

Prospects for Gamma-Ray Bursts detection by the Cherenkov Telescope Array

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The first Gamma-Ray Burst (GRB) catalog presented by the Fermi-Large Area Telescope (LAT) collaboration includes 28 GRBs, detected above 100 MeV over the first three years since the launch of the Fermi mission. However, more than 100 GRBs are expected to be found over a period of six years of data collection thanks to a new detection algorithm and to the development of a new LAT event reconstruction, the so-called “Pass 8”. Our aim is to provide revised prospects for GRB alerts in the CTA era in light of these new LAT discoveries.

We focus initially on the possibility of GRB detection with the Large Size Telescopes (LSTs). Moreover, we investigate the contribution of the Middle Size Telescopes (MSTs), which are crucial for the search of larger areas on short post trigger timescales. The study of different spectral components in the prompt and afterglow phase, and the limits on the Extragalactic background light are highlighted. Different strategies to repoint part of – or the entire array – are studied in detail.

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1. Introduction

Gamma-Ray Bursts represent a very interesting case study in astrophysics, mainly due to their multi-disciplinary nature. At present time, a GRB can trigger one or more of the dedicated instruments based on several satellites orbiting around the Earth, such as Swift, Fermi, MAXI or INTEGRAL. The observed keV-MeV prompt emission may be accompanied by X-ray, optical or radio emission. Rapid follow-up of this keV-MeV emission is possible thanks to communication through the Gamma-ray Coordinates Network (GCN), where the GRB position is spread out in real time to all other observatories. This includes all currently operative Imaging Atmospheric Cherenkov Telescopes (IACTs) like MAGIC, H.E.S.S., and VERITAS. Unfortunately, none of them ever succeeded in capturing a high-energy signal from a GRB, but several upper limits from a single or from a sample of bursts were published by each collaboration over the last years. In this contribution, we aim to investigate the possibility by the Cherenkov Telescope Array (CTA) [1] to detect such elusive GRB emission.

2. CTA configurations

CTA is a worldwide project aiming to build and operate a third generation of IACTs. In its current design, two huge arrays for a total amount of more than 100 telescopes are foreseen, one in each hemisphere, to extend the energy range of currently operating IACTs mainly to higher energies and to improve the sensitivity of about one order of magnitude with better angular and energy resolutions.

In order to cover the energy range from 20 GeV to more than 100 TeV, three kinds of telescopes are envisaged: Large Size Telescopes (LSTs, 20 GeV \div 100 GeV), Medium Size Telescopes (MSTs, 100 GeV \div 10 TeV), and Small Size Telescopes (SSTs, 10 TeV \div > 100 TeV). This configuration is driven by the features of the Cherenkov signal at different energies: near the threshold, the number of source photons is relatively high but the Cherenkov image is poor, so few huge telescopes (3 or 4, with a diameter of 23 m) are used to collect the faint showers. In this region, the challenge is to distinguish between Cherenkov and Night Sky Background (NSB) photons, and to discriminate primary gammas from the overwhelming flux of cosmic rays hadrons. On the other hand, the effective area is not an issue, so a small number of big telescopes close to each other is the best configuration. At higher energies, the Cherenkov signal starts to increase and the flux from the source is rapidly fading, so a compromise array of ~ 25 telescopes of 12 m diameter scattered over an area of around 3 km² is the best choice. At the highest energies the situation is completely different: the Cherenkov signal is very strong, but the steep spectra reduce the signal to a handful of primary gammas. To overcome this, a huge effective area up to 6-7 km², covered by ~ 70 SSTs (4 m diameter) is needed. We notice that for energies $\gtrsim 10$ TeV the Cherenkov images are so rich that it is not only easy to discard the NSB photons, but also to discriminate gammas from hadrons, approaching a background-free working mode for which the sensitivity is proportional to the effective area and not to its square root. Due to the Extragalactic Background Light (EBL) absorption, that strongly depresses the high-energy spectra of distant sources detected on Earth (the limit being $E \lesssim 1$ TeV for $z \geq 0.1$) and to the fact that the Galactic plane is mostly visible from the Southern hemisphere, the SST array is not expected to be built in the Northern observatory.

3. High-energy GRB observations

Due to their elusive nature, GRBs represent a very interesting candidate for future observations by CTA, as highlighted also in [2]. Prospects for VHE GRB observations by CTA were also presented in detail by [3]. Most of these analyses relied on extrapolations taken (1) from the GRB spectral parameters published in the catalogs of the Burst and Transient Source Experiment (BATSE, 20 keV–2 MeV) or of the *Swift* Burst Alert Telescope (BAT, 15–150 keV); and (2) from some very energetic GRBs detected by Fermi before 2012.

