PROCEEDINGS OF SCIENCE

Status of the ASTRI program: technology and science with wide-field aplanatic IACT

Andrea Giuliani,[a,*] **Giovanni Pareschi,**[b] **Salvo Scuderi,**[a] **Saverio Lombardi**[c] **and Stefano Vercellone**[b] **for the ASTRI Project***

[a] *INAF, IASF Milano,*
Via Alfonso Corti 12, I-20133 Milano, Italy
[b] *INAF, OA Brera,*
Via Brera, 28, I-20121 Milano, Italy
[c] *INAF, OA Roma,*
Via Frascati 33, I-00078 Monte Porzio Catone, Italy
[*] *http://www.astri.inaf.it/en/library/*

E-mail: andrea.giuliani@inaf.it

The ASTRI program began about 10 years ago aiming at the development of pathfinders of small-size (4 m diameter) dual-mirror aplanatic wide-field IACT telescopes in view of the implementation of the array of small-size telescopes (SSTs) of the Cherenkov Telescope Array (CTA) observatory at its southern site. In the beginning, it was supported by INAF and MUR (the Italian Ministry for Universities and Research), but then other important international partners like the University of Sao Paulo/FAPESP, Nort-West University/South Africa, IAC, FGG, and Université de Geneve have joined the effort at different stages of the project. The first important achievement was the realization of the ASTRI-Horn prototype as an end-to-end system and its installation at the INAF site of Serra La Nave (on the slope of the Etna Mount volcano in Sicily) equipped with an innovative compact camera based on SiPM sensors. The telescope allowed us to prove for the first time the Schwarzschild-Couder optical configuration as an aplanatic system, and to detect the Crab Nebula in gamma rays. Now, after a major refurbishment, the telescope is used for extensive observational campaigns of bright gamma-ray sources, cosmic rays, and muon radiography studies of the volcano. In the meantime, the ASTRI Mini-Array of 9 wide field ($> 10^o$) telescopes is being implemented at Tenerife for studying the gamma-ray sky in the 1- 100 TeV energy band with unprecedented angular resolution (3 arcmin), representing an ideal complementarity with LHAASO. In this paper we will report on the status of the project, discussing the scientific goals and expectations.

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*Speaker

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1. The ASTRI project

The ASTRI (Astrofisica con Specchi a Tecnologia Replicante Italiana) project was born in 2010 as “Progetto Bandiera” funded by the Italian Ministry of University and Scientific Research, with the initial aim to design and realize an innovative end-to-end prototype of the 4 meters class telescopes in the framework of the CTA observatory.

The first step of the project was the installation on the slope of the Etna volcano (at the INAF station of the Catania Astrophysical Observatory in Serra La Nave) in 2014 of a prototype of the ASTRI telescope, called ASTRI Horn[1]. ASTRI Horn is a 4-meter class, Cherenkov telescope. It adopts a dual mirror configuration based on a modified Schwarzschild-Couder optical design with a segmented primary mirror and a monolithic secondary mirror (figure 5, left). This optical configuration allows us to obtain a better correction of aberrations at large incident angles, even for small focal ratios, and good angular resolution across the entire field of view. The optical system has the additional advantage of reducing the plate scale, allowing for smaller pixel sizes than usual Cherenkov telescopes and the consequent possibility to use solid-state photosensors such as the Silicon Photo-Multipliers (SiPMs). It demonstrated the potentialities of this optical configuration and those of the ASTRI camera with a campaign of observations of the Crab Nebula [1] the first gamma-ray source ever observed with a dual-mirror Cherenkov telescope. In the last few years, it has been subject to major refurbishment which involved both mirrors and camera. The telescope is now used regularly for observational campaigns of gamma-ray sources, cosmic ray measurements and muon radiography of the Etna volcano [2–4].

