Detection prospects for short time-scale transient events at VHE with current and next generation Cherenkov observatories

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Abstract: In the current view of Gamma-Ray Burst (GRB) phenomena, an emission component extending up to the very-high energy (VHE, \(E > 30\) GeV) domain is thought to be a relatively common feature at least in the brightest events. This leads to an unexpected richness of possible theoretical models able to describe such phenomenology. Hints of emission at tens of GeV are indeed known since the EGRET observations during the ‘90s and confirmed in the Fermi–LAT data. However, our comprehension of these phenomena is still far to be satisfactory. In this respect, the VHE characterization of GRBs may constitute a breakthrough for understanding their physics and, possibly, for providing decisive clues for the discrimination among different proposed emission mechanisms, which are barely distinguishable at lower energies. The current generation of Cherenkov observatories, such as the MAGIC telescopes, have opened the possibility to extend the measurement of GRB emission, and in general to any short time-scale transient phenomena, from few tens of GeV up to the TeV energy range, with a higher sensitivity with respect to \(\gamma\)-ray space-based instruments. In the near future, a crucial role for the VHE observations of GRBs will be played by the Cherenkov Telescope Array (CTA), thanks to its about one order of magnitude better sensitivity and lower energy threshold with respect to current instruments. In this contribution, we present a method aimed at providing VHE detection prospects for observations of GRB-like transient events with Cherenkov telescopes. In particular, we consider the observation of the transient event GRB 090102 as a test case for the method and show the achieved detection prospects under different observational conditions for the MAGIC telescopes and CTA.

Keywords: icrc2013, VHE, Cherenkov telescopes, short time-scale transient GRB-like events.

1 Introduction

Time domain astrophysics is going to play a key role in our understanding of different kind of cosmic sources. In particular, the discovery of high-energy \(\gamma\)-rays from an unexpected large variety of transient events with time-scale ranging from millisecond up to days poses a new series of theoretical problems [1]. The list of \(\gamma\)-ray band transient sources comprises both local phenomena, as terrestrial and solar \(\gamma\)-ray flares, as well as galactic and extra-galactic transient events. Furthermore, short time-scale variability has long been observed in active galaxies, especially for blazars-class objects [2]. The extension, when possible, of the multi-wavelength coverage up to very high energy (VHE, \(E > 30\) GeV) can provide powerful diagnostic tools to understand the nature of these objects and discriminate among the different proposed interpretative scenarios. In particular, Gamma-Ray Bursts (GRBs) have long been seen as the transient events per excellence. At their peak activity, GRBs become the most luminous objects of the Universe releasing enormous amounts of energy from \(10^{52}\) erg to \(10^{54}\) erg of isotropic-equivalent energy over brief periods of \(0.01 – 1000\) s. They usually show their phenomenology mainly in the 10 keV – 1 MeV energy band with extremely rapid and irregular variability (see e.g. [3] for a review). However, recent results from the Fermi–LAT (Large Area Telescope) have showed that, at least for the brightest events, a GeV emission from GRBs is a relatively common phenomenon [3]. Interestingly, in the majority of the LAT GRBs, GeV emission occurs with a significant delay with respect to the MeV and sub-MeV emission and it lasts longer than the emission detected by the Fermi–GBM (Gamma-ray Burst Monitor).

While sub-MeV GRB emission can often be explained by electron synchrotron processes, the theoretical framework of a possible second emission component in the high-energy regime is still less clear. Furthermore, the recent detection of GRB 130427A with photons up to 94 GeV [5] also indicates the possibility of an observable VHE counterpart. Several authors have derived predictions for the VHE emission from the GRB prompt and afterglow phase taking into account non-thermal leptonic and hadronic processes [6] as well as photospheric up-scattered emission [7]. VHE observations with sufficiently high sensitivity may definitively solve, or at least strongly constrain, the mechanisms for prompt and early afterglow emission through broader energy band coverage. At the same time, and also for other GRB-like transient phenomena, such as Tidal Disruption Events [8], VHE data may throw light on some physic aspects which are still poorly understood, including the determination of the bulk Lorentz factor of the outflow, the dynamics of particle acceleration, and the jet formation.

The capabilities of a significant detection at VHE from such a kind of events are strongly related, on the one hand, to the scientific performance of the instrument, and, on the other hand, to the short-time scale features of the \(\gamma\)-ray signal. The strong time dependence of the emission hence makes the usual considerations based on the sensitivity of the instrument not suitable for providing detection prospects for transient events at VHE.
In this work, we illustrate a method for evaluating the detectability of GRB-like events with the MAGIC stereoscopic system and the next generation Cherenkov Telescope Array (CTA) based on the time evolution of the significance of the observation. As a test case, we consider the particular event GRB 090102 \[2\] (which was observed by the MAGIC-I telescope \[10\]) and show its detection prospect results.