Since June 2008, the Fermi mission is constantly enhancing the number of GRB detections. The Fermi Gamma-Ray Burst Monitor (GBM, [4]) is sensitive in the energy range between 8 keV and 40 MeV and its field of view covers almost 4π sr. The GBM trigger rate lies at ~ 250 GRB/yr (i.e. higher than BAT with ~ 100 GRB/yr) and the second GBM catalog (covering 4 years of operation) includes almost 1000 bursts [5]. Furthermore, thanks to the LAT [6] onboard Fermi, the number of high-energy GRBs dramatically increased with respect to the bunch of events seen in the '90s by the Energetic Gamma-ray Experiment Telescope (EGRET, 20 MeV–30 GeV). LAT operates at energies between 100 MeV and >300 GeV and its first GRB catalog [7] already included ~ 30 GRBs observed during the first three years of operation above 100 MeV with the standard event reconstruction analysis. This number gets even larger when considering dedicated low-energy techniques (LLE) exploring the energy region between 10 and 100 MeV, where the LAT and GBM energy ranges overlap.

The current number of official LAT GRB detections is constantly kept up-to-date on the LAT Public Table website [8] and lists almost 100 GRBs at the time of this writing, that is after seven years into the Fermi mission. However, this number is meant to grow as soon as the new event reconstruction algorithm (the so-called *Pass 8*) will be released and the catalog will be updated (see [9] for more details).

Fermi's GRBs exhibit dozen of GeV photons with unprecedented high energies. The current record holder is GRB 130427A, which emitted a 95 GeV photon [10] and was detected at a low redshift of 0.34. It was followed-up by a very large number of telescopes, including the Veritas array [11]. Unfortunately, Veritas' observations only began almost 20 hours post trigger, leading to no GRB detection. The upper limit (UL) was placed at 3.3×10^{-12} erg cm $^{-2}$ s $^{-1}$.

In the near future, we plan to revisit the latest prospects for VHE GRB observations in the light of the newest simulations produced by the CTA collaboration. We want to focus on the extrapolation to high energies of Fermi-like GRBs, both from the prompt emission using the GBM sample and from the late emission using the LAT sample, in particular using those bursts with measured redshift. For this contribution, we use the extremely fluent GRB 130427A as a test case and see how well we might observe this event at several epochs after the trigger with various CTA configurations.

4. Simulation of GRB observations with ctools

In order to estimate the possible detection of GRBs by CTA, we intend to set up a library of GRBs at different times, extrapolating the LAT flux to the highest energies and properly taking into account the time evolution of their flux. However, since we do not yet model the effect of the EBL,

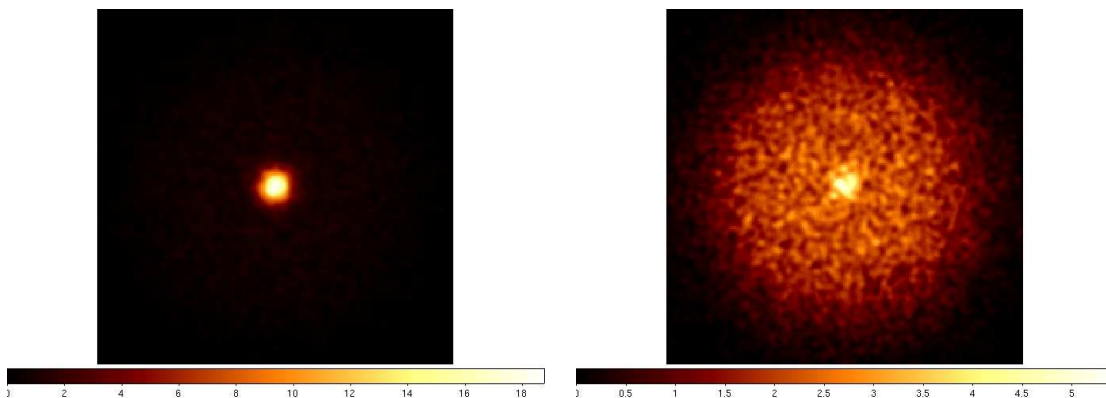


Figure 1: Simulation of GRB 130427A with *ctools*. *Left panel:* Count map of GRB 130427A as seen by CTA North in 600 s, after 1000 s from the trigger in the energy range 20 GeV–100 GeV; *Right panel:* Count map of GRB 130427A as seen by CTA North in 1800 s, after 10000 s of the trigger in the energy range 20 GeV–100 GeV

our current simulations are limited up to 100 GeV, an energy where the effect of the cosmological attenuation is not relevant (see Section 5. for more details).

