The ASTRI Project: prototype status and future plans for a Cherenkov dual-mirror small-telescope array

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ASTRI (“Astrofisica con Specchi a Tecnologia Repliche Italiana”) is a flagship project of the Italian Ministry of Education, University and Research. Within this framework, INAF is currently developing a wide field of view (9.6° in diameter) end-to-end prototype of the CTA small-size telescope (SST), devoted to the investigation of the energy range from a fraction of TeV up to tens of TeVs, and scheduled to start data acquisition in 2014. For the first time, a dual-mirror Schwarzschild-Couder optical design will be adopted on a Cherenkov telescope, in order to obtain a compact optical configuration. A second challenging, but innovative technical solution consists of a modular focal surface camera based on Silicon photo-multipliers with a logical pixel size of 6.2 mm × 6.2 mm. Here we describe the current status of the project, the expected performance, and its possible evolution in terms of an SST mini-array. This CTA-SST precursor, composed of a few SSTs and developed in collaboration with CTA international partners, could not only peruse the technological solutions adopted by ASTRI, but also address a few scientific test cases that are discussed in detail.

1. THE ASTRI PROJECT AND PROTOTYPE

ASTRI (“Astrofisica con Specchi a Tecnologia Repliche Italiana”) is a flagship project of the Italian Ministry of Education, University and Research strictly linked to the development of the ambitious Cherenkov Telescope Array (CTA [Actis et al. 2011]). CTA plans the construction of many tens of telescopes divided in three kinds of configurations, in order to cover the energy range from a tens of GeV (Large Size Telescope, LST), to a tens of TeV (Medium Size Telescope, MST), and up to 100 TeV and beyond (Small Size Telescope, SST). Within this framework, INAF is currently developing an end-to-end prototype of the CTA small-size telescope in a dual-mirror configuration (SST-2M) to be tested under field conditions, and scheduled to start data acquisition in 2014.

For the first time, a wide field of view (FoV = 9.6° in diameter) dual-mirror Schwarzschild-Couder (SC, Vassiliev et al. 2007) optical design will be adopted on a Cherenkov telescope, in order to obtain a compact (f-number f/0.5) optical configuration and equipped with a light and compact camera based on Silicon photo-multipliers with a logical pixel size of 6.2 mm × 6.2 mm, corresponding to an angular size of 0.17° (obtained by means of an optimization process among the commercially-available detectors, the optics performance, and the overall costs of the prototype). Figure 1 (left panel) shows the proposed telescope layout, whose mount exploits the classical alt-azimuthal configuration, and which is fully compliant with the CTA requirements for the SST array. The ASTRI SST–2M prototype will be placed at Serra La Nave, 1735 m a.s.l. on the Etna Mountain near Catania, at the INAF “M.G. Fracastoro” observing station, and will begin data acquisition in 2014 [Maccarone 2011].

2. THE ASTRI DUAL-MIRROR SMALL-SIZE PROTOTYPE

2.1. The Optical Design

The proposed layout [Canestrari et al. 2011] is fully compliant with the CTA requirements for the SST array. Moreover, our design has been optimized in order to ensure a light concentration higher than 80% within the dimension of the pixels over the entire field of view (Figure 1 right panel) and taking into account the segmentation of the primary mirror (M1) and the dimension and position of the camera. The telescope design is compact having a 4.3 m-diameter
2.2. The Mirrors

The primary mirror M1 is segmented into 18 tiles; the central one is not used because completely obstructed by the secondary mirror M2. The segmentation requires three types of segments having different surface profiles. Figure 2 shows an image of a prototype of one M1 mirror segment manufactured with the glass cold-shaping technology. The segments have hexagonal shape with an aperture of 849 mm face-to-face. Each segment will be equipped with two actuators plus one fixed point for alignment. Only tilt misplacements will be corrected. The secondary mirror is monolithic, and has a radius of curvature of 2200 mm and diameter of 1800 mm. M2 will be equipped with three actuators. The third actuator also makes the piston/focus adjustment for the entire optical system available.

2.3. The Telescope Structure

The optical design will be implemented by means of a telescope structure composed of primary and secondary mirrors cells, a pillar and counterweights, the drives systems and a focal surface interface. The telescope mount exploits the classical alt-azimuthal configuration (see Figure 1 left panel).

