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The ASTRI mini-array within the future Cherenkov Telescope Array

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Abstract. The Cherenkov Telescope Array (CTA) is a large collaborative effort aimed at the design and operation of an observatory dedicated to very high-energy gamma-ray astrophysics in the energy range from a few tens of GeV to above 100 TeV, which will yield about an order of magnitude improvement in sensitivity with respect to the current major arrays (H.E.S.S., MAGIC, and VERITAS). Within this framework, the Italian National Institute for Astrophysics is leading the ASTRI project, whose main goals are the design and installation on Mt. Etna (Sicily) of an end-to-end dual-mirror prototype of the CTA small size telescope (SST) and the installation at the CTA Southern site of a dual-mirror SST mini-array composed of nine units with a relative distance of about 300 m. The innovative dual-mirror Schwarzschild-Couder optical solution adopted for the ASTRI Project allows us to substantially reduce the telescope plate-scale and, therefore, to adopt silicon photo-multipliers as light detectors. The ASTRI mini-array is a wider international effort. The mini-array, sensitive in the energy range 1–100 TeV and beyond with an angular resolution of a few arcmin and an energy resolution of about 10–15%, is well suited to study relatively bright sources (a few $\times 10^{-12}$ erg cm⁻² s⁻¹ at 10 TeV) at very high energy. Prominent sources such as extreme blazars, nearby well-known BL Lac objects, Galactic pulsar wind nebulae, supernovae remnants, micro-quasars, and the Galactic Center can be observed in a previously unexplored energy range. The ASTRI mini-array will extend the current IACTs sensitivity well above a few tens of TeV and, at the same time, will allow us to compare our results on a few selected targets with those of current (HAWC) and future high-altitude extensive air-shower detectors.

1. Introduction

The very high-energy (VHE) portion of the electromagnetic spectrum (above ≈ 100 GeV) is currently being investigated by means of ground-based imaging atmospheric Cherenkov telescopes (IACTs, see [1] for a recent review). In order to dramatically boost the current IACT performance and to widen the VHE science, a new Cherenkov telescope array (CTA) has been proposed, as described in [2] and more recently in [3]. The wide energy range covered by the CTA (from a few tens of GeV to above 100 TeV) requires different kinds of telescopes. Four large size telescopes (LSTs, $D \sim 23$ m) will be placed at the center of the array, to lower the energy threshold down to a few tens of GeV. A few tens of medium size telescopes (MSTs, $D \sim 12$ m, SCTs, $D \sim 9.5$ m) will cover approximately 1 km², to improve by

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Figure 1. *Left panel:* the ASTRI SST-2M prototype at the Serra La Nave observing station. *Right panel:* Artistic concept (not to scale) of the ASTRI mini-array.

a factor of ten the sensitivity in the energy range 0.1–10 TeV. Finally, 70 small size telescopes (SSTs, primary mirror $D \sim 4$ m, $A_{\text{eff}} \sim 5\text{--}10 \text{ m}^2$) covering about 10 km^2 will enhance Galactic plane source studies in the energy range beyond 100 TeV. A detailed review of the CTA project is given in [4].

2. The ASTRI Project and its end-to-end prototype

Within the CTA framework, the Italian National Institute for Astrophysics (INAF) is leading the “Astrofisica con Specchi a Tecnologia Replicante Italiana” (ASTRI) Flagship Project [5] of the Ministry of Education, University and Research. Primarily, INAF has designed and developed an end-to-end prototype of the CTA small-size telescope in a dual-mirror configuration (SST-2M). This prototype is currently being tested under field conditions at the INAF “M.C. Fracastoro” observing station in Serra La Nave (Mount Etna, Sicily). The ASTRI SST-2M prototype was recently inaugurated during the CTA Consortium Meeting in September 2014. Figure 1 (left panel) shows the prototype in front of the domes. Currently all telescope sub-systems are in place and properly working. The camera is being assembled, an it will be installed at the telescope focal plane at the beginning of 2016.

A new dual-mirror, Schwarzschild-Couder (SC) aplanatic design has been proposed [6]. In the SC telescope, the focal plane is located in-between two aspherical mirrors, close to the secondary mirror. No Cherenkov telescope has adopted this optical system before. The dual-mirror optical system will reduce the dimension, the weight, and the cost of the camera at the focal plane of the telescope, and will obtain a more compact and stiffer mechanical structure, and an optimal imaging resolution across a wide field of view. Moreover, due to the reduced plate-scale, silicon-based photo-multipliers (SiPMs) can be adopted as light detectors.

