PROCEEDINGS OF SCIENCE

The ASTRI Mini-Array observations of TeV transient events

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After about five years since the first detection of a very high energy (VHE) emission component from gamma-ray bursts (GRBs), efforts in improving the follow-up observation programs on transient events by the most important VHE instruments kept growing. The need to widen the accessible observational window above the TeV band has been proven by the detection of multi-TeV signals in events such as GRB 190829A and, recently, GRB 221009A. Furthermore, the association of high-energy neutrinos and gravitational waves with astrophysical sources has opened the era of multi-messenger astrophysics, potentially providing unique insights into the physics of extreme cosmic accelerators. The ASTRI Mini-Array experiment, composed of nine imaging atmospheric dual-mirror Cherenkov telescopes, is being built at the Teide Observatory site. Although not specifically thought of as a transient facility, it might play an important role in studying the TeV component in transient sources, opening new opportunities for time-domain astrophysics. The array will be equipped with a dedicated transient handler that will allow us to perform specific follow-up campaigns on a wide range of astrophysical sources like GRBs, galactic transients, and the possible VHE electromagnetic counterpart of neutrinos and gravitational waves. We studied the feasibility of detecting a TeV emission component from transient events such as on- and off-axis GRBs. This preliminary study explores the physical parameters space that would maximize the possibility of producing detectable TeV signatures from nearby events. The implementation and optimization of a possible ASTRI Mini-Array observational strategy based on specific science cases will also be discussed.

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1. Transient Astrophysics at TeV energy

The first firm detection of Gamma-ray Bursts (GRB) by Imaging Atmospheric Cherenkov Telescopes (IACTs) has proven that observations in the very-high-energy band (VHE, E>100 GeV) represent a powerful tool to study these extreme cosmic accelerators. At present, a bunch of detection has been reported by IACT such as in the case of GRB 180720B [1], GRB 190114C [2] and GRB 190829A [3]. As the VHE gamma-ray horizon is limited by absorption on the extragalactic background radiation fields, GRBs were expected to be detected mainly in the few-tens-of-GeV edge of the VHE band. However, many events have shown (somehow surprisingly) that also long-lasting TeV signatures can be detectable under favorable conditions. The close-by and very low luminosity burst GRB 190829A [3] was detected by the H.E.S.S. telescope up to few TeV for three consecutive nights while the recent detection of GRB 221009A by LHAASO up to 18 TeV [4, 5] has definitively proven that instruments operating in the energy range above few TeV band, although not specifically designed for transients and time-domain astrophysics, might play a key role in the follow-up programs of these events. In the next years, new VHE facilities such as the Cherenkov Telescope Array Observatory [7, CTAO] will start their operations opening space to new discoveries. The ASTRI Mini-Array will be one of the first entering in operation, delivering its first scientific results already during commissioning phase, that will start at the end of 2023.

The ASTRI (*Astronomia con Specchi a Tecnologia Replicante Italiana*) Mini-Array [6], consists of nine IACTs, under construction at the Observatorio del Teide (Tenerife, Canary Islands) and it will be the largest IACT array until the beginning of operations of the CTAO. Compared to currently operating IACT systems, ASTRI Mini-Array will achieve a significantly better sensitivity at energies larger than a few TeV with 50 hours of observations extending its energy range up to 100 TeV and beyond [8]. However, the ASTRI telescopes, with a primary mirror of $\sim$ 4 m diameter and distributed over an area of $\approx 10^5$ m^2, will allow us to perform observations in the 0.5-200 TeV range. Furthermore, the dual mirrors optical configuration based on a modified Schwarzschild - Couder design [9] guarantees a usable field of view (FoV) of $\sim 10°$. The degradation of the off-axis sensitivity remains in the entire energy range within a factor of ~1 (~2) of the on-axis performance up to $\sim 3°$ ($\sim 5°$). This makes the ASTRI Mini-Array an ideal instrument, among the pointed ones, for searching gamma-ray counterparts within a large (few square degrees) uncertainty sky region, such as in the case of Gravitational Wave (GW) alerts or poorly localized GRBs and neutrino events. Transient and time-domain astrophysics belongs to the ASTRI core science program [8]. A specific follow-up program of external alerts, in particular GRBs, GWs and neutrino alerts is going to be set up already during the commissioning phase. To this end, a dedicated *transient handler* system will take care of the ASTRI Mini-Array response to external triggers provided (mainly but not exclusively) by the General Coordinate Network (GCN[1]). The ASTRI transient handler will handle the communication with external resources according to their specific communication protocols, receiving and parsing the incoming alerts. The forthcoming selection of the "good" candidates alerts will be restricted to low-redshift targets (when this information is available) or to those events with the highest fluence beside a set of observability criteria that will include the zenith distance of the source and the uncertainty in the sky position provided in the alert. The system will then interface with the ASTRI Mini-Array central control [10] to provide new observation schedule