2.4. The Camera

The SC optical configuration allows us to design a compact and light camera. Currently, the ASTRI camera has a dimension of about 500 mm × 500 mm × 500 mm, including the mechanics and the interface with the telescope structure, for a total weight of about 50 kg (see Figure X for a camera system breakdown). Such small detection surface, in turn, requires a spatial segmentation of a few square millimeters to be compliant with the imaging resolving angular size. Among the available light sensors that offer photon detection sensitivity in the 300–700 nm
Figure 3: Camera system breakdown at component level.

Figure 4: Modular approach adopted to cover with active detectors the entire ASTRI FoV.

band, a fast temporal response and a suitable pixel size, we selected the Hamamatsu Silicon Photomultiplier (SiPM) S11828-3344M (Hamamatsu [2011]). In order to cover the full 9.6° FoV, we used a modular approach, as shown in Figure 4. We call Unit the physical aggregation (imposed by the manufacturer) of 4×4 pixels (3 mm×3 mm each pixel). The logical aggregation of 2×2 pixels is called logical pixel, which turns out to be of 6.2 mm×6.2 mm (0.17°), while the Photon Detection Module (PDM) is composed of 4×4 Units. The ASTRI focal surface, covering the whole FoV, requires 37 PDMs. The advantage of this design is that each PDM is physically independent of the others, allowing maintenance of small portions of the camera. To fit the curvature of the focal surface, each PDM is appropriately tilted with respect to the optical axis. Figure 5 shows an on-axis simulated event for a primary gamma-ray with E=10 TeV, a core distance of 142.77 m and including a night-sky background of \( 1.9 \times 10^{12} \text{ ph m}^{-2} \text{s}^{-1} \text{sr}^{-1} \), (about 3 p.e. pixel\(^{-1} \)). The color-bar shows the number of photo-electrons (p.e.) in each pixel.

2.5. The Prototype Expected Performance

Although ASTRI SST–2M will mainly be a technological prototype, it will perform scientific observations on the Crab Nebula, MRK 421, and MRK 501. Preliminary calculations (Vallania et al. [2012]) show that in the maximum sensitivity range (\( \geq 1 \text{ TeV} \)) we can detect a flux level of 1 Crab at 5\( \sigma \) in a few hours, while in the energy range \( \geq 10 \text{ TeV} \) a flux level of 1 Crab at 5\( \sigma \) can be reached in a few tens of hours. Figure 6 shows a comparison among the expected ASTRI prototype sensitivity as a function of the energy (yellow stars, computed at 5\( \sigma \) and 50 hr of observation) and those of a few Image Atmospheric Cherenkov Telescope (IACT) ones (Whipple, MAGIC, H.E.S.S., CTA) and of large field of view detectors for one-year integration (Fermi-LAT) Because of their strong flux and spectral variations in the two Markarian sources, estimates of exposures are more uncertain. In case of large flares, with fluxes up to 5–10 Crab Units, detection could be reached on a much shorter time-scale (Bonnoli and Vercellone [2012]), allowing intra-night variability studies.
3. THE ASTRI SST-2M MINI-ARRAY

A remarkable improvement in terms of performance could come from the operation, in 2016, of a mini-array, composed by a few SST-2M telescopes and to be placed at final CTA Southern Site. Preliminary Monte Carlo simulations [Di Pierro et al. 2012] yield an improvement in sensitivity that for 7 telescopes could be a factor 1.5 at 10 TeV w.r.t. H.E.S.S., as shown in Figure 7. The ASTRI SST–2M 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 a few arcmin and an energy resolution of about 10–15%. The ASTRI SST–2M mini-array sensitivity were calculated taking into account 5 energy bins per decade, a 5$\sigma$ significance, a number of event/energy-bin $\geq 10$, a signal rate $> 5\%$ w.r.t. the background rate, an integration time of 50 hr, a minimum number of images used in the event reconstruction of 3 and 5, respectively, and for an array configuration as shown in Figure 8.

