ASTRI SST-2M prototype and ASTRI mini-array data analysis and scientific prospects in the framework of the Cherenkov Telescope Array

Saverio Lombardi[1,2]
on behalf of the ASTRI Collaboration[3] **and for the CTA Consortium**[4]
[1]INAF – Osservatorio Astronomico di Roma, Via Frascati 33, 00040 Monteporzio Catone (Roma), Italy
[2]ASI Science Data Center, Viale del Politecnico s.n.c., 00133 Roma, Italy
[3]`http://www.brera.inaf.it/astri/`
[4]`http://www.cta-observatory.org`
E-mail: `saverio.lombardi@oa-roma.inaf.it`

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Abstract

In the framework of the international Cherenkov Telescope Array (CTA) observatory, the Italian National Institute for Astrophysics (INAF) is developing the ASTRI small-sized, dual-mirror (SST-2M) end-to-end prototype, installed at Mt. Etna (Italy) on September 2014. INAF is also leading, in collaboration with Universities from Brazil and South Africa, the ASTRI mini-array composed of nine ASTRI SST-2M telescopes and proposed to be installed at the CTA southern site. The project is also including the full data handling chain, from raw data up to final scientific products, and a dedicated software for data reduction and scientific analysis is under development for both the ASTRI SST-2M prototype and mini-array, in compliance with the CTA requirements. In this contribution, we discuss the preliminary outcome of the developed scientific analysis on simulated data, provide information on the expected sensitivity, and introduce the main scientific prospects for the ASTRI mini-array.

1 The Cherenkov Telescope Array

Very high-energy (VHE, E $\gtrsim$ 50 GeV) gamma-ray astronomy is a rather young and flourishing field with high scientific potential [1]. Gamma rays of such energies represent a unique probe for casting light on fundamental issues of galactic and extragalactic astrophysics, particle physics, fundamental physics, and cosmology [2]. The VHE sky is currently being investigated with high collection areas by means of ground-based imaging atmospheric Cherenkov telescopes (IACTs) [3], such as H.E.S.S., MAGIC, and VERITAS. In the last decade, with the firm detection of $\sim$150 galactic and extragalactic sources [4], these arrays have demonstrated the huge physics potential at these energies as well as the maturity of the detection technique.

In order to dramatically boost the current IACT performance and to widen the VHE science, a new-generation Cherenkov telescope array (CTA) has been proposed [5, 6] as an observatory open to the world-wide astronomical community. The full sky coverage will be assured by two CTA facilities, one in each Earth hemisphere. The two arrays will make use of $\sim$100 telescopes at southern site and $\sim$20 at northern site of three different sizes – large (diameter D$\sim$23 m); medium (D$\sim$12 m and D$\sim$9.5 m); small (D$\sim$4 m) – in order to cover the wide energy range from few tens of GeV up to few hundreds of TeV. The expected CTA sensitivity will be one order of magnitude better than current IACTs [7] in the whole energy window and will give the possibility to fruitfully investigate several galactic, extragalactic, and fundamental physics science cases [8].

2 The ASTRI SST-2M prototype and the ASTRI mini-array

ASTRI (*Astrofisica con Specchi a Tecnologia Replicante Italiana*) is a flagship project of INAF (Italian National Institute for Astrophysics) funded by the Italian Ministry of Education, University, and Research, strictly linked to the development of the CTA international project. The main goals of the ASTRI project are the realization of an end-to-end prototype of the CTA small-size telescope in dual-mirror (SST-2M) Schwarzschild-Couder configuration and, in a second phase, the deployment of a mini-array composed of nine ASTRI SST-2M telescopes, proposed to be placed at the CTA southern site [9, 10].

Being an end-to-end project, ASTRI is including (besides all hardware and control software systems) the full data processing and archiving chain, from raw data up to final scientific products. For this purpose, a dedicated software for *on-line/on-site/off-site* data reduction and scientific analysis is under development for both the ASTRI SST-2M prototype and mini-array, in compliance with the CTA requirements [11].