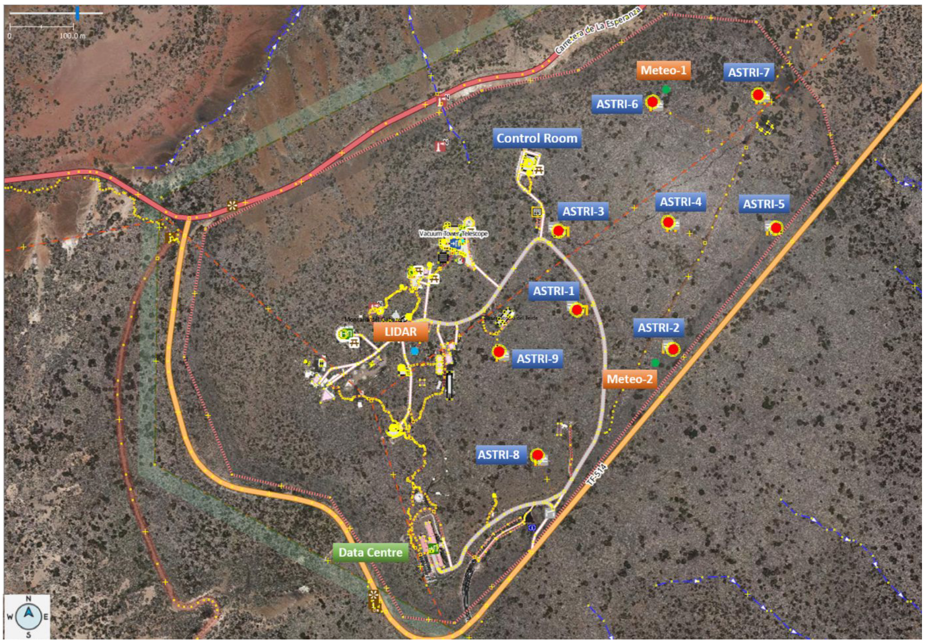

Figure 1: Future layout of the nine telescopes of the ASTRI Mini-Array at the Teide Observatory (IAC)

Currently, the ASTRI collaboration includes more than 150 researchers in 5 countries, en-

[1]in honor of Guido Horn D’Arturo, the Italian astronomer who first proposed the use of tessellated mirrors for astronomy.

compassing several INAF institutes (in Bologna, Catania, Milan, Padua, Palermo, and Rome), universities (Perugia, Padua, Catania in Italy, the University of Sao Paulo in Brazil, the North Western University in South Africa, the Geneva University in Switzerland), the Fundación Galileo Galilei and the Instituto de Astrofísica de Canarias.

2. The ASTRI Mini-Array

The ASTRI collaboration is now engaged in the realization of an array of 9 ASTRI telescopes (the ASTRI Mini-Array) at the Teide Observatory in Tenerife, Spain [5]. The array layout and altitude (2400 m) and the telescopes' design are optimized for observing the gamma-ray sky in the 1-200 TeV energy band, extending the operational range of energies of the current imaging Cherenkov telescopes. Once built (in 2025), the ASTRI Mini-Array will be the largest Cherenkov facility in use. The ASTRI collaboration is responsible also for the array's calibration [6], operation and scientific exploitation.

Figure 2: The ASTRI Cherenkov camera electronics at the Merate laboratories.

The experience with the ASTRI Horn prototype was crucial for developing the Mini-Array. The telescopes are an evolution of the telescope installed on Mount Etna but with significant improvements. The electro-mechanical structure has been optimized for mass (reduced by 30%), functionality and maintainability (see figure 5). The coating of the mirrors was also improved using a combination of Al, SiO_2 and ZrO_2.

The camera system is also being improved evolving the prototype one mounted on ASTRI Horn, through an industrial contract issued by INAF to the CAEN-EIE GROUP industrial pool (See figure 2). SiPM tiles of sensors are produced by Hamamatsu Photonics. The innovative electronics for peak detection for the camera, developed by INAF in collaboration with the Weeroc company, will ensure a small amount of data ([7] and [8]). An interferential filter is used as the front window reducing the sensitivity at wavelengths greater than 550 nm, where the contribution from the night sky background dominates over the Cherenkov light produced by the showers.

The ASTRI telescopes exploit stereoscopic observations [9], based on a layout that covers a strip of approximately 650 x 270 square meters (see figure 1). The ASTRI Mini-Array software, developed mainly by the team, is designed to manage an observing cycle in every aspect, namely observation preparation, observation execution, data processing [10–13] and dissemination to the community. The ASTRI Mini-Array ICT (Information and Communication Technology) facilities will be located on both Tenerife Island and Italy. Tenerife will include the Local Control Room, the On-Site Data Centre at the Teide Observatory and the Array Operation Center at IACTEC in La Laguna. Italy will host the Data Centre in Rome, plus a few Remote Array operation centers in other INAF institutes.