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[1] http://gcn.gsfc.nasa.gov/

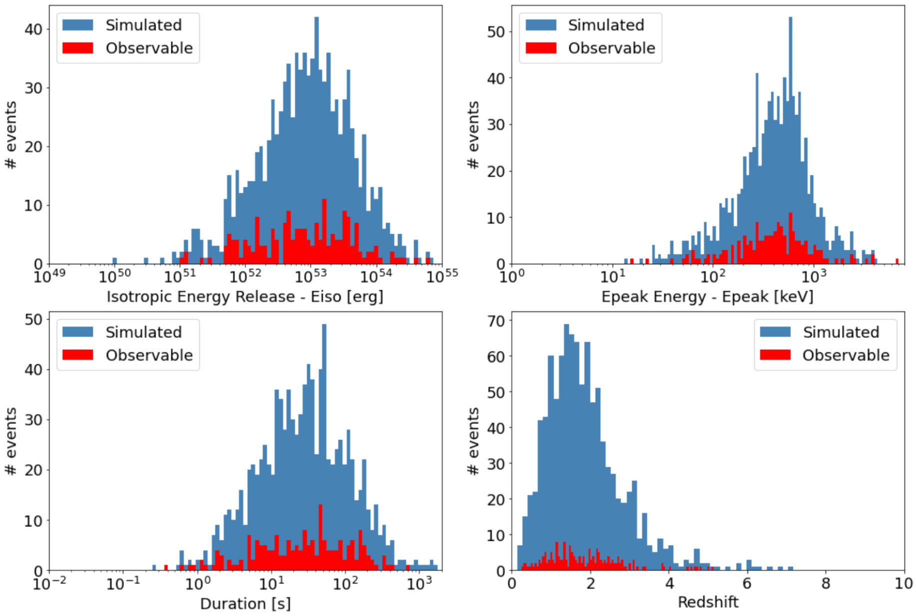

Figure 1: The distribution of the main physical parameters characterizing the synthetic GRB population. Blue histograms represents the total GRB sample while red histograms are the subsample of events observable from the ASTRI Mini-Array according to the basic visibility criteria reported in Sec. 3. Top paneles: GRB isotropic energy and E_{peak}. Bottom panels: duration and redshift distributions.

automatically triggering the telescope's repointing in order to reduce latencies in the follow-up observations. Although the repointing time of the ASTRI mini-array will not be as fast as the one of MAGIC [11] or the LST-1 prototype [12]), the nine telescopes of the array will be able to repoint on a relatively short timescale ranging from less than one up to few minutes. This will allow us to catch TeV emission from nearby GRBs in the early afterglow phase, up to tens of minutes from the burst.

In this contribution we perform preliminary investigations on the prospects for the detection of TeV emission from GRBs during the afterglow phase with ASTRI Mini-Array. We base our study on a synthetic population of long GRBs already used to perform preliminary estimates of GRB detections with CTA [13] and analyse their VHE afterglow emission with the ASTRI high-level analysis pipeline. This approach will allow us to test different follow up strategies, taking into account the sensitivity on the appropriate time scales, and study which region of the physical parameter space of the GRB population can be constrained by ASTRI Mini-Array observations.

2. The Simulated GRB sample

To perform preparatory studies in view of the ASTRI Mini-Array commissioning phase, we used a simulated sample of 1000 long GRBs which represent the brightest GRBs detectable by *Swift*/BAT. Some of the characteristics of the population are shown in Fig. 1. This sample was extracted from a synthetic GRB population [14, 15] where the basic intrinsic properties of the sources (e.g. luminosity function, redshift dependent event rate, prompt emission spectrum) are simulated and calibrated through observed samples of GRBs detected by Swift and Fermi. In simulating long

