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The mini-array of ASTRI SST-2M telescopes, precursors for the Cherenkov Telescope Array

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Abstract. In the framework of the Cherenkov Telescope Array (CTA) Observatory, the Italian National Institute of Astrophysics (INAF) has recently inaugurated in Sicily (Italy), at the Serra La Nave astronomical site on the slopes of Mount Etna, a large field of view (FoV, $\sim 9.6^{\circ}$) dual-mirror prototype (ASTRI SST-2M) of the CTA small size class of telescopes (SST). The CTA plans to install about 70 SST in the southern site to allow the study of the gamma rays from a few TeV up to hundreds of TeV. The ASTRI SST-2M telescope prototype has been developed following an end-to-end approach, since it includes the entire system of structure, mirrors optics (primary and secondary mirrors), camera, and control/acquisition software. A remarkable performance improvement could come from the operation of the ASTRI mini-array, led by INAF in synergy with the Universidade de Sao Paulo (Brazil) and the North-West University (South Africa). The ASTRI mini-array will be composed of nine ASTRI SST-2M units and it is proposed as a precursor and initial seed of the CTA to be installed at the final CTA southern site. Apart from the assessment of a number of technological aspects related to the CTA, the ASTRI mini-array will, if compared for instance to H.E.S.S., extend the point source sensitivity up to $\sim$ 100 TeV, also improving it above 5-10 TeV. Moreover, the unprecedented width of the FoV, with its homogeneous acceptance and angular resolution, will significantly contribute to the achievement of original results during the early CTA science phase.

1. Introduction

The very high-energy (VHE, $E_\gamma \gtrsim 50\,\mathrm{GeV}$) portion of the electromagnetic spectrum 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]. Two such arrays will be built at $\pm$ 30° latitudes, in order to monitor the whole sky, and will be operated as an observatory open to the world-wide astronomical community. The wide energy range covered by the CTA (from a few tens of GeV to above 100 TeV) requires different kinds of telescopes. The planned multiplicity of telescopes is different for the Northern and Southern site, with the last being larger. In each site, four large size telescopes (LST, 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. In the Southern site, a few tens of medium size telescopes (MST, D$\sim$ 12 m, SCT, D$\sim$ 9.5 m) will cover $\sim 1\,\mathrm{km}^2$, to improve by a factor of ten the sensitivity in the energy range 0.1–10 TeV. Finally, 70 small size telescopes (SST, primary mirror D$\sim$ 4 m, $A_{eff} \sim 5 - 10\,\mathrm{m}^2$) covering

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about $10\,\mathrm{km}^2$ will lead the performance in the energy range beyond 10 TeV. In the Northern site, ~ 15 MSTs and no SST are foreseen. Recently, the CTA Consortium has announced the results of the site selection process, with Paranal (Chile) and La Palma (Spain) sites chosen for final negotiations, currently ongoing. A detailed review of the CTA project is given in [3].

2. The ASTRI project and the ASTRI SST-2M end-to-end prototype

The Italian National Institute for Astrophysics (INAF) is leading since 2011 the "Astrofisica con Specchi a Tecnologia Replicante Italiana" (ASTRI) Flagship Project [4] of the Ministry of Education, University and Research. This project aims to design and develop, within the CTA framework, an end-to-end prototype of the SST in a dual-mirror configuration (SST-2M). Other two SST prototypes are currently being developed within the CTA Collaboration, namely the single mirror SST-1M and another dual-mirror, the GCT prototype. The ASTRI SST-2M prototype, installed at the INAF "M.C. Fracastoro" observing station in Serra La Nave (Mount Etna, Sicily) [5] was inaugurated during the CTA Consortium Meeting held in the nearby Giardini Naxos in September 2014 (see fig. 1, left panel). This prototype is currently being tested under field conditions, and will soon start a science verification phase (SVP) 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 blazars Mrk 421 and Mrk 501. Currently, an optical camera (fully representative in terms of mechanical interfaces) is installed at the telescope focal plane, allowing us to assess the optical performance of the instrument. For this telescope a new dual-mirror, Schwarzchild-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. This design improves the optical performance, in particular by achieving an homogeneous and unaberrated point spread function (PSF) across a wide field of view (FoV) and by reducing the plate-scale, so that the wide FoV can be imaged on a small, light camera equipped with innovative silicon photo-multipliers (SiPM). These advantages come at the price of an increased complexity of the instrument, a reduced optical effective area for a given diameter of the primary mirror, due to obscuration of the secondary and its supports over the primary mirror, and a delicate alignment of the optical elements. No IACT has adopted a dual mirror optical system before, and no telescope has ever adopted the SC design so far to the best of our knowledge; therefore the image of Polaris taken (although under bad weather conditions and with only a coarse mirror alignment) on 24 May 2015 with the ASTRI SST-2M equipped with the optical camera, can be considered the first image ever taken with a SC telescope (fig. 1, right panel). 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 (RoC) of 2.2 m, a focal length F=2.15 m, a FoV$\sim 9.6°$, for a ratio F/D_1=0.5. Optical PSF is $\sim 6'$ while plate-scale is $\sim 2'$mm. The mirror manufacturing process is the "glass cold shaping" technique, specifically developed by INAF for Cherenkov mirrors [7, 8]. The curved focal plane (RoC $\simeq$ 1 m) hosts 1984 logical pixels ($6.2\,\mathrm{mm} \times 6.2\,\mathrm{mm}$, 0.17°). The current photo-sensors are Hamamatsu S11828-3344M SiPM, but other sensors are also being tested [9]. The ASTRI camera [10] is extremely compact ($\sim 50\,\mathrm{cm} \times 50\,\mathrm{cm} \times 50\,\mathrm{cm}$) and light ($\sim 70$ kg). Contrary to the other CTA telescopes adopting a signal-sampler front-end electronics (FEE), the ASTRI camera adopts as FEE the CITIROC [11], a customized version of the EASIROC [12] ASIC signal-shaper manufactured by Omega[1]. The ASTRI SST–2M is mainly a technological prototype. Nevertheless, after a thorough commissioning phase, it will perform scientific observations of the Crab Nebula, Mrk 421 and Mrk 501. This SVP will cross-check the prototype performance with the predictions of Monte Carlo simulations [13]; we expect that a flux level of 1 Crab will be detected at 5σ in a few hours in the whole sensitivity range (E$\geq$ 2 TeV).