3. The ASTRI Mini-Array performance and science program

The combination of telescope design, array layout, and altitude of the site, makes the ASTRI Mini-Array best suited for the observation of the sky in the multi-TeV regime, with a good sensitivity up to 200 TeV, combined with a good angular and energetic resolution. Montecarlo simulations [14, 15] show indeed that the ASTRI Mini-Array can reach an angular resolution of 3 arcmins with an energy resolution of 10-15 %. These performances will allow us to better characterize the morphology of extended sources at the highest VHE (above 10 TeV). Another important feature of the ASTRI Mini-Array is its large field of view ($\geqslant$ 10 degrees in diameter) with an almost homogeneous off-axis acceptance. (the off-axis sensitivity is similar, within a factor of 2, to the on-axis value for large angles). This feature will allow the ASTRI Mini-Array to study extended sources, perform surveys, and, on Galactic fields, collect exposure on more than one source at a time. The scientific observations of the ASTRI Mini-Array will cover both Galactic and extragalactic targets. The characterization and identification of the PeVatron candidates detected by particle shower detectors like HAWC or LHAASO will be one of the main scientific goals. The ASTRI Mini-Array will be able to resolve the morphology of these sources, to better identify the astrophysical process at the basis of the emission, and then help to understand the nature of the Galactic PeVatrons [16, 17]. The ASTRI Mini-Array will contribute on the extragalactic side to monitor and characterize Blazar emissions. The observation of these sources can also lead to evidence of exotic processes of fundamental physics, like e.g. Lorentz Invariance Violation (LIV) or Axion-like particles (ALP) productions. ASTRI Mini-Array will also follow up transient events of particular interest (for example, events with known low redshift) like Gamma-Ray Bursts and Gravitational Events [18]. The ASTRI Mini-Array science is not limited to γ-ray astrophysics, but it will include the measurement and study of primary Cosmic Rays and stellar intensity interferometry studies. All these studies require long exposures , especially for energies larger than a few tens of TeV. The observational strategy will then focus on a few sky fields to obtain long exposures on selected targets. At this scope, the large field of view of the ASTRI Mini-Array will play an important role in allowing the observation (on the Galactic plane) of a few sources at a time (see figure 3). Observations at large zenith angles will also contribute to reaching the required statistics, especially in the multi-TeV energy range. Long deep exposures will be feasible also thanks to the characteristics of the ASTRI camera that allow observations in moderate moonlight conditions, that is, under a high night sky background rate [19]. Observation with moonlight will increase the maximum observational time for a given target with respect to a pure dark time, up to 50 percent. Figure 4 shows the ASTRI Mini-Array sensitivity for deep exposures ASTRI Mini-Array will then detect fluxes of a few times 10^{-13} erg cm^{-2} s^{-1} for energies of a few tens of TeV, typical of the sources detected by particle shower detectors.

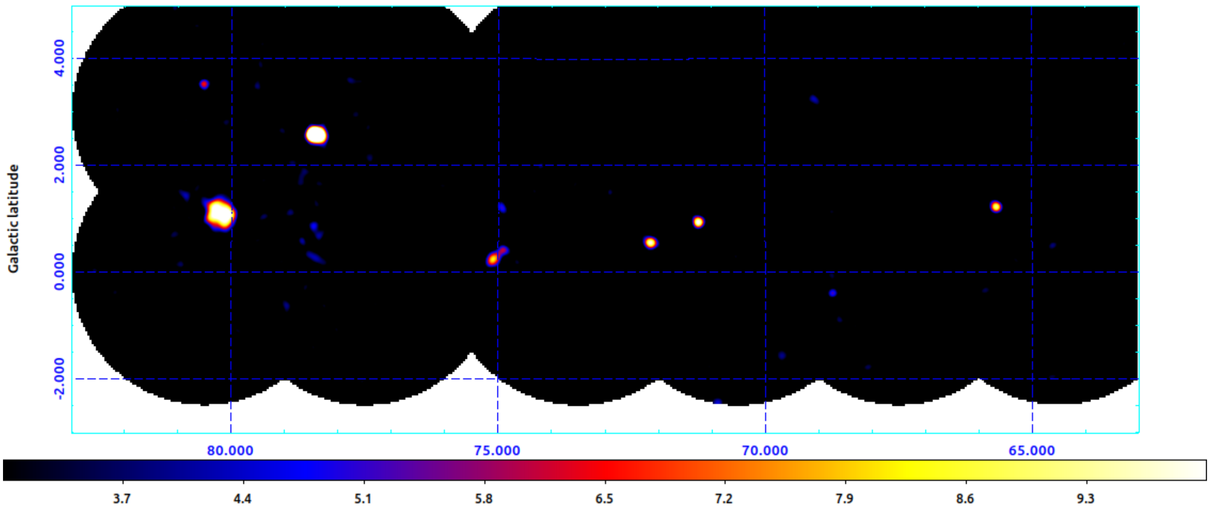

Figure 3: Significance map (Test Statistic) of a simulated survey of the Cygnus region. The large FOV of the ASTRI Mini-Array will allow us to cover large sky regions with few pointings.

