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Search for Gamma-Ray Bursts with the MAGIC Telescope

D. Bastieri[b], N. Galante[c], M. Garczarczyk[a], M. Gaug[d] and S. Mizobuchi[a]
on behalf of the MAGIC collaboration
(a) Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 München, Germany
(b) Università and INFN – Padova, Via Marzolo 8, 35131 Padova, Italy
(c) Università di Siena and INFN – Pisa, Via Buonarroti 2, 56127 Pisa, Italy
(d) IFAE, Edifici Cn. Facultat Ciències UAB, 08193 Bellaterra (Barcelona), Spain
Presenter: M. Garczarczyk (garcz@mppmu.mpg.de), ger-garczarczyk-M-abs1-og24-poster

The MAGIC Telescope, now taking data with a trigger threshold of ~ 50 GeV, is able to take full advantage of its fast slewing capability to respond to Gamma-Ray Burst alarms. With the low energy threshold and maximal orientation time to any sky position within a few tens of seconds, MAGIC could be one of the first ground-based experiments to detect prompt emission of Gamma-Ray Bursts (GRB) in the few tens of GeV energy domain. Besides giving an overview of the expected performance, we report about the response to some recent GRB alarms.

1. Introduction

GRBs are still, in many aspects, enigmatic cosmic objects. The upper end of their spectra has not been measured so far. In one case (GRB940217) delayed GeV emission has been observed. It is therefore a challange to search for possible γ emission in the GeV domain. Besides fast flaring AGNs, GRBs might be the best candidates for testing quantum gravity effects. Such a study would benefit very much from data in the GeV range. Past ground based experiments were not sensitive since their thresholds were well above the predicted γ-energy cut-off due to absorption by the extragalactic background light (γ-ray horizon).

The MAGIC Telescope is a new generation, high performance imaging air Cherenkov telescope (IACT). It was commissioned in 2004 and has already observed a few very high energy (VHE) gamma-ray (γ) emitting sources such as the well established sources CRAB, Mkn 421, Mkn501, 1ES1959. It has also seen evidence of a few new sources [1]. The telescope has been built to explore the γ-spectrum starting well below ~ 100 GeV. As many novel elements have been used in the construction, it will still take some time to fully understand the telescope performance and to reach the design goal of a 30 GeV threshold. The superstructure of the telescope was built mainly from Carbon Fiber (CF) tubes and some aluminium components in order to reduce weight and inertia in order to eventually allow slewing to any new position in the sky within less than 20 seconds. Contributing to the low weight are novel lightweight all-aluminium mirrors. For the compensation of the residual deformation of the CF mirror support frame an *Active Mirror Control system* (AMC) [2] is being used. These features, together with the low energy threshold, give MAGIC the potential to follow up GRBs very shortly after a fast satellite alert. One of MAGIC's dedicated goals is the observation of GRBs early after the start of prompt emission into the early afterglow stadium, where some past observations have shown delayed VHE γ emission. Further technical details of MAGIC can be found in [3]

MAGIC is part of the *GRB Coordinates network* (GCN) [4], made up of satellites that can recognise GRB events with their on-board detectors and can quickly react and send the celestial coordinates of presumed GRB events. GCN takes care of broadcasting the data to ground instruments like many optical- and radio- telescopes as well as MAGIC.

In this work we make quantitative predictions for GRB observation with MAGIC and present results from the first tests made with alerts sent by SWIFT and HETE-2.

2. The Probability to observe GRBs

The main parameter influencing the chances to observe GRBs is the telescope *duty-cycle* [5]. The duty-cycle of the telescope was calculated as the fraction of the sky area accessible to MAGIC per year. The following conditions had to be met:

1. the Sun must be at zenith angle $> 108°$;
2. the minimum angular distance from the Moon must be $30°$;
3. the night sky must be clear and the relative humidity of the air must be below $80\,\%$;
4. the wind speed must be below $10\,\mathrm{m/s}$.

