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Science with the ASTRI mini-array for the Cherenkov Telescope Array: blazars and fundamental physics

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Abstract. ASTRI (“Astronomia a Specchi con Tecnologia Replicante Italiana”) is a flagship project of the Italian Ministry of Research (MIUR), devoted to the realization, operation and scientific validation of an end-to-end prototype for the Small Size Telescope (SST) envisaged to become part of the Cherenkov Telescope Array (CTA). The ASTRI SST-2M telescope prototype is characterized by a dual mirror, Schwarzschild-Couder optical design and a compact camera based on silicon photo-multipliers. It will be sensitive to multi-TeV very high energy (VHE) gamma rays up to 100 TeV, with a PSF $\sim 6'$ and a wide (9.6°) unaberrated optical field of view. Right after validation of the design in single-dish observations at the Serra La Nave site (Sicily, Italy) during 2015, the ASTRI collaboration will be able to start deployment, at the final CTA southern site, of the ASTRI mini-array, proposed to constitute the very first CTA precursor. Counting 9 ASTRI SST-2M telescopes, the ASTRI mini-array will overtake current IACT systems in differential sensitivity above 5 TeV, thus allowing unprecedented observations of known and predicted bright TeV emitters in this band, including some extragalactic sources such as extreme high-peaked BL Lacs with hard spectra. We exploited the ASTRI scientific simulator *ASTRIsim* in order to understand the feasibility of observations tackling blazar and cosmic ray physics, including discrimination of hadronic and leptonic scenarios for the VHE emission from BL Lac relativistic jets and indirect measurements of the intergalactic magnetic field and of the extragalactic background light. We selected favorable targets, outlining observation modes, exposure times, multi-wavelength coverage needed and the results expected. Moreover, the perspectives for observation of effects due to the existence of axion-like particles or to Lorentz invariance violations have been investigated.

1. Introduction

The Cherenkov Telescope Array (CTA) project is an initiative to build the next generation ground-based very high-energy gamma-ray instrument [1]. It will serve as an open observatory to a wide astrophysics community and will provide a deep insight into the non-thermal high-energy universe, owing to a significant boost in the performance with respect to current



arrays of Imaging Atmospheric Cherenkov telescopes (IACT) such as H.E.S.S., MAGIC and VERITAS. A recent review of the IACT field can be found in [?] while the status of CTA is reviewed in detail in these proceedings [3]. Within the CTA framework the Italian National Institute for Astrophysics (INAF) is leading since 2011 the “Astrofisica con Specchi a Tecnologia Replicante Italiana” (ASTRI) Flagship Project of the Ministry of Education, University and Research. This project aims to design and develop an end-to-end prototype of a CTA small-size telescope in a dual-mirror configuration (SST-2M). The ASTRI SST-2M prototype, installed at the INAF “M.C. Fracastoro” observing station in Serra La Nave (Mount Etna, Sicily) was recently inaugurated during the CTA Consortium Meeting held in the nearby Giardini Naxos in September 2014. This prototype is currently being tested under field conditions, and will soon start the Scientific Verification Phase eventually aiming to assess the instrument performance by means of observations targeted at bright TeV sources such as the calibration standard Crab Nebula and the bright extragalactic sources Mrk 421 and Mrk 501. It will be sensitive to multi-TeV very high energy (VHE) gamma rays up to 100 TeV, with a PSF $\sim 6'$ and a wide (9.6°) unaberrated optical field of view. Details on the ASTRI project and the ASTRI SST-2M prototype can be found in [4], while the Monte Carlo simulations assessing the performance of the telescope are described in [5]. The ASTRI SST-2M will allow single-dish observations of the extended air showers, assessing the end-to-end performance of the single unit. A collaborative effort, within the CTA framework, is being carried on by Italy, Brazil and South-Africa aiming to deploy to the final CTA Southern site, once it is established, an array of 9 ASTRI SST-2M telescopes, proposed as a precursor of the full CTA. The ASTRI mini-array will likely be commissioned in 2017 and begin its verification phase in 2018. It will be able to verify the wide FoV performance to detect very high energy showers with the core located at a distance up to 500 m and to compare the actual performance with the expectations from Monte Carlo simulations, by means of deep observations of a few selected targets. Moreover, the ASTRI mini-array will allow us to perform the first CTA “early science”, with its first solid detections during the first year of operation, as described in [6]. Preliminary Monte Carlo simulations of the performance of the mini-array are described in detail in these proceeding [7]; these yield a point source sensitivity that, for 9 telescopes, improves the one of H.E.S.S. above 10 TeV, up to 100 TeV. The ASTRI mini-array will be able to study in great detail relatively bright (a few $\times 10^{-12}$ erg cm $^{-2}$ s $^{-1}$ at 10 TeV) sources with an angular resolution of $\sim 6'$ and an energy resolution of about 10–15 %. Remarkably, while the sensitivity is significantly worse than that of the full SST array planned for CTA, energy and angular resolution are closer to the ones for the 70 telescopes. This is due to the fact that few events are expected to trigger more than 9 units for the assumed 257 m spacing, and the accuracy in the reconstruction of each shower image is not improved by adding telescopes, while event statistics of course grows with the extension of the array. Under this respect, the mini-array can be seen as a “building block” of the full SST array. More details on the ASTRI mini-array can be found in [4] and references therein.