The ASTRI SST-2M prototype adopts a segmented 4.3 m primary mirror (M1) composed of 18 facets, a monolithic 1.8 m secondary mirror (M2, with a radius of curvature of 2.2 m), a focal length $F=2.15$ m, a field of view $\text{FoV} \sim 9.6^\circ$, for a ratio $F/D_1=0.5$. The mirror manufacturing process is the “glass cold shaping” technique, specifically developed by INAF for Cherenkov mirrors [7, 8]. The curved focal plane (~ 1 m of radius of curvature) hosts 1984 logical pixels ($6.2 \text{ mm} \times 6.2 \text{ mm}$, 0.17°). The current photo-sensors are Hamamatsu S11828-3344M silicon-based photo-multipliers, but other sensors are also being tested [9]. The ASTRI camera [10] is extremely compact ($\sim 50 \text{ cm} \times 50 \text{ cm} \times 50 \text{ cm}$) and light ($\sim 50 \text{ kg}$). Contrary to other CTA telescopes adopting a signal-sampler front-end electronics (FEE), the

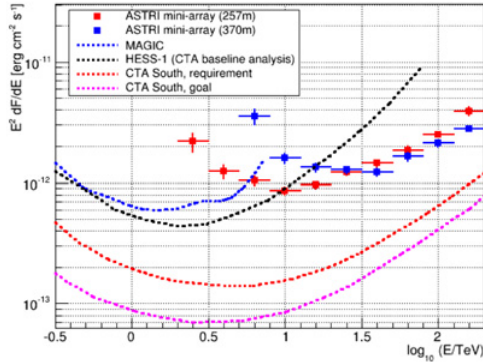


Figure 2. ASTRI mini-array differential sensitivity for 9 telescopes (blue and red points, for two different telescope relative distances) compared to the MAGIC, H.E.S.S.-I, and CTA (requirements and goal) ones (blue, black, red, and magenta dashed lines, respectively). See [13] and references therein.

ASTRI camera adopts as FEE the CITIROC, a customized version of the EASIROC [11] ASIC signal-shaper manufactured by Omega¹.

We are completing the commissioning phase during which we tested all the mechanical and optical subsystems, as well as the control software. The commissioning of the camera will take place in Spring 2016. A science verification phase, during which we will observe Mrk 421, Mrk 501, and afterwards the Crab Nebula, will start at the end of Spring 2016. The results of these observations will allow us to cross-check the prototype performance with our Monte Carlo simulations. We estimate that, in the sensitivity range ($E \geq 2$ TeV), we can detect a flux level of 1 Crab at 5σ in a few hours [12].

3. The ASTRI mini-array

A remarkable improvement in terms of performance could come from the operation, in late 2016, of a mini-array, composed of nine SST-2M telescopes (see Fig. 1, right panel, for an artistic concept) to be placed at the final CTA southern site. The ASTRI mini-array is a collaborative effort led by INAF in synergy with the University of São Paulo and FAPESP (Brazil) and the North-West University (South-Africa). Preliminary Monte Carlo simulations [13] yield an improvement in sensitivity that, for nine telescopes, could surpass the H.E.S.S. sensitivity above 10 TeV, extending it up to about 100 TeV, as shown in Fig. 2. The ASTRI mini-array will be able to study in detail relatively bright (a few $\times 10^{-12}$ erg cm⁻²s⁻¹ at 10 TeV) sources with an angular resolution of a few arcmin and an energy resolution of about 10–15%.

Thanks to the array approach, it will be possible 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 mini-array performance with the Monte Carlo expectations by means of deep observations of a few selected targets. Moreover, it will be possible to perform the first CTA science, with its first solid detections during the first year of operation, as described in [14]. Prominent sources such as extreme blazars (KUV 00311–1938), nearby well-known BL Lac objects (Mrk 501) and radio-galaxies (M 87), galactic pulsar wind nebulae (Crab Nebula, Vela-X), supernovae remnants (Vela-junior, RX J1713.7–3946), as well as

¹ <http://omega.in2p3.fr/>; manufactured under INAF intellectual property.