2 Observations of GRB-like events with current and next generation Cherenkov telescopes

Despite the remarkable results of the Fermi–LAT, the number of detected photons above few tens of GeV remains rather limited, motivating follow-up observations with much better sensitivity in the VHE band with the use of Imaging Atmospheric Cherenkov Telescopes (IACTs) \[11\]. Thanks to the technical evolution of such kind of instruments, in the last decade, intense studies have been performed on GRB science with IACTs to explore possible VHE band emission for these enigmatic events.

Since already several years, current IACTs, such as MAGIC\[12\], H.E.S.S.\[13\], and VERITAS\[14\], despite their reduced duty cycle, started observational programs on GRB follow-up, making the ~100 GeV – TeV energy range accessible to GRB observations. As a matter of fact, several attempts to observe GRB emission have been reported by current IACT collaborations (e.g. \[15\]–[16]–[17]). In all cases only upper limits have been derived. However, it is well known that the flux above ~100 GeV is affected by the attenuation by pair production with the lower energetic (optical/IR) photons of the diffuse Extragalactic Background Light (EBL) \[18\]. The consequent Universe opacity heavily affect Cherenkov observations, almost hindering the detection for relatively high redshift (\(z > 0.5\)) sources. This is the case for GRBs which have long been known to have redshift slightly larger than 2. This basically implies that the expected detection rate for current Cherenkov telescopes is estimated to be around 0.1 – 0.2 GRBs/year and should significantly improve only with the coming CTA, for which GRBs will be among primary targets \[19\].

The CTA project \[20\] aims at developing the next generation ground-based instrument dedicated to the observations in the VHE \(\gamma\)-ray band. In the current layout of CTA, the arrays will consist of three types of telescopes with different main mirror sizes in order to cover the full energy range from few tens of GeV up to a hundred of TeV. The lowest energy band (i.e., where GRBs are mainly foreseen on GRB science with IACTs to explore possible VHE band emission for these enigmatic events).

3 Detection prospects for transient events at VHE

The basic quantities that are normally taken into account for evaluating the detectability at VHE of a given \(\gamma\)-ray source with IACTs are the sensitivity\[^{\text{\textsuperscript{3}}}\] of the instrument and the flux level of the source. However, these quantities are useful for detection considerations under the hypothesis of a steady \(\gamma\)-ray emission. In case of transient \(\gamma\)-ray events, whose flux is strongly time dependent, a different approach is therefore needed. In this respect, a more useful quantity that can be considered is the significance of the observation (\(\sigma\)) as a function of time, provided an emission model for the transient source. In this way, in fact, it is possible to evaluate whether the typical detection condition \(\sigma > 5\) is achieved or not (in a certain energy interval and for different observational conditions).

The commonly used definition of \(\sigma\) for IACT observations is given in Eq. 17 of \[23\]:

\[
\sigma(N_{\text{on}}, N_{\text{off}}, \alpha) = \sqrt{2 \left( N_{\text{on}} \ln \left[ \frac{1 + \alpha}{N_{\text{on}} + N_{\text{off}}} \right] + N_{\text{off}} \ln \left[ \frac{1 + \alpha N_{\text{off}}}{N_{\text{on}} + N_{\text{off}}} \right] \right)}, \tag{1}
\]

where \(N_{\text{on}}\) and \(N_{\text{off}}\) are the number of events in the signal region of the ON and OFF \[^{\text{\textsuperscript{4}}}\] data sets, and \(\alpha\) is the ON–OFF normalization factor expressed (for real observations) as the ratio between the effective time of the ON and OFF data sets, which implies that the expected amount of irreducible background in the \(\text{ON}\) data set is \(N_{\text{bg}} = \alpha N_{\text{eff}}\).

Since \(N_{\text{on}}\) and \(N_{\text{off}}\) refer to a given energy interval \(\Delta E\) and are functions of time, the significance is energy and time dependent. In addition, in case of transient event observations, the starting time of observation \(T_0 = T_0 + \Delta T\) (where \(T_0\) is the time of the transient event burst) must be taken into account to define the initial time at which the source emission must be considered.