2. Preliminary scientific simulations for the ASTRI mini-array

In order to assess the scientific potential of the ASTRI mini-array, a scientific simulator has been developed within the ASTRI Collaboration, **ASTRIsim** [8]. The simulator makes use of the Instrument Response Function (IRF) for the array, using at present the results from the so called “CTA prod 2” ([9]). This provides, at each energy, the effective area, the energy resolution, and the background rate, computed for observations at small angular distance from the zenith (Zenith Angle, or ZA $\simeq 20^\circ$). Given a distribution of point sources described by their spectra and nominal positions, the direction in the sky and the effective on time of the observation, an event list is produced in output, allowing to produce skymaps, compute significance of detections and hence fluxes, spectra and lightcurves, or upper limits.

SSTs are optimised for hard spectrum source observations, which will favour galactic source

observations; in this field preliminary simulations for the ASTRI mini-array are ongoing on many targets, mainly pulsar wind nebulae, supernova remnants, micro-quasars. A few preliminary results can be found in these proceedings [4] or in previous works such as [10].

In parallel, a work aiming to assess the potential of the system for observations of extra-Galactic sources has been initiated. The energy band $E \gtrsim 10$ TeV corresponds to the hard tail of the Inverse Compton peak of High-Peaked BL Lacs (HBL). This band is therefore interesting for probing the far end of the distribution of accelerated particles, possibly hinting at the involved particles and to the acceleration mechanisms. On the other hand, at these energies observed fluxes are effectively suppressed by pair production against the Extragalactic Background Light (see e.g. [11]) even for the nearest sources such as the two bright Mrk 421 and Mrk 501 at $z \sim 0.03$. In turn this makes these sources effective probes of the poorly known (but see e.g. [12]) infrared background at wavelengths $\lambda > 10\mu m$, where stellar radiation reprocessed by dust fills the evolved Universe. Deeply linked to this, the multi-TeV power emitted by blazars can be effectively use to constrain (in intensity and coherence length) the Inter-Galactic Magnetic Field (IGMF), another key cosmological ingredient (see e.g. [13]). Moreover, claimed anomalies in the opacity of the Universe to VHE gamma rays could hint to the existence of new particles extending the Standard Model, such as the Axion-Like Particles (ALPs), also viable WIMP candidates for the constituents of the Dark Matter (see e.g. [14]). Eventually, one of the measurable effects of the Lorentz Invariance Violation due to effects of Quantum Gravity arising at the Planck scale, could be an anomalous transparency of the Universe at $E \simeq 20$ TeV [15, 12] that could be effectively observed exactly in the passband where the ASTRI mini-array leads current IACTs in sensitivity, provided that a convenient (in flux, spectrum and distance) TeV beacon is available. On top of