The ASTRI SST-2M prototype has been installed on September 2014 at the INAF "M.C. Fracastoro" observing station in Serra La Nave (Mt. Etna, Sicily) and it is currently undergoing engineering tests. A detailed description of the SST-2M prototype structure, double-mirror optics, silicon photomultiplier camera, electronics, data acquisition system, and preliminary Monte Carlo (MC) based performance is provided in [12, 13, 14, 15, 16, 17], respectively. Although the prototype is meant to be mainly a technological demonstrator, a scientific and performance validation phase of the whole integrated system – during which the Crab Nebula, Mrk 421, and Mrk 501 will be observed – is foreseen to start by mid 2016 and accomplished by early 2017.

Compared to the prototype, a remarkable improvement in terms of performance and science feasibility is foreseen to come from the deployment and operation – led by INAF in synergy with the Universidade de São Paulo (Brazil) and the North-West University (South Africa) – of a mini-array composed of nine ASTRI SST-2M telescopes, likely by 2018. The mini-array will represent one of the future CTA observatory precursors and will allow us to test hardware and software solutions that are proposed to be eventually adopted by CTA. Furthermore, thanks to its expected sensitivity [18] (better than the current IACTs ones above $\sim$10 TeV) and large field of view (FoV, $\sim 10^\circ$), the ASTRI mini-array will be able to perform simultaneous observations of multiple targets and to study in great detail relatively bright (a few $\times 10^{-12}$ erg cm^{-2} s^{-1} at 10 TeV) galactic and extragalactic sources [10, 19].

3 The ASTRI scientific analysis software

The ASTRI scientific analysis software is the official package being developed for the ASTRI prototype and mini-array data processing, in compliance with the CTA requirements [11]. The software can handle both (real and MC) prototype and mini-array data, and will provide all necessary algorithms and analysis tools for characterizing the scientific performance of the ASTRI SST-2M prototype and, afterwards, for carrying on the mini-array scientific program. It will be one of the first CTA data reduction and analysis software precursors to be developed and tested on real-data bases. Furthermore, it will be suitable for all the pipeline analyses foreseen by the CTA requirements, namely the Level A (*on-site/on-line*) analysis (to be performed at observatory on real-time bases), the Level B (*on-site/off-line*) analysis (to be performed at observatory at the end of each observation), and the Level C (*off-site/off-line*) analysis (to be performed at the off-site data center).

The software is composed by a set of independent modules organized in efficient pipelines that implement all the necessary algorithms to perform the complete data reduction and scientific analysis, from raw data to the final scientific products. To better exploit the parallel computing architectures (multi-core CPUs) and new hardware architectures based on low-power consumption processors (e.g. ARM [20]) and graphic accelerators (e.g. GPUs), the software components are coded in *C++*, *Python*, and *CUDA*, and efficiently wrapped in *Python*. The final scientific products are then achieved by means of either science tools currently being used in the CTA Consortium (e.g. *ctools* [21]) or specifically developed ones.

The data levels (DL) of the ASTRI SST-2M prototype and mini-array have been defined in compliance with the CTA data model [22], and they are: raw data (DL0); telescope-wise reconstructed data (DL1); array-wise reconstructed data (DL2); reduced data (DL3); science data (DL4); observatory data (DL5). The FITS data format [23] has been adopted for all ASTRI data levels, from DL0 up to final scientific products, although it is already foreseen that, in the case of the mini-array, the DL0 data will be handled in their original raw (rather than FITS) format. Throughout the whole analysis chain, the *CFITSIO* and *CCFITS* libraries [24] are used for reading, processing, and writing FITS data.

The data processing steps implemented in the ASTRI scientific analysis software are compliant with the logical design and data model of the CTA pipelines and can be summarized as follows:

- **Calibration and telescope-wise reconstruction (DL0→DL1)**
  The raw data containing the full information available per pixel (integrated signal amplitude in ADC-counts and arrival time), for each triggered event and telescope, are calibrated in order to extract and convert the signal into physically meaningful units (photoelectrons). After the calibration, the data of each telescope undergo an image cleaning procedure (aimed at removing pixels which most likely do not belong to a given Cherenkov shower image) and parameterization (based on the moments up to the third order of the light distribution on the camera [25] and on arrival time information). A set of training MC gamma-ray and real background data are then used to train a machine learning method for the calculation of single-telescope look-up-tables (LUT1) for gamma/hadron separation, energy reconstruction, and arrival direction estimation. The LUT1 are finally used to get the fully telescope-wise reconstructed data.