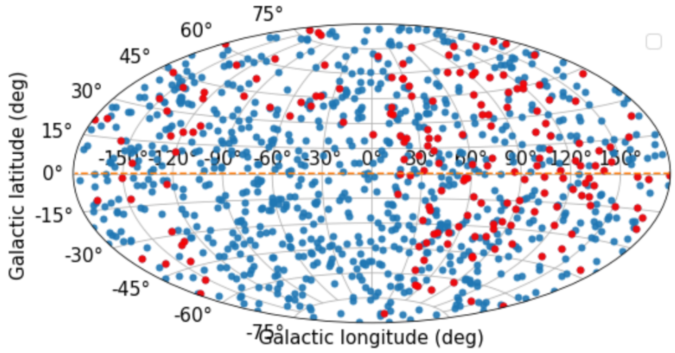

Figure 2: The sample of simulated GRBs in galactic coordinates. Blue points are the full sample while red points are the events observable from the ASTRI Mini-Array site.

GRBs, it is also assumed that there is an instrinsic correlation between their isotropic energy (E_{iso}) and the peak of their nuFnu spectrum (E_{peak} - so called Amati correlation [16]). In order to derive the final expected spectrum (and light curve) for each event, the afterglow emission is modeled according to a widely-used leptonic synchrotron and synchrotron self-Compton model (SSC) [17]. Within this theoretical framework, synchrotron radiation from high-energy electrons accelerated in relativistic shocks is responsible for the observed GRB sub-GeV emission. An extra component, dominant in the VHE band and whose existence was proven by recent IACT observations, is generated by the synchrotron photons Compton up-scattered by the same electrons accelerated in relativistic shocks [see e.g., 17].

3. Prospects with the ASTRI Mini-Array

We tested the capabilities of the ASTRI Mini-Array to detect and investigate the properties of a sub-sample of bright GRBs. We used the synthetic GRB spectra and light curves obtaining the number of detected events using the ASTRI Mini-Array official instrument response function (IRF) [18] and publicly available science tools commonly used in the VHE community (e.g. gammapy [19]). The IRFs are produced by means of dedicated Monte-Carlo (MC) simulations of gamma-ray and background (protons and electrons) showers, analyzed with the analysis software of the ASTRI Project [20]. A complete set of IRFs for the ASTRI Mini-Array covering different zenith angles and optimised for different exposure times are currently under production and not yet available at the time of this writing. To evaluate the detectability of each GRB, we make use of a single IRF optimized at 20° of zenith and 50h of observing time. The latter is clearly an observing time not optimized for short time-scale transients, thus the reported numbers have to be considered preliminary. The visibility of each GRB is evaluated according to an observing strategy that includes a maximum zenith angle for the alert to be observable of 60°, zenith of the sun $> 105°$ and an angular distance from the Moon $> 30°$ (Fig. 2). The maximum observation time window (OTW) from the GRB onset is considered to be 4 h. This strategy accounts for a total of 185 events observable within the OTW, corresponding to a duty cycle of $\sim$ 18% that is compatible, taking into account the reduction that might be attributed to non-optimal weather conditions, to the duty cycle reported by other IACT ($\sim$ 10%). The aitoff projection of the GRB (full sample and

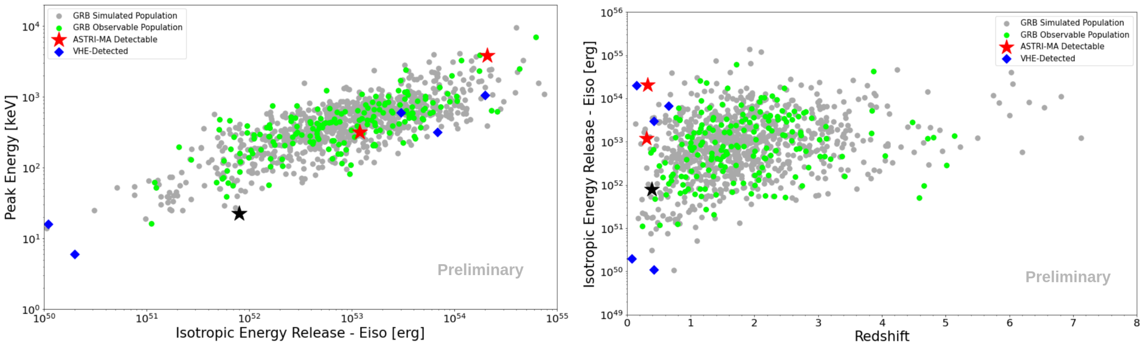

Figure 3: The empirical correlation (Amati relation) between the isotropic equivalent energy $E_{\rm iso}$ and the peak energy (left panel) and the Eiso vs redshift distribution (right panel) reproduced for the full synthetic GRBs population (grey points) and the sub-sample of GRBs visible from the ASTRI location (green points). Red stars are the GRBs that resulted as detectable by the ASTRI Mini-Array. Black star is an event that shows hint of detection. As a reference, blue diamonds represent the positions of the GRBs already detected in the VHE band.