the bright Markarians, that expecially during flares proved to emit photons at $E \simeq 20$ TeV, suitable candidates could be constituted by the so called Extreme HBLs (EHBL) where the IC peaks well above several TeV. Just a handful of these sources are known at present: the archetypal ones are 1ES 0229+200 and 1ES 0347-121, while some others are known both in the Northern and in the Southern Sky [16]. Criteria are under test to select EHBLs from the behaviour at lower energies (e.g. [17]) while it is arguable that HAWC [18] will effectively survey them in the local Universe. These sources also appear to be steady, at variance with more standard HBL, possibly hinting at an origin of the observed VHE flux in a large region faraway from the central engine, perhaps in EBL and CMB mediated cascades initiated or by primary photons emitted in the jets, or by primary UHE protons (see e.g. [19, 20, 21]). It has been shown that detection of photons at $E > 20$ TeV from 1ES 0229+200 by CTA would favor the latter [20] and we tried to assess the potential of the ASTRI mini-array in tackling this issue already during the CTA early science phase. The steady emission is also a key observational issue, allowing to integrate long exposure times. In order to assess the potential of the ASTRI mini-array on hard and bright flares of nearby HBLs, we assumed a large Mrk 501 flare (see Figure 1, left panel) such as the one observed up to several TeV by VERITAS (blue filled triangles) in 2009, in 2.5 h over 3 days [22]. This flare occurred during a longer active state, observed by ARGO (red open squares) up to ~ 20 TeV [23]. The ARGO spectrum, averaged on a few weeks and the VERITAS spectrum are compatible within errors, and a simple powerlaw with photon index $\Gamma = 1.9$ (green dashed line) can account for the observed SED once EBL absorption [11] is considered (red solid line). This flare is also consistent with the giant 1997 flare observed, up to 20 TeV, by HEGRA [24]. We simulated 2 h of integration (Figure 1, middle panel, VERITAS data in magenta), and 20 h (right panel, ARGO data in green), assuming that only one night, or several nights of a prolonged flare can be observed respectively. In both cases the ASTRI mini-array outperforms VERITAS and ARGO, allowing precise measurement of the far end of the spectrum at TeV, constraining either the source model or the EBL depending on the assumptions. From the CTA-South site the northern Mrk 501 is observable at best at $z \simeq 65^\circ$. This limits the probability that such a flare is actually observable by the ASTRI mini-array

and requires dedicated simulations (in progress). However as far as hard and bright HBLs are concerned, no obvious alternative to Markarians is available in the Southern sky (PKS 2155-300 has never shown comparably hard spectra even in giant flares such as the one in 2006). Another request is that a fast trigger from wide field instruments such as Swift/BAT, or Fermi/LAT, or from optical or e.g. HAWC is received and promptly followed.

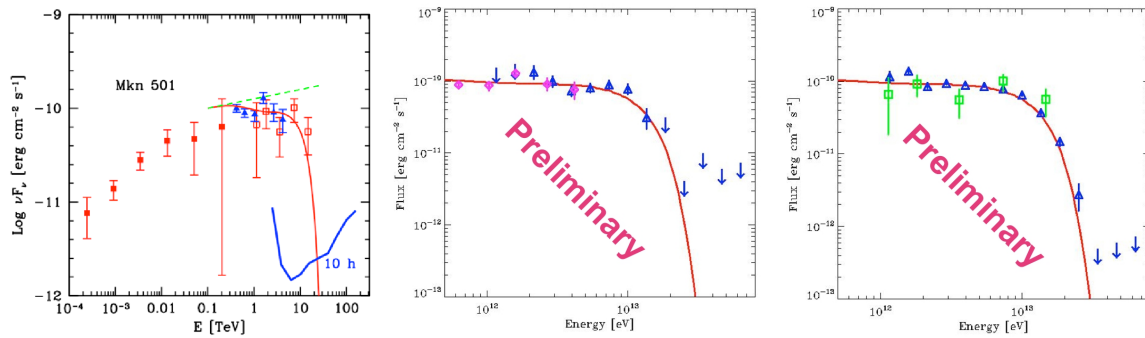


Figure 1. See text.