- **Array-wise reconstruction (DL1→DL2)**
  The telescope-wise fully reconstructed data of each telescope are merged and a set of basic array-wise image parameters per event (such as the geometrical estimation of the shower direction, maximum height, and impact parameters relative to each telescope) are calculated. A set of training MC gamma-ray and real background data are then used to compute array-wise look-up-tables (LUT2) for gamma/hadron separation, energy reconstruction, and arrival direction estimation. In this step, telescope-wise and array-wise pieces of information are used together to train the machine learning method. Finally, the LUT2 are used to get the fully array-wise reconstructed data.

- **Data reduction (DL2→DL3)**
  The fully array-wise reconstructed data are further processed to achieve the final reduced event-list (EVT3) and instrument response functions (IRF3). In this data processing step, both quality and gamma/hadron separation cuts are applied to the data.

- **Scientific analysis (DL3→DL4)**
  The fully reduced data (EVT3/IRF3) are finally analysed with either science tools currently being used in the CTA Consortium (e.g. *ctools* [21]) or with specifically developed ones. The final scientific products, such as detection plots, spectra, sky-maps, and light-curves, are thus generated and, in case, further processed and merged to get high-level observatory data (DL5).

4 The ASTRI mini-array performance

In order to access the expected performance and the scientific capabilities of the ASTRI mini-array, dedicated MC simulations have been produced and analysed with the MC pipelines currently being used in the CTA Consortium [26]. According to the preliminary results [18], the mini-array will be able to perform observations with an angular resolution of a few arcmins, an energy resolution of 10–15%, and a sensitivity better than the current IACTs ones above ∼10 TeV and extended up to ∼100 TeV. In Fig.1, the expected differential sensitivity of the mini-array (blue and red points, for two different telescopes' relative distances) compared to the MAGIC [27], H.E.S.S.-1-like (derived with

CTA MC and analysis) [28], and CTA-South [29] (requirements and goal) ones (blue, black, red, and magenta dashed lines, respectively) is shown. Also shown, the preliminary differential sensitivity (for the mini-array telescopes' relative distance of 257 m) achieved from DL0 MC data with the ASTRI scientific analysis software (green points), in reasonable agreement[1] with the estimates obtained by the MC pipelines currently being used in the CTA Consortium (red points).

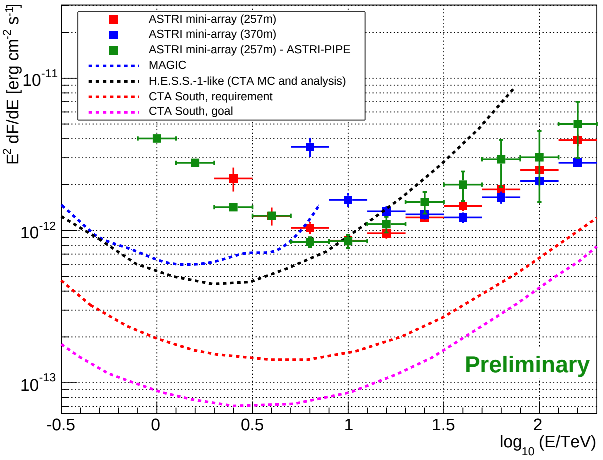

Figure 1: ASTRI mini-array expected differential sensitivity (blue and red points) [18], compared to the MAGIC [27], H.E.S.S.-1-like (derived with CTA MC and analysis) [28], and CTA-South [29] (requirements and goal) ones (blue, black, red, and magenta dashed lines, respectively) [18]. The preliminary results achieved with the ASTRI scientific analysis software (green points) are also shown.

5 The ASTRI mini-array scientific prospects

Thanks to its sensitivity, angular and energy resolution, and wide FoV, the ASTRI mini-array will be able to carry out simultaneous deep observations of multiple sources, with a rather homogeneous spatially acceptance, and to contribute to the early CTA science (for energies above a few TeV) with few solid detections during the first year of operation [30].