Using the weather data and ephemeredes for the year 2001, we estimate a chance to observe a GRB slightly below 10%. Provided that a satellite GRB alarm is received, roughly $\frac{1}{10}$ of all GRB alerts can, in principle, be pursued. From this fraction of tagged GRBs it is possible to estimate how many GRBs might be detected, i.e., that their detection significance will exceed 5σ. The number of σ can be calculated in first order using the Li-Ma formula:

$$N_\sigma = Q\frac{(R_{\mathrm{on}} - R_{\mathrm{off}})T}{\sqrt{(R_{\mathrm{on}} + R_{\mathrm{off}})T}} = Q\frac{R_\gamma\sqrt{T}}{\sqrt{R_{\mathrm{on}} + R_{\mathrm{off}}}} \tag{1}$$

where Q, the so called *quality factor*, which represents the γ-hadron separation efficiency of the analysis is of order unity at energies close to the threshold. T is the actual acquisition time and R_i are the actual rates. Each R takes into account the particle flux Φ and the detector sensitivity to the flux itself, expressed as the *effective area* of the telescope, $A_{\mathrm{eff}}(E,\vartheta)$. For instance, the expected rate from the GRB is: $R_\gamma = \int \Phi_{\mathrm{GRB}}(E)A^\gamma_{\mathrm{eff}}(E,\vartheta)\mathrm{d}E$ while the cosmic-ray background is: $R_{\mathrm{off}} = \int \Phi_{\mathrm{CR}}(E,\vartheta)A^{\mathrm{CR}}_{\mathrm{eff}}(E,\vartheta)\mathrm{d}E$. The effective area of MAGIC close to Zenith reaches $10^5\ \mathrm{m}^2$ around $100\,\mathrm{GeV}$ and drops to $10^4\ \mathrm{m}^2$ around $50\,\mathrm{GeV}$.

The expected VHE GRB flux is derived from the typical power-law spectrum found for GRBs in the BATSE catalogues, but taking also into account the prediction of the cosmological cut-off due to the absorption of high-energy γ's by the Metagalactic Radiation Field via the process $\gamma_{\mathrm{HE}}\gamma_{\mathrm{MRF}} \rightarrow \mathrm{e}^+\mathrm{e}^-$ [6]. This estimate also requires a simple model for the GRB distribution as a function of the redshift.

Of paramount importance for the detection of GRBs is the delay between the GRB onset and the time when MAGIC can actually start to observe the GRB. This delay sums up from three different times:

1. The time needed by the satellite to sum up significant number of γ-induced events from a GRB.
2. The time elapsing between analysing the events to find the sky coordinates and sending the alert, the broadcast via GCN and the final acknowledgement by MAGIC. The latter three actions take $\sim$ 2 seconds.
3. The slewing time needed by MAGIC to point to the GRB position, focussing the mirrors and starting the observation.

From our studies we found that a quick response of a few seconds is very important. For example, a reduction of the response time from 1 minute to 15 seconds increases the number of promptly observable GRBs by a factor five.

It should be noted that the zenith angle ϑ enters critically in the estimate of the rate of observable GRBs. The number of observable GRBs, e.g., is not obtained simply by a straightforward multiplication of the duty-cycle ($\approx 10\%$) by the number of GRBs expected to have a significance $N_\sigma > 5$, but is better estimated by:

$$N_{GRB} = \sum_\vartheta D(\vartheta)\eta(\vartheta) \tag{2}$$

where $D(\vartheta)$ is the duty-cycle in a given bin of zenith angle and $\eta(\vartheta)$ is the number of GRBs (extrapolated from BATSE catalogues) actually observable in that given bin of zenith angle. The sum is performed over all zenith angle bins. For this calculation we neglected the influence of the rising threshold as a function of zenith angle.

Values of $\eta(\vartheta)$ range between 5 and 24, strongly depending on the delays from the GRB onset to the actual observation of the GRB by MAGIC. The final result of this analysis is that MAGIC should be able to observe $0.5 \div 2$ prompt GRBs per year. Here we define "prompt" such that MAGIC will start observing while the GRB is still fully active in the X-ray domain.

3. Telescope Performance

Currently, MAGIC is still in an experimental phase, optimizing the operation for GRB searches. While initially it could be proven that the telescope fulfils the slewing requirements for fast repositioning, we finally used a conservative step-by-step improvement approach to fully automise the operation, starting with a rather conservative slow slewing.