In the field of EHBLs, we first considered the possibility to discriminate the photon-induced and proton-induced cascade spectra proposed by [20]. Left panel in Figure 2 shows the γ -ray SED of 1ES 0229+200 as measured by Fermi/LAT (black filled squares) and H.E.S.S. (red triangles). A hard ($\Gamma = 1.3$) unbroken intrinsic power law spectrum is compatible with observations. Photon-initiated (solid light green) and hadron-initiated (dashed black) cascade emission can be distinguished above 10 TeV. The ASTRI mini-array 5σ , 0.2 dex bin, sensitivity curve for point sources in 50 h (dashed red) and 100 h (solid red) observations are displayed, as well as the 1 year (dashed cyan) and 5 year (solid cyan) HAWC sensitivity curves for comparison. Both models are barely grazed by the ASTRI mini-array differential sensitivity curve, even for 100 h. We tried to assess if the integrated excess could separate the two cases. We simulated 1000 times 100h of observations for each model, finding two distributions of the outcome excess that can be in principle rejected from the real observation at some CL (Figure 2, middle panel). Then we considered the possibility that an anomalous transparency effect due to LIV is present, for various values of the mass scale. For an unbroken hard spectrum, this produces an upturn at $E > 20$ TeV. Again we find that for mass scales M_{QG} in the range $3 \times 10^{19} \text{ GeV} \leq M_{QG} \leq 10^{20} \text{ GeV}$ the expected excess distribution in 100 h is well separated from the standard EBL-absorbed case (Figure 2, right panel). Even in this case, we neglected the mismatch between the used IRF

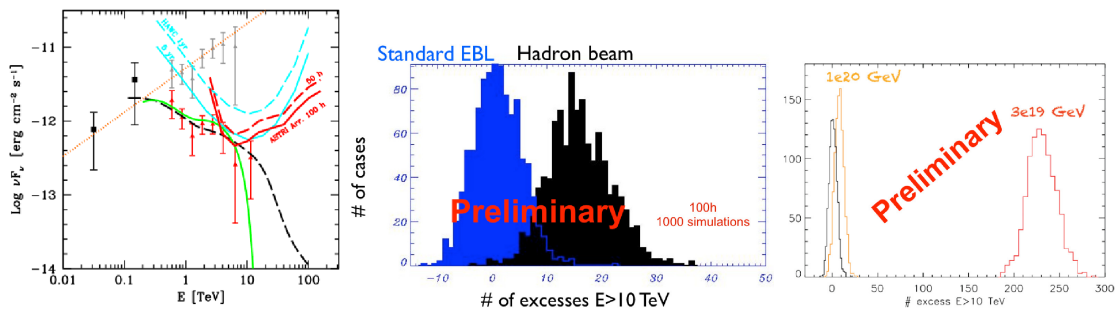


Figure 2. See text.

for $ZA \sim 20^\circ$ and the real case. Also, a strong assumption on the unbroken intrinsic spectrum

is made. Clearly, the assumption that an IACT can be used in long integrations as a “counting experiment” relies on a mature, well known instrument, stable and well monitored observing conditions, but we consider this as a stimulus to go in that direction that is in any case desirable.

3. Conclusions

Preliminary simulations of the scientific capabilities of the ASTRI mini-array have been performed, by means of the dedicated scientific simulator **ASTRIsim**. Some test cases have been investigated, namely a flare from the nearby bright blazar Mrk 501 similar to the ones already observed by HEGRA in 1997 or more recently by VERITAS and ARGO in 2009, and deep observations of the EBL 1ES 0229+200. Results have been summarily outlined here, but will be discussed in full detail in a forthcoming publication, where simulations on a wider catalog of sources observable from the Southern CTA site will be available, too.

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