[1] `http://omega.in2p3.fr/`; manufactured under INAF intellectual property.

Figure 1. *Left*: the ASTRI Collaboration in front of the telescope during the official inauguration on 2014, September the 24th. *Right*: Optical image of Polaris taken on 24th May 2015 with the ASTRI SST-2M prototype and the temporary CCD camera installed during commissioning; to the best of our knowledge, the first ever image of the sky taken with a Schwarzschild-Couder telescope.

3. The ASTRI mini-array

The ASTRI SST-2M will allow single-dish observations of the extended air showers (EAS), but a key issue of the CTA is the stereoscopic imaging of each event. Therefore building an array, and not a single telescope, is mandatory to fully test the performance of the telescopes, of the array control system, of the array trigger system. 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, an array of 9 ASTRI SST-2M telescopes, proposed as a precursor of the full CTA. The ASTRI mini-array will be deployed to the CTA-South site once it is established, being likely commissioned in 2017 and beginning its verification phase in 2018. 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 [15]. Preliminary Monte Carlo simulations [14] yield a point source sensitivity that, for 9 telescopes, improves over that of H.E.S.S. above 10 TeV, up to 100 TeV (see fig. 2, right panel). The ASTRI mini-array will be able to study in great detail relatively bright (a few $\times 10^{-12}\,\mathrm{erg\,cm^{-2}s^{-1}}$ at 10 TeV) sources with an angular resolution of a few arcmin and an energy resolution of about 10–15 %. Remarkably, while the sensitivity is significantly worse than that of the full SST array planned for the CTA, energy and angular resolution are closer to the ones for the 70 telescopes, as few shower events are expected to trigger more than 9 units. Thus, the mini-array can be seen as a "building block" of the full SST array.

Sources such as Galactic pulsar wind nebulae (Crab Nebula, Vela-X), supernovae remnants (Vela-junior, RX J1713.7−3946), as well as the Galactic Center can be observed in a previously unexplored energy range. Also, bright BL Lac objects (PKS 2155-300, or, at high ZA, Mrk 421 and Mrk 501) and radio-galaxies (M 87), and extreme blazars (such as 1ES 0220+200 or 1ES 0347-121) can be observed. These observations are crucial 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. More details on the preliminary scientific simulation in the

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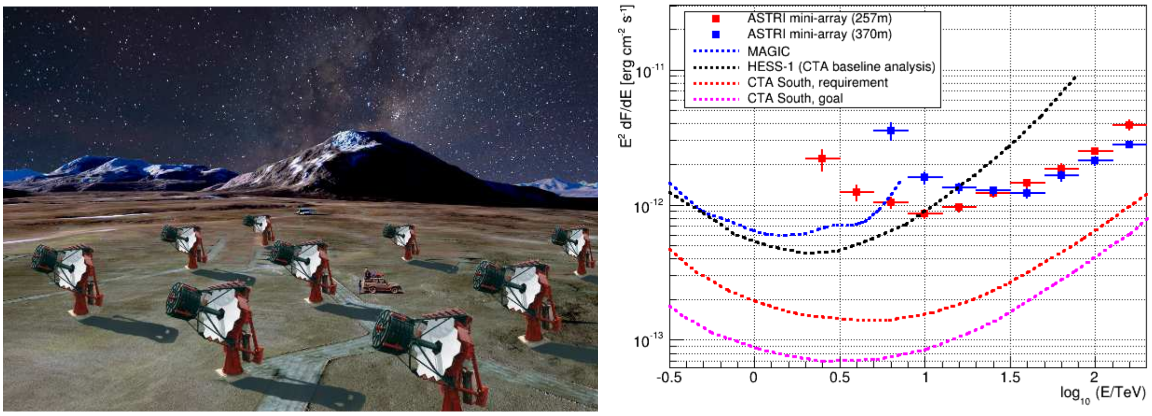

