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Observations of Gamma-ray Bursts with the *Fermi* Large Area Telescope

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Abstract

The *Fermi* observatory, with its two instruments, the Gamma-Ray Burst Monitor (GBM) and the Large Area Telescope (LAT), is observing Gamma-ray Bursts (GRBs) with a very large spectral coverage and deep sensitivity, from ~ 10 keV to > 300 GeV. Here we present a review of the main results of the first LAT GRB catalog, containing the 35 GRB detected by the LAT above 100 MeV in the first 3 years of the mission. We also discuss some results on high-energy photons from GRBs obtained with the preliminary Pass 8 new event-level reconstruction. Finally, we present and briefly discuss the LAT observation of the exceptional GRB 130427A.

1 The *Fermi* satellite

Fermi was launched on June 2008, carrying two instruments on board, namely the Gamma-ray Burst Monitor (GBM) [1], a full sky monitor made of 12 NaI detectors and two BGO detectors, sensitive respectively in the 8 keV - 1 MeV and 150 keV - 40 MeV energy range, detecting GRBs at a rate of $\sim$ 250/yr; and the Large Area Telescope (LAT) [2], a pair production γ–ray telescope sensitive from 20 MeV to $>$ 300 GeV. The LAT features a field of view of 2.4 sr at 1 GeV, a broad energy range, a low dead time per event (27 μs) and a the largest effective area for gamma-ray space satellites at GeV energies[1]. This allows the LAT to get a larger number of GRB detections at energies $> \sim$ 20 MeV ($\sim$ 9 GRBs/year) with respect to its predecessor EGRET (5 GRBs in 10 years) and to AGILE (7 GRBs in 6 years), in rough agreement with the pre-launch expectactions [3].

2 The *Fermi*/LAT GRB catalog

The first *Fermi*/LAT GRB catalog [4] covers 3 years of observations, from August 2008 to July 2011. In such time period *Fermi*/GBM detected $\sim$ 750 GRBs, with around half of them in the LAT field of view. Two detection algorithms were used: a standard likelihood algorithm, providing both detection and localization with $<$ 1 deg accuracy, using the post launch so called "Pass 6 v3 Transient" [5] events above 100 MeV; and a counting analysis using the LAT Low Energy (LLE) [6] class of data, featuring a large effective area starting at $\sim$20 MeV but no localization capability. With the likelihood analysis we detected and localized 28 GRBs, while using the LLE analysis we detected 7 more bursts, for a total of 35 GRBs.

2.1 High-energy emission

While the number of GRBs detected at high-energy by *Fermi*/LAT is a small fraction of the total number of GRBs in the field of view, this sample allows us to uncover unique features of GRBs emerging only at high energies.

2.1.1 Energetics

Since LAT observations are photon-limited rather than background-limited, the detection efficiency is directly related to the counts fluence of the source. This is an important difference with respect to *Fermi*/GBM, which is background

[1] The actual LAT perfomance can be found at this link `http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm`

limited and for which the peak flux of the source is more relevant. Of course, the low-energy fluence is highly correlated with the high-energy fluence. The fact that the LAT detects preferentially GRBs with a high low-energy fluence is therefore not surprising. The typical ratio between the high-energy fluence (above 100 MeV) and the low-energy fluence (10 keV - 1 MeV) is ~ 0.1. It is interesting to note that in the catalog there are four *hyper-energetic* bursts for which the ratio exceeds greatly the typical value, being closer or even above 1. The same conclusion can be reached taking the ratio of the rest frame total energy E_{iso} in the two energy bands, which demonstrates that this is not an effect of the distance of these bursts, which are distributed between redshift 0.9 and 4.35.

2.1.2 Delayed and temporally extended emission

The emission above 100 MeV is systematically delayed with respect to the low-energy emission. When using T_{05} as a measure of the onset of the emission for both the 10-300 keV energy range (from [7]) and the 100 MeV - 10 GeV energy range, it is clear that the latter is systematically larger than the former. Also, the duration of the high-energy emission appears to be systematically longer, and features a smooth decaying phase after the end of the low-energy prompt emission. Such decaying phase is well described by a power law in all but three cases, for which we found that a broken power law describes better the data. The time of the temporal decay break is found in all three cases after the end of the low-energy emission, as measured by T_{90}. If we define a *late time decay index* α_L as the index of the power law for the light curves well described by a simple power law, and the index after the break for the three GRBs described by a broken power law, we find that $\alpha_L \sim -1$. This value is foreseen by the standard afterglow model for an adiabatic expansion of the fireball, while a radiative expansion would foresee a decay with an index of 10/7, which is not observed in our data.