observable ones) is showed in Fig. 2. For each of the observable events, the observation windows is evaluated. In case the GRB is immediately observable, we assume a total delay of the ASTRI Mini-Array system (processing of the alert and corresponding repointing of the telescopes) to be of 100 seconds. The corresponding theoretical spectrum (at the beginning of the observation) and light curve are used to generate a spectral-temporal template simulating the GRB using Gammapy version 1.1.

Preliminary results on the ASTRI Mini-Array detectabilty prospects are summarized in Fig 3. Although the statistic of the GRB population reported in this work is still rather limited to draw firm conclusions, from the energetic point of view, GRBs with moderate $E_{\rm iso}$ ($\gtrsim 10^{53}$ erg) can be easily detectable by the ASTRI system. Such an energetic release is rather common within GRBs. However, due to the relatively high energy threshold of the system ($\sim 0.5 - 1$ TeV depending on the observability conditions), the possibility to detect the very high energy emission component is mainly limited by the GRB distance and the corresponding EBL absorption. From this preliminary study, detection would be limited to those events with redshift $\lesssim 0.5$. These results confirm the first estimate obtained in [21] by using GRB 190114C as a template for the VHE emission. It is important to remark that these detections are achieved even considering a delay in the follow-up observation up to ~2 minutes from the GRB onset, a delay that is well within the ASTRI Mini-Array hardware performance.

Our preliminary analysis is based on a synthetic sample of very bright GRBs and does not include dimmer events, which are detectable at low redshifts by *Swift* and other GRB satellites. Due to the largely reduced effect of EBL at low redshift, these events may also be detectable with ASTRI. Moreover, given the large FoV of ASTRI, also poorly localised GRBs (such as those detected by Fermi-GBM) can be followed-up and will play an important role. Considering the detection rate of *Fermi*-GBM and *Swift*-BAT and the estimates presented in this work, we predict a detection rate of about ~ 0.2 GRB yr^{-1}.

