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TeV Transients with the ASTRI Mini-Array: a case study with GRB 190114C

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The recent discovery of a teraelectronvolt (TeV) component in a few long GRBs and possibly in the short GRB 160821B, deepened the insight on GRB physics and opened the new TeV window in their observation, and in the study of the multi-messenger counterparts, e.g. gravitational waves. The exact nature of the TeV component and the details on the implications on the emission region need to be confirmed with successive detections. The planned ASTRI Mini-Array, composed of nine imaging atmospheric dual-mirror Cherenkov telescopes at the Teide Observatory site, will play a crucial role in the study of the new TeV component, by further extending the explored range to energies greater than few TeV. We have studied the capabilities of the ASTRI Mini-Array to detect transients using the observed and modelled TeV light curve and spectrum of GRB190114C as a template to simulate the emission from GRBs, rescaled for shorter cosmological distances. The proper amount of absorption due to the extragalactic background light (EBL) has been included. The simulations show the feasibility of the detection of TeV emission by the ASTRI Mini-Array from GRB 190114C, and the ability to confirm the afterglow emission from nearby GRBs, at redshift between about 0.1 and 0.4. The spectrum can be measured at energies between 1 and 10 TeV, up to few minutes from the onset of the burst. In case of detection, for the closest and bright bursts, the ASTRI Mini-Array can reveal the presence of a > 1 TeV spectral cutoff, either originated by the EBL absorption or intrinsic.

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1. Transient astronomy with the ASTRI Mini-Array

Multi-messenger and time-domain astronomy emerged in the past few years as two crucial and revolutionary branches to study the most extreme phenomena in the Universe and to provide complementary information on their astrophysical nature and environment. The direct detection of gravitational waves (GW)[1] and of astrophysical neutrinos[2], and their association with electromagnetic counterparts[3, 4] ushered in this new phase of the study of the extreme Universe. Very-high-energy (VHE, $> 100\,\mathrm{GeV}$) gamma rays are the bridge between these two major fields, being emitted in extreme processes associated to the production of high-energy neutrinos in cosmic ray accelerators, such as supernovae remnants, jet formed from accreting compact objects, and to the production of GW in stellar collapses, compact object mergers. Most of these processes are common in transient and highly-variable emitters, such as blazars, microquasars, magnetars and gamma-ray bursts (GRBs). Examples of recent, major advances with VHE observations, are the discovery of TeV radiation from GRB 190114C [5], followed by the announcement of TeV emission from other GRBs [6, 8–11], and the observation of VHE radiation from the blazar TXS 0506+056 in association with the detection of an astrophysical neutrino by the IceCube observatory [4]. The expected improvements in the VHE detection instruments and techniques in the next years are paving the road to a thriving multi-messenger and transient astrophysics with the VHE gamma rays [12].

The ASTRI Mini-array is along this path and will deliver its first scientific results during and soon after the commissioning phase, that will start in 2023. The ASTRI (*Astronomia con Specchi a Tecnologia Replicante Italiana*) Mini-Array [13, ASTRI Mini-Array], consists of nine imaging atmospheric Cherenkov telescopes (IACTs), under construction at the Observatorio del Teide (Tenerife, Canary Islands). The telescopes, having a relatively small reflective area with a primary mirror of $\sim 4\,\mathrm{m}$ diameter, will be distributed over an area of $\approx 10^5\,\mathrm{m}^2$, yielding a correspondingly wide collection area. The large collection area together with its large field of view of $\sim 10^\circ$, will allow us to observe gamma rays in the 0.5-200 TeV range. The differential sensitivity at energies $\sim 1\,\mathrm{TeV}$, for 50(0.5) hours of integration time, is $\sim 2(20) \times 10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ and scales approximately with the square root of the time (see figure1, and refer to [14] for more details on the performance of the ASTRI Mini-Array). The degradation of its sensitivity for offset angles is contained within a 10–20 % up to 3.5°; the degradation reaches 40–50 % for an offset angle of $\geq 4.5^\circ$. 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 GW and neutrino events (see section3).