To estimate the detectability of a GRB we make use of the *ctools*, a software package specifically developed for the scientific analysis of CTA data [12]. In these first tests, we simulate the high-energy emission of GRB 130427A as detected by LAT, with a spectral index $\gamma = 2.2$ (which is almost constant from 400 s up to 70 ks post trigger) and a power law decay with a temporal index $\tau = 1.35$ (valid for $t > 380$ s). We cross checked our extrapolation to the CTA energies by comparing it with the UL placed on this GRB by VERITAS [11]. This was calculated assuming an intrinsic GRB spectrum of $(dN/dE) \propto E^\gamma$ absorbed using the EBL model of [13].

We simulate two possible observations of this GRB by CTA: (a) the first one lasting 10 min at $t = 1$ ks post trigger; (b) the second one lasting half an hour at $t = 10$ ks post trigger. We assume both observations on axis with respect to the CTA array and a zenith angle $\theta = 20^\circ$. Figure 1 shows two count maps of the simulated GRB in the energy range 20 GeV–100 GeV. They were obtained using the *ctools* functions *ctobssim* and *ctbin*, and adopting the recently provided CTA instrument response functions (IRFs) [14]. In this particular case, we made use of the *North_0.5h* and *North_5h* IRFs, respectively. A preliminary *ctlike* analysis is performed on the two observations, getting a significant detection in both cases. We plan to perform similar analyses for other Fermi GRBs with known redshift, using different observing profiles and spectra.

5. Effect of the Extragalactic Background Light

The interaction of extragalactic VHE photons with EBL at UV–optical wavelengths produces an e^+e^- pair and thus an exponential attenuation of the gamma-ray flux. This absorption increases with the redshift of the source, the gamma-ray energy and the photon density of the EBL (for a review, see [15]). Moreover, it is particularly important for GRBs, since they are cosmological sources with a mean redshift $z \simeq 2$. Many EBL models have been published in the last decades, with a general trend towards a decrease of the corresponding optical depth due to the observation of VHE photons at larger redshifts [16], which were recently detected from blazars at $z \simeq 1$ [17, 18, 19].

The EBL models are getting close to the firm lower limits derived from integrated galaxy number counts [20]. As an indication, the high-energy spectrum of a source at $z \simeq 1$ shows a cutoff at $E \approx 100$ GeV. In our future work we will consider the EBL model by [21]. For simplicity, in our simulations we will extend the spectrum only up to 1 TeV, the maximum energy after which the source is assumed to be totally absorbed.

However, the observed spectral indices in blazars do not seem to follow the amount of softening with increasing redshift predicted by the EBL absorption [22], and there are other indications of an overestimation of the EBL photon density (e.g., [23]). A possible explanation of these results could be the oscillation from photons to Axion-Like Particles (ALPs), which propagate unimpeded over cosmological distances before reconversion, reducing the optical depth along the VHE gamma-ray path [24]. In this framework, GRBs, with their cosmological distances, may be useful to add stronger constraints on the EBL and give new hints on the existence of ALPs.

6. CTA operating modes

CTA's complex and varied experimental layout will be run in different ways depending on the target features:

1. highest sensitivity observations, with all telescopes pointing toward a single source;
2. normal operations, with the array split into sub-arrays with different targets;
3. sky survey, with the aim of covering large portions of the sky to detect new or transient sources.

Case 1. applies mainly to flaring or varying sources, when the observation cannot be postponed and the maximum sensitivity over the whole energy range is required. This is not the case of deep observations, since the comparison of the primary spectra with the expected sensitivity shows that the core energy window (around 1 TeV) will be covered in a time considerably smaller than the high energy tail. We therefore expect for deep field observations that the SST array will make very long exposures on selected candidates suggested by MSTs on the basis of hard spectrum or high flux. This is case 2., with the array split into the different telescope types, but mainly for MSTs, this can apply also to telescopes of the same type. Case 3. is the most relevant one for this study, since it allows the detection of serendipitous sources, variable or unexpected, and GRBs are both. This observation mode will be therefore analyzed in more details.

The current field of view (FoV) of operating IACT arrays ($4\text{--}5^\circ$) will be widened by MSTs and SSTs up to $8\text{--}10^\circ$. Unfortunately, since the detection of primary photons is through the Cherenkov images, the sensitivity is not uniform inside the FoV and dramatically drops towards its edge. This means that, if we want to enlarge the total FoV by pointing the telescopes towards different directions, the FoV of each telescope must overlap in order to obtain a uniform sensitivity. At present, only the Galactic plane was scanned, starting from HEGRA [25, 26] up to the 1400 hours-long survey by H.E.S.S. [27, 28, 29]. Outside the Galactic plane, only small promising regions were observed, limiting our knowledge of the VHE sky to a few per cent.