In order to evaluate how the significance of a given short time-scale transient event observation evolves with time, in a given energy interval \(\Delta E\) and for a given starting time of observation \(T_3\), the following quantities must be taken into account:

1. The sensitivity \(S\) of an IACT in a given energy interval \(\Delta E\) is defined as the minimum flux of \(\gamma\)-ray events in \(\Delta E\) (per unit time and area) that, in a given observation time, results in a statistically significant excess above the isotropic background of cosmic-ray initiated showers. When comparing different instruments, it is most often assumed that the source is point-like, and that its energy spectrum is a pure power-law of spectral index of \(-2.6\) (which is the Crab Nebula index around 1 TeV). A common sensitivity unit for different IACTs is the flux that will be measured with a significance (\(\sigma\)) greater than 5 in 50 hours of observations (i.e. \(S_{\gamma\text{ph}}\)). The flux is typically expressed as a fraction of the Crab Nebula flux (Crab Units, CU).

2. In the IACT observations, the OFF data set is needed to estimate the amount of irreducible background events \(N_{\text{bg}}\) in the ON data set. The number of \(\gamma\)-ray excess events in the ON data set is given by \(N_\gamma = N_{\text{on}} - \alpha N_{\text{off}} = N_{\text{on}} - N_{\text{bg}}\).

3. In this work we consider the energy bins \(\Delta E\) defined in \[21\], i.e. 5 logarithmic energy bins per decade in the 10 GeV – 100 TeV band. Hereafter, generic energy intervals are defined as \(\Delta E \equiv \Delta E^{\text{\textsuperscript{I}}} = \sum_{i} \Delta E^{\text{\textsuperscript{I}}}\) (with \(1 < j < 20, 1 < k < 20, j < k\),...}
The Spectral Energy Distribution (SED) of the event can be expressed as:

\[ N_{\gamma}^{[\Delta E]}(i) = \frac{\exp(-\alpha_i E_{\text{min}})}{\exp(-\alpha_i E_{\text{max}})} \times \frac{dN_{\text{eff}}^{[\Delta E]}}{dt} \times E_i, \]

where \( \alpha_i \) is the (average) effective collection area of the instrument in the \( i \)-th energy bin, and \( d\Phi/dE \) is the differential energy spectrum model of the given transient event emission as a function of energy and time. The effect of the \( \gamma \)-ray attenuation by pair production with EBL photons is taken into account in the spectrum model.

The number of background events as a function of time, in the energy bin \( \Delta E \), given by:

\[ N_{\text{bkg}}^{[\Delta E]}(i) = \frac{dN_{\text{bkg}}^{[\Delta E]}}{dt} \approx \left( \overline{\alpha_i} \right) \sigma_i \Delta E \]  

where \( dN_{\text{bkg}}^{[\Delta E]}/dt \) is the background rate of the instrument in the \( i \)-th energy bin. In the present work, this quantity is assumed to be independent of time and of the telescope azimuthal pointing.

The significance of a given transient event observation as a function of time, in a given energy interval \( \Delta E \), and for a given starting time of observation \( T_S \), is thus given by:

\[ \sigma_{\text{diff}}^{[\Delta E]}(i) = \sigma \left( \sum_{j} N_{\gamma}^{[\Delta E]}(i) + N_{\text{bkg}}^{[\Delta E]}(i) \right)^{1/2} \times \left( \sum_{j} N_{\text{bkg}}^{[\Delta E]}(i) \right)^{1/2} \times \alpha \]  

In Tab. 1 the main quantities needed for the calculation of the significance as a function of time (providing the transient source) for MAGIC [21] and CTA (candidate array D) [22], in 5 logarithmic energy bins between 10^4 GeV and 10^9 GeV are shown. All quantities refer to point-like source observations. For completeness, the differential sensitivities \( S_{5\sigma,50h} \) of the MAGIC telescopes and CTA (candidate array I) are also reported.