2.1.3 High-energy photons

The LAT has observed photons up to 30 GeV coming from bright GRBs, which in the case of high-redshift GRBs can become more than 100 GeV in the rest frame of the progenitor of the burst. This result poses a big challenge for the efficiency of the particle acceleration mechanisms, especially when considering the fact that some of this high-energy events have been detected within seconds since the start of the low-energy emission. In the context of the standard fireball model [8] the presence of such high-energy photons constrains also the bulk Lorentz factor of the emitting shells to be $\Gamma > 1000$ in some cases, a value much higher than what previously thought. High-energy photons from high redshift GRBs allow also to constrain the opacity of the Universe connected with the interaction of the > 10 GeV γ–rays with optical and UV photons of the Extragalactic Background Light (EBL). In the case of the short GRB 090510, the short time delay observed between low and high-energy events can be used to place tight limits on the energy dependence of the speed of light, which is postulated for example by some quantum gravity theories [9].

2.2 GRBs with Pass 8

Since 2010, the *Fermi*/LAT collaboration is developing a comprehensive revision of the event-level analysis, known as Pass 8 [17]. Using its preliminary achievements, the LAT collaboration re-analyzed the prompt phase of ten bright GRBs previously detected by the LAT, finding four new gamma rays with energies greater than 10 GeV in addition to the seven previously known. Among these four there is a 27.4 GeV gamma-ray from GRB 080916C, which, at a redshift of 4.35, makes it the gamma ray with the highest intrinsic energy (147 GeV) detected so far from a GRB [17].

3 Broad-band spectroscopy

Fermi is an exceptional observatory for GRB spectroscopy (see also [10, 11]). In particular, it has unprecedented spectral coverage, starting around 10 keV up to 300 GeV. We exploited this feature by performing a broad-band spectral analysis of all the GRBs contained in the sample. Before *Fermi* most of the GRB spectra were well described by the empirical Band model [12], which has become the *de-facto* standard model. The spectra of all the brightest bursts inside the LAT FoV present, on the contrary, significant deviations from a Band function, requiring additional components such as power laws, high-energy cutoffs, or both. Other GRBs, observed at low off-axis angles, and with a corresponding high effective area, show deviations as well. We conclude that the empirical Band model seems to be not sufficient to describe all the spectral features of LAT GRBs. Unfortunately, there is no common recipe, and different components can be required depending on the particular event. This calls for a better broad-band modeling of the spectra of GRBs, opening new questions and prompting new theoretical developments.

4 The afterglow of LAT-detected GRBs

A subsample of LAT-detected GRBs have been studied at other wavelengths, in particular during their afterglow emission. A systematic study published by [13] shows that in many ways the properties of the afterglow of LAT bursts are typical of the general afterglow population, but the ratio between the luminosity of the prompt emission and the luminosity of the afterglow is larger. Therefore, either their prompt emission is more efficient in producing γ-rays, or, conversely, their afterglows are somehow suppressed. In two cases, GRB 090510 and GRB 110731A, Swift and other instruments observed the afterglow when the high-energy extended emission was still detectable by the LAT. A broadband study, from optical wavelengths to γ-rays, showed that the emission is compatible with being from external shocks [14, 15]. In one other case, GRB 100728A, high-energy emission was detected by the LAT only in correspondence with an X–ray flare, which was successfully modeled from X–ray to γ-ray energies as internal shock emission [16].

5 GRB 130427A

The observations of the exceptionally bright GRB 130427A by *Fermi* [18, 19] provide further constraints on the GRB phenomenon and their emission processes. GRB 130427A had the largest fluence, highest observed energy photon (95 GeV), longest γ-ray duration (20 hours), and one of the largest isotropic energy releases ever observed from a GRB. The temporal and spectral analyses of GRB 130427A presented in [18] challenge the widely accepted model that the non-thermal high-energy emission in the afterglow phase of GRBs is synchrotron emission radiated by electrons accelerated at an external shock.

6 Towards the second LAT GRB catalog

The *Fermi* LAT collaboration is actively working to produce the second version of its GRB catalog. This catalog will contain more GRBs, not only due to an extended period of data, but also due to renewed algorithms to search on a wider angular region centered on GBM GRB trigger positions and to new Pass 8 data selection, with larger effective area both at low and high energies. The recent detections by the LAT are currently maintained and kept updated on the publicly available GRB tables [20, 21].

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