The scientific program of the ASTRI Mini-Array is based on a science core program addressing fundamental question in Galactic, extra-galactic and time-domain astrophysics [16]. The transient and time-domain section of the core-program foresees the follow-up of a few selected alerts provided on GRBs, on GW events and on high-energy neutrinos. Alerts are distributed through the GCN network within few seconds to few minutes from the burst detection. ASTRI Mini-Array will observe as target-of-opportunity (ToO) a selected sample of VHE transient candidates within several seconds to few minutes from the communication of the alert. The selection of good candidates will be restricted to low-redshift targets, when this information is available, or to those events with the highest fluence. The requirement on the redshift is a consequence of the strong absorption

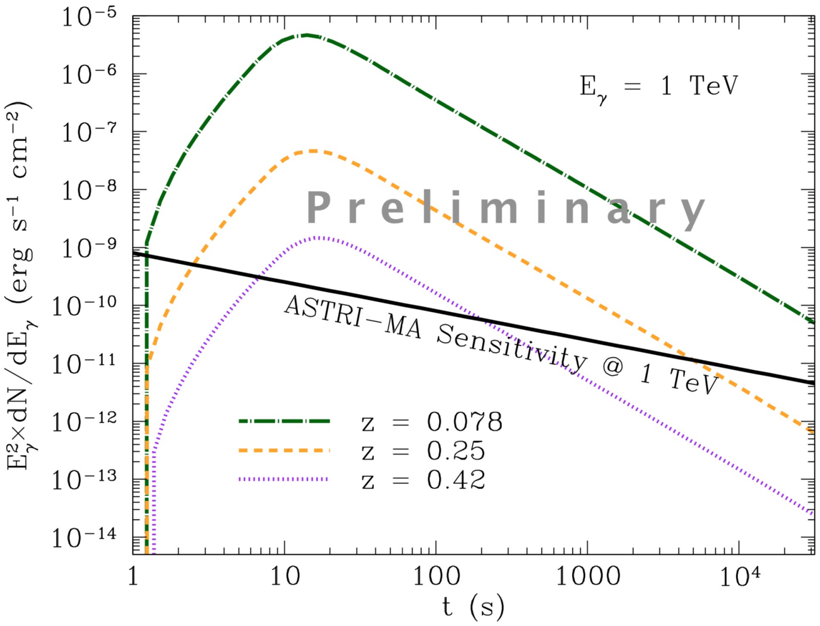

Figure 1: Simulated light curves of three GRB190114C-like GRBs, at distances of $z = 0.42$, $z = 0.25$ and $z = 0.078$.The black line shows the sensitivity of the ASTRI Mini-Array at 1 TeV, rescaled for the corresponding integration time on the x-axis.

by the ultraviolet to infrared extragalactic background light (EBL) affecting the VHE gamma-rays. The absorption increases with the energy of the radiation, limiting the maximum distance of the detectable sources. Such gamma-ray horizon (opacity greater than 1) can be approximately set at $z \sim 0.3$ for energies $\sim$ 1 TeV, and $z \sim 0.1$ at $\sim$ 10 TeV. Further criteria will be set on the observational conditions (e.g. the sky position should be immediately observable at zenith angles $< 60°$) and on the uncertainty in the sky position provided in the alert, that should be comparable or smaller than the FoV of ASTRI, namely few tens of square degrees). We estimate that the selection criteria will limit the observed transient candidates to a few per year.

In this contribution we provide a glance in the preliminary studies towards the search of the energetic gamma-ray counterparts of GRB, GW and neutrino astrophysical sources, to demonstrate the feasibility of the transient program with the ASTRI Mini-Array.

2. A study case: prospects with GRB190114C-like gamma-ray bursts

The detection of VHE emission from the GRB 190114C at $z = 0.42$ by the MAGIC telescopes [5] did reveal a new energetic component stemming from the GRB afterglow. MAGIC observations, complemented by multi-wavelength observations [17], interpreted the new and energetically relevant component in GRBs, as possibly due to synchrotron self Compton (SSC) emission, extending into the TeV energy range. The production of VHE radiation in GRBs and its detectability by Cherenkov telescopes have been confirmed by the observations of three additional events, two by the H.E.S.S. telescopes hours after the burst (GRB 190829A at $z = 0.078$ and GRB 180720B at $z = 0.65$, [6, 8]) and one by the MAGIC telescopes, starting $\sim$ 1 minute after the burst (GRB 201216C at $z = 1.1$,

