT combined spectral analysis was performed in each one. The second time bin contains the main LAT peak discussed above. In every bin the spectrum is best fit with a Band function. The evolution is shown in figure 5 : soft-to-hard with the late arrival of the LAT emission, then hard-to-soft which is consistent with the emission from a cooling particle outflow. None of these spectra shows evidence for an extra component or a cutoff.

The measurement of GRB 080916C redshift, $z = 4.35 \pm 0.15$, has important consequences. As far as the enrgetics is concerned, thehuge isotropic energy release $E_{iso} \simeq 8.8 \times 10^{54} erg$ strongly favours the hypothesis of a narrow collimated jet as the source of the emission. The highest energy photon has an observed energy of 13.2 GeV and an energy of 70.6 GeV in the

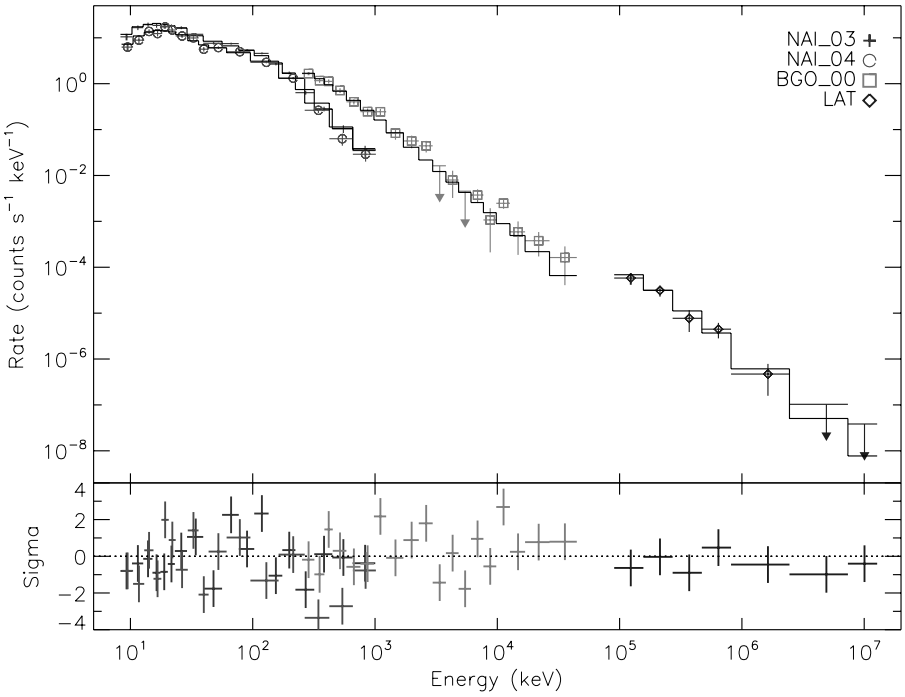

Figure 4: GRB 080916C main LAT peak counts spectrum — photon spectrum convolved with the instruments responses. Crosses and circles are fluxes in the GBM NaI, squares are fluxes in the GBM BGO, and diamonds show LAT signal above 100 MeV. This multi-detector spectrum is best fit with a Band function (two smoothly joined powerlaws) see table 1. 68% C.L. error bars are given, or 95% C.L. upper limits.

Table 1: GRB 080916C : spectral parameters for main LAT peak. Band function fit.

Parameter	Value	Error (68% C.L.)	
Alpha	-1.02	0.02	low-energy slope
Beta	-2.21	0.03	high-energy slope
E_{peak} (keV)	1170	142	νF_ν spectrum maximum
Amplitude ($s^{-1}.cm^{-2}.keV^{-1}$)	0.035	0.001	

source frame. Its delayed arrival, 16.5 s after the trigger time, allows to put strong and robust constraints on Lorentz invariance violation, and more particularly on the Quantum Gravity mass scale : $M_{\rm QG} > 1.50 \times 10^{18} GeV/c^2 \sim 0.1 M_{\rm Planck}$ [14].

GRB 080916C spectrum shows no evidence of a spectral cutoff in any time bin, in particular at early times. This probably excludes pair-production opacity effects as the main cause of the delay observed in the high-energy emission. This actually allows to put a high lower limit on the bulk Lorentz factor in the jet : $\Gamma_{min} = 600$ from bin d, $\Gamma_{min} = 890$ from bin b [14], which is the highest obtained so far.

Finally, no extra spectral component is observed in any time bin. This suggests that the emission from keV to GeV range comes from a unique mechanism, but its origin remains unclear. In a leptonic model framework, this observation suggests that the inverse Compton emission would peak well above 10 GeV. In a hadronic model, Ultra High Energy Cosmic Rays production would produce an extra component in the photon spectrum, which is not observed.

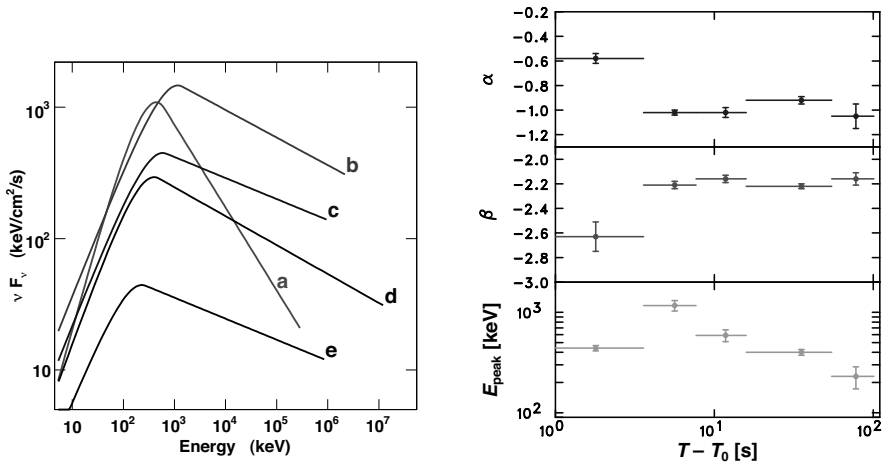

Figure 5: GRB 080916C spectrum temporal evolution. Left : νF_ν photon models for all 5 time bins. Right : fitted parameter values in each time bin (Band function) The high-energy slope beta hardens and the flux increases in the second time bin when the LAT emission arrives. Then the total flux decreases and the high-energy slope remains constant.

Conclusion

In six months of operations, *Fermi* GBM detected ∼120 bursts, including 4 LAT detections. Detailed temporal and spectral analyses have been performed for these four bursts, combining data from both instruments.

GRB 080916C is a very bright event allowing a rich analysis. It shows evidence for a delayed and temporally extended high-energy emission, lasting up to 23 minutes after the low-energy trigger. It was the most energetic burst ever observed, among bursts of known redshift. All time-resolved spectra are consistent with a Band function.

GRB 080916C analysis strongly suggests the existence of a narrow collimated jet, and that the emission in the whole keV–GeV range is due to a unique mechanism. It is not clear yet whether this emission is of leptonic or hadronic origin. Finally, we were able to put the best constraints ever on the jet bulk Lorentz factor $\Gamma > 600$ to 900 and on the Quantum Gravity mass scale $M_{\rm QG} > 1.50 \times 10^{18} GeV/c^2 \sim 0.1 M_{\rm Planck}$.

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