In April 2005, the Burst Alarm System *Gspot* (Gamma Sources Pointing Trigger) has been included into the control software of the MAGIC telescope. It receives the alerts from *GCN* and selects candidates which fulfil the following criteria:

1. the Sun has to be below the astronomical horizon
2. the zenith angle of the GRB candidate has to be less than 70°
3. the angular distance between the GRB position and the Moon has to be larger than 30°

If the above criteria are fulfilled within at most five hours after the GRB onset and the telescope is in observation phase, it automatically moves to the target position and starts the observation. With such a conservative approach we can also catch a possible afterglow of a GRB that has occurred during late afternoon.

A coarse estimate of the expected observation time of GRBs can be derived from an estimated number of GRB follow-up observations, which can be expressed in the following formula:

$$N_{obs} = N_{alert} \cdot DC \cdot F_{overlap} \tag{3}$$

where N_{obs} is the mean number of observed bursts, N_{alert} the mean number of alerts, DC the duty cycle (including the reduction of sky coverage due to the maximum allowed zenith angle) and $F_{overlap}$ a reduction factor due to the non-overlapping sky coverage between the satellites and MAGIC.

The claimed GRB alert frequency N_{obs} from SWIFT is about 150-200 GRBs/year. With the duty-cycle of 10% and a slightly optimistic overlap factor $F_{overlap}$ of 0.5, the expected number of GRB responses of MAGIC is in the order of 0.6 to 1.6 per month.

During the three months after the implementation of *Gspot*, improvements of the telescope performance were carried out. Especially the precision of fast repositioning was carefully tested. During this time a total number of 24 (SWIFT) + 15 (HETE-2) + 6 (INTEGRAL) = 45 alerts with useful GRB coordinates were received from *Gspot*. Out of this sample the following GRBs have been observed by MAGIC:

Nr.	GRB	Satellite	Time burst onset	Δt_{alert}	$\Delta t_{observation}$	Zd_{GRB}	redshift
1.	GRB050408	HETE	16:22:50 UTC	14 sec	3138 sec	48°	1.2357
2.	GRB050421	SWIFT	04:11:52 UTC	58 sec	112 sec	52°	
3.	GRB050502	SWIFT	02:14:18 UTC	18 sec	990 sec	33°	3.793
4.	GRB050505	SWIFT	23:22:21 UTC	540 sec	793 sec	50°	4.27
5.	GRB050509A	SWIFT	01:46:29 UTC	16 sec	115 sec	57°	
6.	GRB050509B	SWIFT	04:00:19 UTC	15 sec	368 sec	69°	0.226
7.	GRB050528	SWIFT	04:06:45 UTC	43 sec	77 sec	52°	

It has to be pointed out that for these bursts the fast movement was not yet used.

Since May 2005, the acceleration and deceleration speed of the telescope has been increased by a factor 2.6 and the maximum allowed velocity has been raised by a factor of six. As an example we obtained a characteristic repositioning in $\Delta Az = 250°$ taking 63 seconds and for $\Delta Az = 60°$ 22 seconds. There is still room to increase the positioning speed by at least a factor two by doubling the acceleration, raising the maximum speed limit and turning the telescope over the Zenith. These performance improvements are planned for this year.

The *Active Mirror Control* of the MAGIC telescope plays an important role for the GRB observation. As mentioned in the introduction, the AMC system corrects the small mirror dish deformations depending on the zenith angle. To avoid time losses, a focussing with Look-Up Tables was implemented such that the telescope can be focussed to the GRB coordinates already during the repositioning. This procedure takes less than 10 seconds.

4. Conclusions

MAGIC is now operating and can be used to follow the GRB events shortly after their onset. Due to a chosen conservative approach to reduce the positioning speed step-by-step it will still take some months for the response time to be reduced to less than 20 seconds.

The analysis of the eight up to now observed GRBs showed no significant signal. However, taking into account the measured redshifts and the threshold energies at the zenith angles at which MAGIC has observed the bursts, no afterglow VHE γ rays are expected due to the limited gamma ray horizon [6].

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