On the galactic side, prominent sources such as pulsar wind nebulae (Crab Nebula, Vela-X), supernovae remnants (Vela-junior, RX J1713-3946, SNR RCW 86, SNR W 28), unidentified gamma-ray sources (HESS J1641-463), and the Galactic Center (GC) can be observed with unprecedented sensitivity above ∼10 TeV up to ∼100 TeV. These observations will be valuable to investigate fundamental astrophysics and particle physics processes, such as electron acceleration and cooling, relativistic and non-relativistic shocks, and cosmic-ray (CR) generation and propagation. In particular, one of most interesting galactic targets to be observed will be the supernovae remnant RX J1713.7-3946. The source has been detected by Fermi-LAT [31] and H.E.S.S. [32] at high energy (HE, $E \gtrsim 50$ MeV) and VHE, respectively. The combined study shows that the emission could be interpreted in the framework of a leptonic scenario. The ASTRI mini-array, with its high and rather uniform (within a FoV of a few degrees) sensitivity at $\geq$10 TeV, could give the possibility 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. The observation of this remnant, as well as of other sources on the galactic plane, may reveal the emission of gamma rays of ∼100 TeV and thus assess the existence of hadronic accelerators (i.e. cosmic PeVatrons) [33]. The potential new insights will be then deeply investigated and established with the full CTA.

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[1] The two extra sensitivity points (at the lower energies) achieved with the ASTRI scientific analysis software are obtained due to the application (from DL0) of different algorithms and (low energies) analysis cuts, with respect to the analysis performed with the MC pipelines currently being used in CTA.

The ASTRI mini-array will also carry out extragalactic observations of extreme blazars (1ES 0220+200 or 1ES 0347-121), bright BL Lac objects (PKS 2155-300, or, at high zenith angles, Mrk 421 and Mrk 501) and radio-galaxies (M 87). These observations may be helpful to study the extragalactic background light and its impact on the spectra of the sources, to provide indirect measurements of the intergalactic magnetic field, and to discriminate hadronic and leptonic scenarios for the VHE emission from BL Lac relativistic jets [19]. For instance, the detection of ≥25 TeV gamma rays from 1ES 0229+200 would represent a smocking gun for the hadronic emission scenario [34]. All these extragalactic scientific topics, and more, will be then fully addressed by CTA.

Finally, the ASTRI mini-array may be also able to study some fundamental physics science cases, such as the Lorentz Invariance Violation through the observation of extreme blazars above ∼10 TeV [19], and indirect Dark Matter (DM) searches in dwarf spheroidal galaxies (dSphs) and in the GC, in the weakly interacting massive particles (WIMPs) cold DM scenario [35]. In Fig.2, the preliminary sensitivity on DM searches for the annihilation channels $b\bar{b}$ (left) and $\tau^+\tau^-$ (right), considering 160 hours[2] of observation of the Segue 1 dSph, are shown for the ASTRI mini-array (red line). The result is compared to the limits achieved by MAGIC [36] (orange line) and to the prospects for a "mixed" mini-array of nine ASTRI SST-2M and four medium-sized telescopes (MSTs) (dashed red line) and for CTA-North (grey line) [37], for the same target and the same exposure time. In the same plots, the Fermi-LAT limits achieved from the combined analysis of 15 dSphs (6-years observations) [38] are also shown. From this preliminary DM constraints comparison study, rather interesting scenarios for the ASTRI mini-array (with respect current IACTs) in exploring WIMP parameter space are obtained in the $\tau^+\tau^-$ leptonic channel for masses above few TeV.