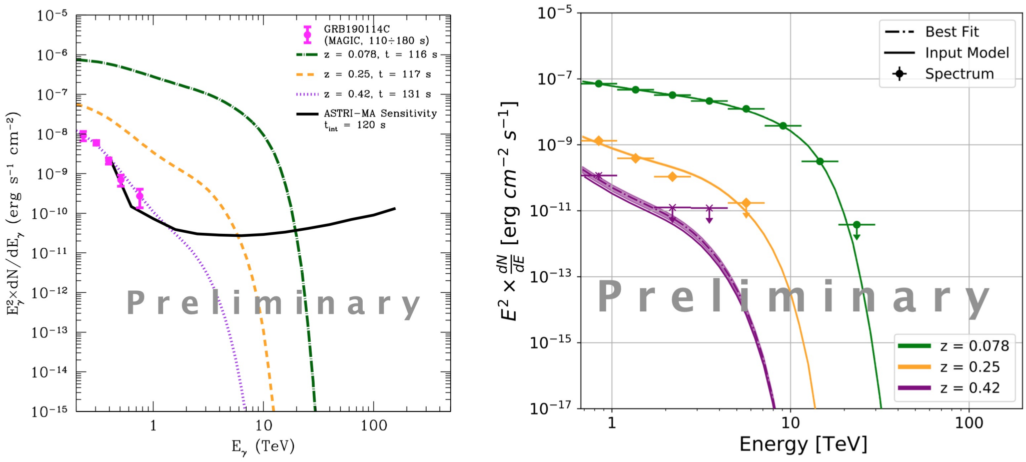

Figure 2: Left: SEDs of the three simulated GRBs, computed at about 2 minutes after the burst. The black line shows the differential sensitivity of the ASTRI Mini-Array for an integration time of 2 minutes. The data points superimposed to the SED for $z = 0.42$ are the spectral points measured by MAGIC on GRB 190114C, in the time interval 110-180 s. Right: simulated spectra of the three synthetic GRBs, as would be observed by ASTRI Mini-Array after 200 s, with an integration time of 600 s.

[9]). The maximum energy observed is limited by the EBL absorption, and in the case of the nearest GRB 190829A photons up to several TeV were detected [8]. The extension in energy of this new emission component up to several TeV opens to the possibility of GRB studies with the ASTRI Mini-Array.

In particular, in the case of nearby GRBs, the ASTRI Mini-Array can complement the measurement of the spectral shape and evolution at energies > 1 TeV of the VHE component, whose exact nature still need to be investigated. The follow-up program of transients with the ASTRI Mini-Array, foresees the selection of alerts of nearby and bright GRBs that can be followed under favorable observing conditions.

The capability of the ASTRI Mini-Array to detect and investigate the properties of gamma-ray bursts was tested using as a template the spectrum and lightcurve of the TeV-GRB 190114C. The SSC theoretical model and model parameters describing the multi-frequency SED of GRB 190114C [17], was used to predict the time evolution and spectra at energies higher than 1 TeV, relevant for the ASTRI Mini-Array. Spectrum and lightcurve of GRB 190114C were then rescaled at shorter cosmological distances: at $z = 0.078$, corresponding to the redshift of GRB 190829A, detected by H.E.S.S., and the intermediate redshift $z = 0.25$. The EBL absorption at that distance was computed from [19].

Figure 1 and figure 2 show the synthetic lightcurves and spectra obtained at the three different redshifts. In the SED, computed at $E > 200$ GeV, the spectral points on GRB 190114C are shown, as measured by MAGIC ≈ 2 minutes after the burst. The lightcurve is computed at 1 TeV, and the corresponding ASTRI Mini-array integral sensitivity at $E > 1$ TeV, for an integration time scaling with the logarithmic time-scale, is shown. As expected, a GRB with similar luminosity as GRB 190114C at smaller redshifts, increases its observable emission considerably, thanks also to the smaller attenuation caused by the EBL. These results already show that ASTRI Mini-Array would have been possibly detect GRB 190114C, if pointed within two minutes from the burst.