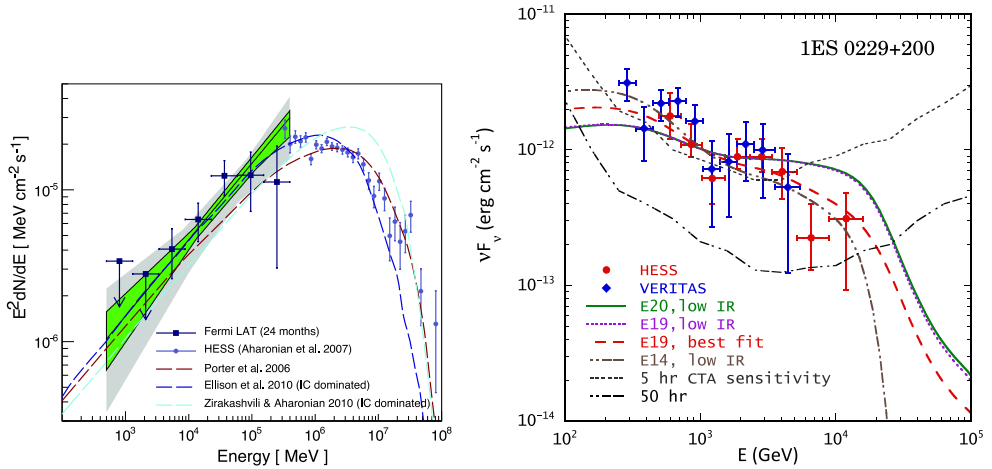


Figure 3. Left panel: supernova remnant RX J1713.7–3946 (see [15] for details). We expect for the ASTRI mini-array sensitivity at least comparable to (or slightly better than) the H.E.S.S. one above a few TeV. Right panel: spectral energy distribution of the extreme blazar 1ES 0229+200 (see [16] for details).

the Galactic Center can be observed in a previously unexplored energy range, in order to investigate the electron acceleration and cooling, relativistic and non relativistic shocks, the search for cosmic-ray (CR) PeVatrons, the study of the CR propagation, and the impact of the extragalactic background light on the spectra of the sources.

On the Galactic plane, one of the best targets is RX J1713.7–3946. Its detection by *Fermi* [15] and the combined study with H.E.S.S. (Fig. 3, left panel) shows that the high-energy and very high-energy (VHE) emission could be interpreted in the framework of a leptonic scenario. The improved and uniform sensitivity (within a few degrees off-axis) and the comparable angular resolution of the ASTRI mini-array at $E \geq 10$ TeV with respect to the current IACTs could allow us to investigate the VHE emission in the different regions of this source, studying their spectra, and to extend the current spectral energy distribution (SED) well above a few tens of TeV, searching for possible spectral cut-offs. Figure 3 (right panel) shows the SED of the extreme blazar 1ES 0229+200 with superimposed different theoretical SED fits (both hadronic and leptonic) assuming different EBL models (see [16] for a detailed discussion) and the $5\text{-}\sigma$ differential sensitivity for 5 and 50 hr observations with CTA (configuration E, as reported in [2]). Because of the uncertainty in EBL models, it is not easy to distinguish between the hadronic and leptonic scenarios at $\sim 1\text{--}10$ TeV energies. At higher energies, however, UHECR-induced cascade emission becomes harder than the gamma-ray one. A detection of ≥ 25 TeV gamma-rays from 1ES 0229+200 would only be consistent with an hadronic scenario.

4. Synergies and conclusions

The ASTRI mini-array will operate when the other IACTs will still be active. Compared to them, the ASTRI mini-array will extend the sensitivity up to 100 TeV and beyond, a never-explored energy range by IACTs. Moreover, it will benefit from a much larger field of view which will allow us to study in detail extended sources at energies about a decade higher than what is currently being explored and to monitor simultaneously a few close-by sources

during the same pointing. Long exposures will be preferred, restricting the number of possible targets, and extending the observations also during moon light periods, thanks to the use of a SiPMs-based camera.

The lower imaging energy threshold of current and future extended air-shower (EAS) detectors (~ 100 GeV) and the wider energy range of the ASTRI mini-array (beyond 100 TeV) will allow us a direct comparison of scientific data (spectra, light-curves, integral fluxes) of those sources which could be monitored simultaneously, although on different integration time-scales. Moreover, the high-energy boundary of both EAS and the ASTRI mini-array will allow us to study the VHE ($E \geq 10$ TeV) emission from extended source such as SNRs and PWN, and to investigate the presence of spectral cut-offs. In summary, the ASTRI mini-array could be considered as the first CTA *seed*, allowing the entire CTA Consortium to start seminal studies on both Galactic and extra-galactic sources.

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