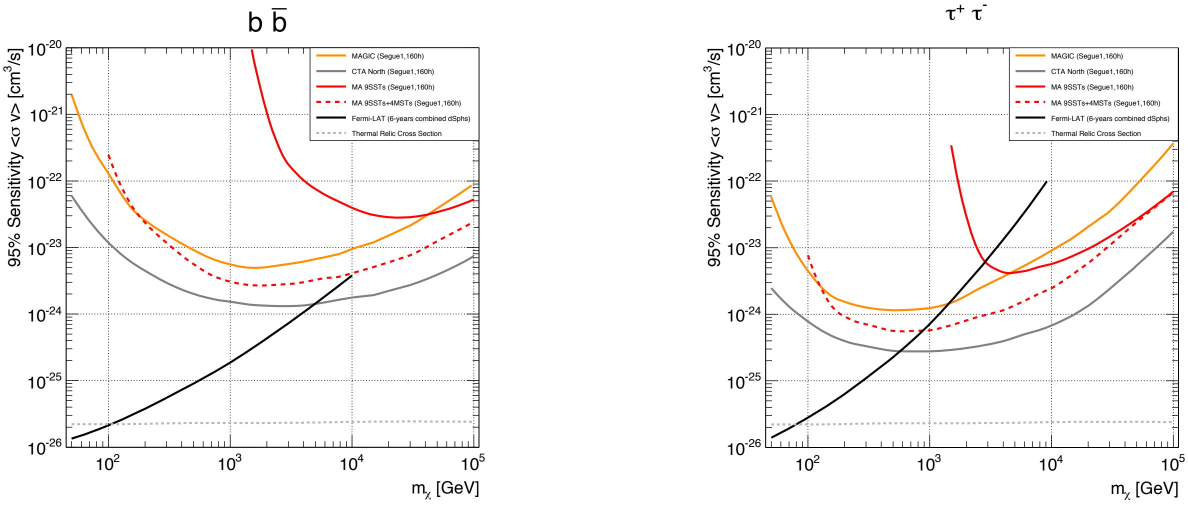

Figure 2: Comparison of sensitivities to DM searches for $b\bar{b}$ (left) and $\tau^+\tau^-$ (right) annihilation channel in 160 hours of observations of Segue 1 dSph with the ASTRI mini-array (red line), ASTRI mini-array plus four MSTs (dashed red line), and CTA-North (grey line) [37]. Also shown the MAGIC limits (at 95% CL, orange line) achieved in 160 hours of observations of Segue 1 dSph [36], and the Fermi-LAT limits (at 95% CL, black line) achieved from the combined analysis of 15 dSphs (6-years observations) [38]. The thermal relic cross section values (dashed grey line) are taken from [39].

6 Conclusions

In the framework of the Cherenkov Telescope Array, the ASTRI project is aimed at developing an end-to-end CTA SST-2M prototype (currently being tested under field conditions at the INAF

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[2] It is worth mentioning that the amount of Segue 1 exposure time considered in this study (160 hours) is only due to comparison reasons. In fact, it is not foreseen that the mini-array will be operated long enough to reach such amount of exposure time for dSphs observations.

observing station at Mt. Etna, Sicily) and deploying a mini-array composed of nine ASTRI SST-2M telescopes (proposed to be placed at the CTA southern site and likely ready to start operations by 2018). Besides all hardware and control software systems, the full *on-line/on-site/off-site* ASTRI data handling chain for both the ASTRI prototype and mini-array is also being developed. Promisingly, the preliminary estimates of the mini-array sensitivity achieved by the ASTRI scientific analysis software (from DL0 MC data) are in reasonable agreement with the results obtained by the MC pipelines currently being used in the CTA Consortium [26].

Since the ASTRI mini-array will operate when the other IACTs (observing in a lower but partly overlapping pass-band) and HAWC (High-Altitute Water Cherenkov gamma-ray observatory) will still be active, direct comparison of scientific results and fruitful synergies with other gamma-ray ground-based instruments are clearly foreseen. Compared to current IACTs, the ASTRI mini-array is expected to significantly exceed the sensitivity above $\sim$10 TeV up to 100 TeV, and beyond, in a never-explored energy range by IACTs. Furthermore, the wide FoV will permit the simultaneous observation and monitoring of a few close-by sources in crowded galactic regions (such as the Crux and 3 kpc Arms) during the same pointing, with a rather homogeneous performance within a FoV of a few degrees. Such a performance will allow us to contribute during the early CTA science to the achievement of valuable results on few remarkable astrophysics, particle physics, and fundamental physics topics.

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