Figure 2. *Left:* Artistic concept (not to scale) of the ASTRI mini-array. The ASTRI mini-array is a collaborative effort, within the CTA framework, among Italy, Brazil and South Africa. Two Brazilian engineers are currently working at the Serra La Nave site. The ASTRI mini-array is proposed to be placed at the CTA southern site. *Right:* Preliminary results for the differential sensitivity of the ASTRI mini-array to point sources (5σ, 50 h, 5 bin/dex; see [14]). We expect that the ASTRI mini-array will be slightly more sensitive than H.E.S.S. above $5 - 10$ TeV.

fields of Dark Matter searches [17] and on blazars and fundamental physics [16] can be found in the proceedings of this conference. As examples on the topic of Galactic science, Figure 3 (left and middle panels) shows how the sensitivity at $E > 10$ TeV can allow us to discriminate emission models for the SNR RCW86 [18]. Also, the wide FoV of the ASTRI mini-array will allow simultaneous observations of multiple sources in crowded Galactic regions such as the Crux Arm with spatially homogeneous acceptance and angular resolution (fig. 3, right panel).

4. Conclusions

The ASTRI mini-array is proposed to be deployed to the CTA-South site once it is established, being likely commissioned in 2017 and beginning its verification phase in 2018. Compared to currently operating IACT systems, 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 FoV which will allow us to monitor simultaneously a few close-by sources during the same pointing. The combination of the sensitivity extended to 100 TeV and of the homogeneous performance across the FoV 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. The energy threshold at few TeV will naturally lead to focusing the schedule on a few, deeply exposed, science-driven targets. The use of a SiPMs-based camera will improve the duty cycle of the system allowing safe and effective operation with any level of moon condition such as already demonstrated by FACT [19]. The ASTRI mini-array will operate when the present IACT systems, observing in a lower but partly overlapping passband, will still be active, allowing direct comparison of scientific data (spectra, light-curves, integral fluxes). Also, fruitful synergies with HAWC, surveying a stripe of the sky that is in large part accessible to pointed observation from the CTA-South site, are clearly foreseen. In summary, the ASTRI mini-array could be considered as the first CTA *seed*, allowing to start seminal studies on both Galactic and extra-Galactic sources, tackling frontier issues at the intersection of the fields of astrophysics, cosmology, particle physics and fundamental physics.

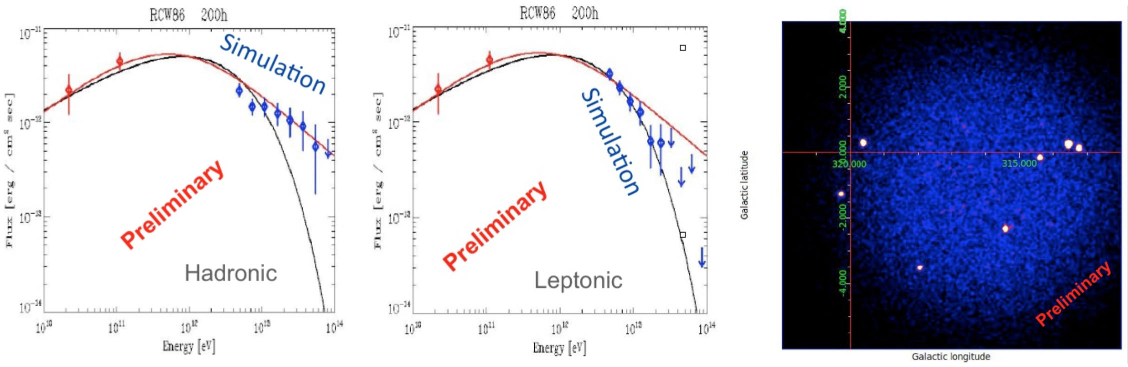

Figure 3. *Left and middle*: Leptonic (black line) and hadronic (red line) models for the emission from the SNR RCW86 can be discriminated at energies above 10 TeV by means of 200 h deep observations with the ASTRI mini-array according to our preliminary scientific simulations [18]. *Right panel*: The wide FoV of the ASTRI mini-array will allow us to observe simultaneously multiple sources (e.g. in crowded Galactic regions) with spatially homogeneous acceptance. Simulations for 230 h deep observations of the Crux arm are shown as an example [18].

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