Moreover, 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, to compare the mini-array performance with the Monte Carlo expectations by means of deep observations of few selected targets, and to perform the first CTA science, with its first solid detections during the first year of operation. Prominent sources such as extreme blazars (1ES 0229+200), nearby well-known BL Lac objects (MKN 501) and radio-galaxies, galactic pulsar wind nebulae (Crab Nebula, Vela-X), supernovae remnants (Vela-junior, RX J1713.7–3946) and microquasars (LS 5039), as well as 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. The large field of view of the ASTRI mini-array will allow us to monitor, during a single pointing, a few TeV sources simultaneously. Figure 9 shows the current TeV sources as listed in the TeVCat\(^1\) compilation. Red, green and cyan circles represent the 9.6$^\circ$ (optical) field of view diameter for three possible pointings along the Galactic Center.

\(^{1}\)http://tevcat.uchicago.edu/
Figure 9: Blue dots are the known TeV sources as listed in the TeVCat Catalogue. The grey line represents the Celestial Equator. The red, green and cyan circles are the ASTRI mini-array (optical) field of view. The left panels are zooms centered on the ASTRI mini-array pointings.

Figure 10: Pulsar wind nebula Vela-X spectral energy distribution. See Hinton et al. [2011] for details.

Plane. The grey line represents the Celestial equator. Although the actual sensitivity will substantially drop for off-axis sources, a few targets can be monitored simultaneously, as shown in the three panels on the left. Simultaneous detection of hard and intense Galactic sources could be feasible, e.g. in the case of Vela–X and Vela–Jr. Several scientific cases can be addressed by the ASTRI mini-array. For the first time, the energy range above a few tens of TeV can be explored with an improved sensitivity compared to the current IACTs. The nearby and powerful pulsar wind nebula (PWN) Vela-X is a typical source which can be considered as a primary target for the ASTRI mini-array. Figure 10 shows its spectral energy distribution (SED), as reported in Hinton et al. [2011], where a clear peak is visible in the H.E.S.S. data (Aharonian et al. [2006a]) at about 10 TeV, and a cut-off at about 70 TeV, making the ASTRI mini-array crucial to explore this portion of the SED.

Figure 11: Supernova remnant RX J1713.7–3946. See Abdo et al. [2011] for details.

Supernova remnants (SNR) are typical Galactic TeV emitters. RX J1713.7–3946 is a young shell-like SNR which could be considered as an excellent laboratory to investigate the cosmic ray acceleration (see Muraishi et al. [2000] and Aharonian et al. [2006b]). The recent detection of this SNR by Fermi (Abdo et al. [2011]) and the combined study with H.E.S.S. (see Figure 11), show that the high-energy and very high-energy (VHE) emission could be interpreted in the framework of a leptonic scenario. Nevertheless, the good energy resolution of the ASTRI mini-array above 10 TeV and its improved sensitivity beyond a few tens of TeV, will improve our knowledge on the main emission mechanism acting in this source in the GeV and TeV energy bands.

The ASTRI mini-array will be extremely important...
to investigate the VHE emission from extragalactic sources as well. Figure 12 shows the SED of the extreme blazar 1ES 0229+200. A clear detection of VHE emission above a few tens of TeV from such a blazar could provide fundamental information on the long-standing debate on the emission mechanisms in this energy band. In particular, since the cosmic-ray-induced cascade displays a significantly harder spectrum above 10–20 TeV, a detection above $\sim 30$ TeV would be only compatible with an hadronic origin of the gamma-rays (Murase et al. [2012]).

4. SUMMARY

The ASTRI SST–2M end-to-end prototype will be installed and operated during Spring 2014 at the INAF Observing Station in Serra La Nave, Sicily. The ASTRI prototype performance will provide crucial information on several topics, such as the dual-mirror Schwarzschild-Couder optical design, the SiPM-based focal surface and the software/data-handling architecture, all of them innovative with respect to the current IACT design. Moreover, the prototype site will allow us to obtain a direct measurement of prominent gamma-ray sources, such as the Crab nebula, MRK 421 and MRK 501. The planned ASTRI mini-array, operated starting from 2016, will constitute the first seed of the future CTA Project, and will be open to the CTA Consortium for both technological and scientific exploitation.

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