In order to efficiently scan large portions of the sky, the divergent mode was firstly proposed. In this mode, instead of having all telescopes pointing towards the same direction (the so called "parallel mode"), each telescope points to an angle slightly increasing from the center to the edges of the array. Another possibility, the so called "convergent mode", envisages that this angle is

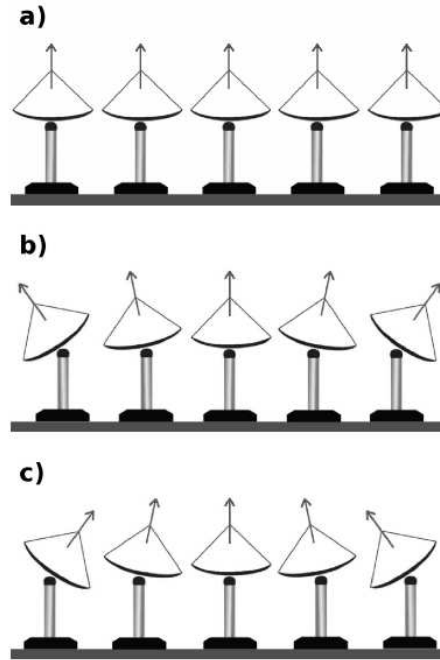


Figure 2: Three modes of configuration of the telescope system used in the sky-survey scans: a) normal (parallel) mode; b) divergent mode; c) convergent mode (taken from [30]).

reduced from the array center to its edges (see the sketch in Figure 2). Both modes were deeply studied for MSTs by means of an accurate simulation of the shower development in the atmosphere and of the telescopes response in [30], for different angle separations. The results show that the maximum sensitivity for sky survey is achieved in divergent mode with large offset angles ($\sim 6^\circ$ from the central to the outermost telescopes), with a decrease of the observing time for a given sensitivity by a factor of ~ 2.3 with respect to the parallel mode. However, the angular and energy resolutions are worsened by a factor up to 2. The convergent mode is a better choice at high energy, favoring the observation of sources with hard spectra. In this work, we propose a third possibility, that is a mixture between parallel and divergent modes.

In the past, exciting observations made by Whipple in the late '80s were performed using a single telescope recording the Cherenkov images by means of a pixelated camera that allowed the discrimination between gammas and hadrons. With just one image, the core location (and thus the primary energy) could be badly determined, limiting the detection inside the Cherenkov “pool” (with radius $r_p \sim 120$ m) where the lateral distribution of photons is approximately flat. After imaging, the next fundamental improvement to the IACT technique was the stereo approach firstly used by HEGRA: with at least two images, the shower axis could be determined geometrically with a better resolution on both energy and arrival direction. This approach was so widely adopted that even for CTA the main trigger will be given by the coincidence of at least two telescopes, and the mono events will be collected only for calibration and testing purposes.

Since for IACTs the single observing unit is a couple of nearby telescopes, we propose here a “coupled divergent mode” in which couples of telescopes are pointing to slightly different positions as in Figure 2b) for single ones. The tilt angle will be chosen on the basis of the sensitivity decrease

over the FoV for each couple of telescopes. If, for example, the sensitivity is halved at 3° , a tilt angle of 6° will assure a uniform sensitivity at least along the line connecting the center of the FoV of the two couples of telescopes. For the entire sky we expect that this value will be reduced, and we plan to perform an accurate simulation to optimize this separation angle. Even if the main contribution in GRB searches will come from LSTs, which due to their paucity can hardly benefit of whatever divergent mode, the contribution of MSTs could still be not negligible. The medium sized telescopes are not designed for fast slewing as LSTs (which can repoint within 100 s or less), but there are indications from EGRET and from Fermi observations that the VHE emission is delayed with respect to the prompt phase. Concerning the energy window, the energy range from 100 GeV to 1 TeV corresponds respectively to an horizon from $z \simeq 1$ to $z \simeq 0.1$, depending on the EBL absorption model. For follow-up observations, the GRB location is often given by fast satellite analysis with large uncertainties, mostly greater than the 50% sensitivity FoV, so some kind of divergent mode must be applied. Moreover, a sky survey with large angular acceptance could reveal a serendipitous GRB.

In the future, Monte Carlo simulations to obtain the expected performance of the MST array operated in “coupled divergent mode” are planned, and the results will be compared with those presented in [30]. An estimate of the rate of serendipitous GRBs detectable during the sky survey will be also given.

7. Acknowledgments

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