The response of the ASTRI Mini-Array, and its capability to reconstruct the spectrum of the GRB in the three different cases, was also evaluated. An observation starting 200 seconds after the burst and lasting 600 s was assumed. The simulations were performed with the `ctools` [18, v. 1.6.3][1] analysis package. The ASTRI Mini-Array instrument response f unctions (IRF) as described in [14]), was used. Such IRFs have been extracted from a dedicated Monte-Carlo (MC) production of gamma rays and background (proton and electron) showers that have been analyzed with A-SciSoft, the data reduction and scientific analysis software of the ASTRI Project [15]. The results are reported in Fig. 2, showing the spectra reconstructed by he ASTRI Mini-Array for the three synthetic GRBs. The simulations clearly show the feasibility of the detection of TeV emission by the ASTRI Mini-Array, and its ability to confirm the afterglow emission at $E > 1$ TeV from close GRBs at redshift smaller than ~ 0.4. In these cases, the spectral cutoff can be measured (intrinsic or originated by the EBL absorption).

3. Alerts from neutrino and gravitational waves

The number of GRBs that are expected to be observable by the ASTRI Mini-Array shortly after the burst is expected to be of the order of ~ 1 per month, as can be deduced from the records of GRB observed by the MAGIC telescopes [20]). The constraints on distance, fluence and good visibility conditions (see section 1) will further reduce this number.

3.1 Gravitational waves follow-up

On the contrary, GW alerts are expected with a higher rate during the LIGO-Virgo-KAGRA scientific run O4 (expected to start in 2022[2]). The number of GW alerts to be followed by the ASTRI Mini-Array will be reduced to a handful per year, selecting the most promising candidates for a detection, tuning the parameters defining the visibility (e.g. small area of the uncertainty region) or the physical parameters provided with the alert (e.g. distance, or nature of progenitor).

TeV emission from GW events is not yet established. Follow-up observations of GW 170817A by H.E.S.S. resulted only in upper limits on the VHE flux [21]. On the other hand, a hint of TeV emission from a short GRB (observed in association with a Kilonova) was found by MAGIC in GRB 160821B ($z = 0.16$) [11]. This hint opens the possibility to the detection of TeV emission from GW events, in consideration of the association of the coalescence of binary neutron stars and their GW emission with short GRB, as proved by GW170817. However, the GW events would preferentially be associated to the off-axis beamed emission of short GRB, as in GRB170817, thus reducing their flux and the chances of detecting their TeV emission, that would be weaker than in the case of a GRB seen on-axis. The hunt is nevertheless open, and ASTRI Mini-Array can contribute, also thanks to the vicinity of the GW counterparts, specifically of binary neutron stars, expected within few hundreds of Mpc.

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[1] http://cta.irap.omp.eu/ctools/.

[2] Refer to this web page for live updates on the run plans: `https://www.ligo.org/scientists/GWEMalerts.php`

3.2 Energetic neutrino follow-up

High-energy ($\geq$ 100 TeV) neutrino events have been associated to flaring activity in blazars, although a clear, highly significant, association is still missing, due to the intrinsic variability of this class of sources. For TXS 0506+056, the gamma-ray blazar first associated to a VHE neutrino event [4], the flaring activity observed at GeV-TeV energies was observed a few days after the IC-170922A detection alert [22], and did last several days. Since neutrino events are not yet associated to fast transients, their ToO observations with the ASTRI Mini-Array are not required to begin close to the neutrino alert, as in the case of a GRB. In these cases, the ToO with the ASTRI mini-array will be evaluated depending mainly on the detection of enhanced MeV-GeV activity from sources positionally and temporarily coincident with the neutrino coordinates and trigger time. Also, high hard-X-ray state from known AGN blazars will be evaluated, up to few days after the trigger time, together with the redshift of the candidate, due to the strong absorption by EBL at energies higher than $\sim$ 10 TeV (see section 1). For these reasons, we do expect only few triggers per year to be selected and interesting for a follow-up with the ASTRI mini-array. The association of energetic neutrinos with hadronic emission processes makes the ASTRI Mini-Array an ideal instrument to explore the region at energies below 100 TeV. In fact, in this energy range, ASTRI Mini-Array is complementary to the IACTs presently in operation, optimal at energies below 10 TeV (and for more distant sources, given the lower EBL absorption below 10 TeV), and to ground-instruments like HAWC and LHAASO.

4. Conclusions

The preliminary study presented here, shows the feasibility of the ASTRI Mini-Array to detect bright and nearby GRBs. Future work will be devoted to compute the expected rate of GRB and the joint GW-VHE rate with the ASTRI Mini-Array. The implementation of a dedicated fast response to repoint the array at the burst sky-location is being implemented [13]. The optimization of the strategy for the selection of the alerts, and for the tiling strategy (in case of GW and neutrino alerts), is being developed.

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