4 Test case: GRB 090102

As a test case for the detection prospect method presented in Sec. 3 we consider the GRB 090102 event. This GRB was detected and located by the Swift satellite on January 2nd, 2009, at 02:55:45 UT [21]. The MAGIC-I telescope observed GRB 090102 after ~1100 s of the event burst, deriving flux upper limits above ~50 GeV [10]. The prompt light curve was structured in four partially overlapping peaks for a total \( T_{90} \) of 27.0 ± 2.0 s. The moderate redshift of \( z = 1.547 \) implies an isotropic energy value of \( E_{\text{iso}} \sim 5.75 \times 10^{53} \) erg. According to the relativistic blast-wave model [6], we use the Synchrotron Self-Compton (SSC) mechanism to derive the expected VHE emission during the afterglow in the IACT energy range. The Spectral Energy Distribution (SED) of the event can be expressed as:

\[ E^2 \frac{d\Phi}{dE}(E,t,z) = \phi_0 \left( \frac{E}{1 \text{ TeV}} \right)^{-2 + \alpha} \left( \frac{t}{1 \text{ s}} \right)^{10 - 9 \alpha} e^{-\tau(E,z)}, \]

where \( \phi_0 = 0.78 \times 10^{-6} \text{ TeV cm}^{-2} \text{s}^{-1} \) is the normalization constant at 1 TeV and \( p = 2.29 \) is the index of the electrons power-law distribution [25], and \( e^{-\tau(E,z)} \) is the EBL absorption factor evaluated for \( z = 1.547 \) using the model by [18]. In Fig. 1 the modeled SED of GRB 090102, at three different times after the event burst, is shown. Using Eq. 1, Eq. 4 the quantities reported in Tab. 1 and the SED emission model defined in Eq. 5 we can estimate how the significance of the GRB 090102 observation would be with the MAGIC stereoscopic system and CTA as a function of time, for different observational conditions. In Fig. 2 we present the achieved results in the energy interval 63.1 < \( E \text{ [GeV]} \) < 158.5 (where, from our estimates, the GRB 090102 detection prospects turn out to be the most favourable) and for three different starting times of observation: \( T_S = T_0 + 180,600,1100 \) s. A systematic error of 50% on the effective collection area values is taken into account in the significance calculations.

As expected, the starting time of observation \( T_S \) in case

4. The \( \gamma \)-ray effective collection area values \( A_{\text{eff}}^{[\Delta E]} \) are obtained from Monte Carlo (MC) simulations and depend on the simulated energy spectrum. The values reported in Tab. 1 for MAGIC and CTA are calculated assuming a spectral power-law slope close to −2.6. In this work we use those values, although the transient event spectrum can have, locally, slopes much different from −2.6 (see e.g. Fig. 1). However, we estimated (with MAGIC MC simulations) that for tentative spectral slopes down to −3 the obtained effective collection area values are within 15% of the values given in Tab. 1 in the considered energy bins. In order to cope with this issue, and to take into account the typical assumed systematic error of the effective collection area (around 30%), we consider a systematic error of 50% on the effective collection area values reported in Tab. 1 and propagate that uncertainty in the calculation of the number of \( \gamma \)-ray excess events provided by Eq. 2.

5. We restrict our attention to these energy bins because transient events are foreseen to have VHE emission that rapidly vanish at energies of a few hundreds of GeV, due the \( \gamma \)-ray EBL absorption.
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5 Conclusions

One of the primary goals for current IACTs, like the MAGIC telescopes, and for future Cherenkov Telescope Array is to catch VHE signal from GRBs. In this contribution, we presented a method aimed at providing detection prospects for short time-scale transient events at VHE (provided their emission model), and considered the particular event GRB 090102 as a test case.

Our estimates show that, for this particular event, MAGIC follow-up observations made within a couple of minutes from the event onset would have the potential to detect the VHE component or at least to derive constraining upper limits. In fact, the steep time decay of the source (as $t^{-1.1+1.2}$) makes a MAGIC detection at later starting times ($T_S > T_0 + 200\,s$) unlikely, while interesting prospects for an afterglow significant detection in the VHE domain at such later times are possible within the CTA context.

The possibility to extend our method to other classes of variable and transient sources is going to be investigated producing reliable detection prospects at VHE for the coming age of time domain astrophysics.

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Fig. 1: The modeled SED emission of GRB 090102 from SSC mechanism at different times: $T_0 + 180\,s$ (green line), $T_0 + 600\,s$ (blue line), and $T_0 + 1100\,s$ (red line). For comparison, the Crab Nebula SED, as measured by MAGIC [21], is also drawn (dashed black line).

Fig. 2: MAGIC (blue area) and CTA (candidate array I, red area) significance of GRB 090102 observation, in the energy interval $63.5 < E[\text{GeV}] < 158.1$, for three different starting times of observation: $T_S = T_0 + 180\,s$ (upper plot), $T_S = T_0 + 600\,s$ (middle plot) and $T_S = T_0 + 1100\,s$ (lower plot). The green dashed horizontal line represents the detection threshold $\sigma = 5$. A systematic error of 50% on the effective collection area values is taken into account in the significance calculations.