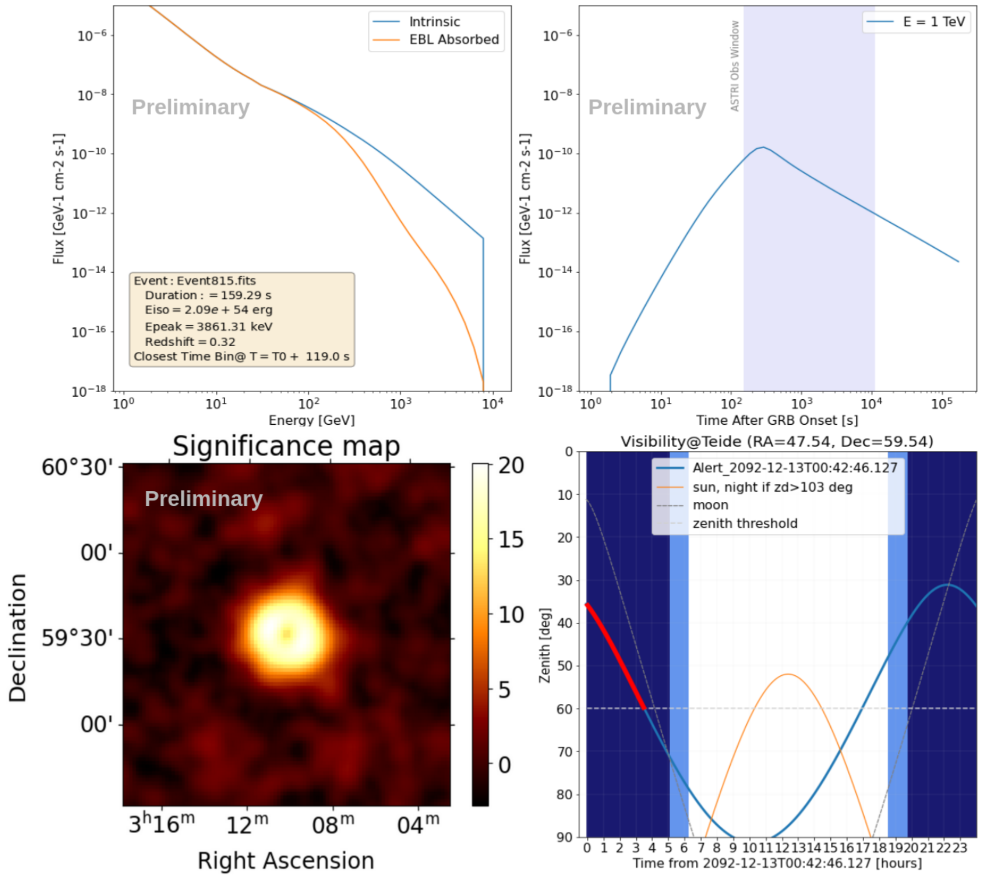

Figure 4: The final outcome of the high-level analysis pipeline for one of the GRB detectable by ASTRI Mini-Array. From top to bottom: spectrum (intrinsic and EBL-absorbed) at the first time of observation and 1 TeV light curve of the event with the corresponding ASTRI observational window evaluated according to the strategy described in Sec. 3. Significance skymap for the observing time and conditions reported in the corresponding visibility plot from the Teide Observatory.

4. Gravitational Waves

The recently started LIGO-Virgo scientific run O4 has shown a significant increase of the number of GW triggers delivered to the astrophysical community. Although TeV emission has not been established yet, the detection of a hint of VHE emission from the short GRB 160821B [22] has proven that also short-GRBs (that are proven to be the GW electromagnetic counterparts) might host a second emission component up to the TeV band. In the case of GW signal, the possible VHE counterpart is associated to the off-axis beamed emission from the short GRB itself, likely reducing, with respect to the on-axis emission (as assumed in normal GRB), the possibility to detect such a VHE signal from these events. Nonetheless, due to the sensitivity of current interferometers, GW horizon is limited to few hundreds of Mpc so that a possible VHE source located at such a nearby distance should be considered of crucial importance as a possible ASTRI Mini-Array target. Furthermore, the rather large FoV of the ASTRI Mini-Array, is particularly suitable for tiling observations that are needed to cover the typical localization uncertainty region characterizing a GW trigger. In parallel to the above-described study on GRB follow-up, a dedicated study is ongoing to evaluate the ASTRI Mini-Array performance on GW follow-up. To this end, a sample of short GRB will be associated to a set of simulated binary neutron star (BNS) mergers extracted from the public database GWCOSMos [23] providing the GW skymap, distance and orientation of the GW trigger. The corresponding VHE emission is derived from the empirical correlations between the X-ray and TeV luminosities as in GRB 190114C. The optimal pointing strategy is then obtained by a dedicated algorithm in order to efficiently cover the sky area of the GW source while the high-level analysis pipeline presented here will be used to evaluate the expected GW detection rate. The outcome of this study will be the subject of a forthcoming dedicated publication.

5. Conclusions

The preliminary study presented here shows the potential of the ASTRI Mini-Array system in detecting transient events such as GRBs and GWs in the energy range above 0.5-1 TeV. The detection of VHE signal from GRBs has been achieved by current generation VHE facilities and it surprisingly showed emission up to the ~few tens of TeV band like in the case of the LHAASO detected GRB 221009A. The ASTRI Mini-Array will start its commissioning phase at the end of 2023 and will be able to perform follow-up observations on a wide range of transient events such as GRBs and GWs. This preliminary study focused on GRBs showed the feasibility of the ASTRI Mini-Array to detect TeV emission from nearby GRBs ($z < 0.5$), assuming a lepton synchrotron self-Compton component at work in all the events. The main limitation is not represented by the intrinsic property of the GRB (energetic) but mainly by distance and corresponding EBL absorption. A detailed estimate of the expected detection rate is ongoing and will include full samples of Swift and Fermi-GBM GRBs. A parallel effort to show the feasibility of the ASTRI Mini-Array in the follow-up of GW triggers is also currently ongoing where the optimization of the strategy for the selection of the alerts, and for the tiling observations is also being developed.

Acknowledgments

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