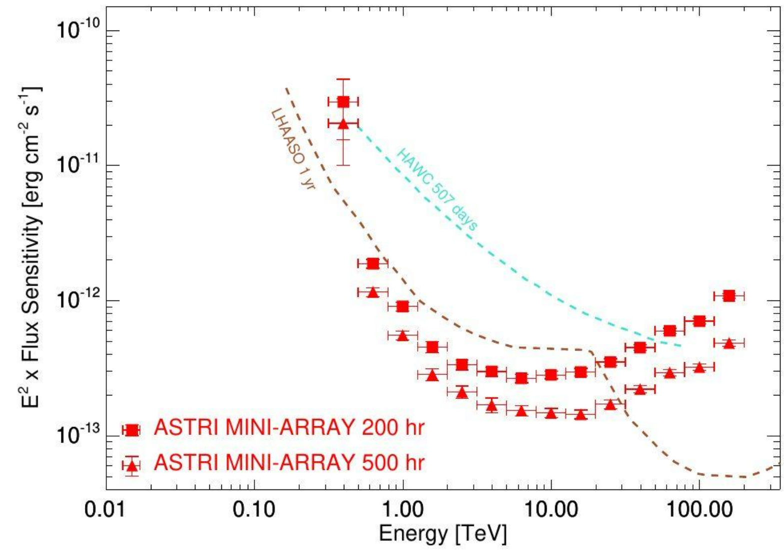

Figure 4: Sensitivity of the ASTRI Mini-Array for 200 and 500 hours of exposure (for a point-like source with a Crab-like spectrum). The HAWC and LHAASO sensitivity (for typical observation times) are also shown for comparison.

A set of ASTRI Mini-Array instrument response functions with a format compatible with science tools packages (e.g. Gammapy and Ctools) are available on Zenodo.org[2]. During the first four years of operations, the ASTRI Mini-Array will be run as an experiment. The ASTRI Science team will develop a strategy to concentrate the observational time on a limited number of programs with clearly identified objectives [20–22]. Since the start of the scientific operations, synergies with other gamma facilities in the northern hemisphere are foreseen.

4. Status and Schedule

The Mini-Array is currently under construction at the IAC Teide observatory. The site infrastructure has been completed and the installation of the telescopes has already started. The first telescope (ASTRI-1) structure, mirrors and camera were installed in 2022.
Two more telescope structures (ASTRI-8 and ASTRI-9) and the first three cameras will be installed during 2023. Once the first three telescopes are ready, a preliminary observational campaign of gamma-ray sources will begin with the aim of both testing the observational chain (stereoscopic observations, data acquisition and processing) and starting to collect data on the brightest sources. The installation of the remaining six telescopes will start in 2024. The ASTRI Mini-Array is expected to be ready for science observations by the end of 2025.

The ASTRI Mini-Array scientific program will start with a first 4-year phase dedicated to the core science goals. In a second phase, the instrument will gradually open up to an observatory-type model, with guest observer programs open to the astronomical community in which a fraction of the time will be assigned to scientific proposals through a Time Allocation Committee procedure.

Figure 5: *Left*: The ASTRI Horn telescope at Serra La Nave. *Right*: the ASTRI-1 telescope at the Teide site.

[2]https://zenodo.org/record/6827882

5. Conclusion

The ASTRI Mini-Array is under construction at the Teide observatory in Tenerife, Spain. Its implementation is expected in 2025 when an array of nine Cherenkov telescopes will be installed. The innovative design of the telescopes and the cameras will allow us to investigate with good angular and energetic resolution the most promising PeVatrons candidates and other Galactic and extragalactic sources up to energies of 200 TeV with an unprecedented field of view for a Cherenkov telescope array. The first four years of observations will be dedicated to a core science program. More information can be found at the ASTRI website (*http://astri.me.oa-brera.inaf.it*), on the social networks[3] or at the outreach events organized by the team [23, 24].

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