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Observatory Galactic Science with the ASTRI-Mini Array during the observatory phase of the project

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The ASTRI-Mini Array will be composed of nine imaging atmospheric Cherenkov telescopes at the Teide Observatory site. The array will observe in the 0.5-200 TeV range with an angular resolution of a few arc-minutes and an energy resolution of about 10%. The deployment of the first cameras will begin in 2022, and in the first four operational years the ASTRI Collaboration has developed a core-science programme focused on a limited number of key science targets. Additionally, thanks to a field-of-view of about 6 degree radius, ASTRI-MA will collect data from many other field sources that will constitute the base of a long-term Galactic observatory programme. In this contribution, I will overview the main themes for this extended observatory science programme for the different astrophysical Galactic environments.

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1. Introduction

The ASTRI (*Astronomia con Specchi a Tecnologia Replicante Italiana*) Mini-Array (ASTRI-MA) [1], a system of imaging atmospheric Cherenkov telescopes (IACTs) composed of nine ASTRI small-sized telescopes (SSTs), is under construction at the *Observatorio del Teide* (Tenerife, Canary Islands) [1]. The commissioning phase will start in 2023, when also the first scientific observations will be carried out. The ASTRI-MA will observe in the 0.5-200 TeV range with a large field of view (FoV) of $\sim 10°$. For an on-axis source, in the 0.5–200 TeV band, the energy resolution is in the range 12-15%; the angular resolution is $\sim 8'$ at 1 TeV, with a minimum value of $\sim 3'$ at 10 TeV, degrading very little up to 100 TeV. The differential sensitivity curve for 50 hours has its minimum value of 7×10^{-13} erg cm^{-2} s^{-1} between 5 and 8 TeV. The dependence of these performances on the offset angle is contained within a 10–20 % degradation from the best nominal values up to 3.5°; the degradation reaches 40–50 % for an offset angle of $\geq$ 4.5°.

After the calibration phase and the validation of the expected performances, in the first four years, the array will be run as an experiment and the ASTRI Mini-Array Collaboration has defined an ambitious observational plan focused on key scientific questions (*Science Pillars*) [2] anchored to a corresponding set of celestial targets that will be deeply (hundreds of hours) observed.

The ASTRI-MA will prioritise observations of core-science cases to investigate in detail the origin of cosmic rays, aspects of cosmology and fundamental physics, GRBs and multi-messenger astrophysics. Observations of additional sources will be either carried out simultaneously to the core-science ones, exploiting the large instrumental FoV, or performed in a subsequent observatory phase. The prospects of extra-galactic astronomy with the ASTRI-MA are covered in an other contribution [3]. Here, we will focus on the observational programme of Galactic TeV sources.

2. Fields and targets of interest

The scientific prospects of the observations of potential ASTRI-MA targets have been evaluated using a suitable set of instrument response functions (IRFs) extracted from a dedicated Monte-Carlo (MC) production of γ-ray and background (proton and electron) showers tailored to the expected array configuration and site atmospheric characteristics. MC data were analysed with A-SciSoft, the data reduction and scientific analysis software of the ASTRI Project [4]. To analyse the high-level scientific simulations, we used ctools v.1.7.2 [5] and Gammapy v.0.18 [6].

The Galactic targets that will be deeply observed for the *Science Pillars* are: the diffuse emission from the Galactic Center (GC), the Pulsar Wind Nebulae (PWN) Geminga and Crab, the mixed-type PWN Supernova-Remnants (SNR) W 28 and VER J1907+062, the young SNRs Tycho, Boomerang, and γ-Cygni. Together, these sources cover eight different sky fields. Two regions are particularly interesting given their high-density of VHE sources: the Galactic Center and the Cygnus region (site of the target γ-Cygni). The Cygnus region for the Northern sky, represents the richest and most interesting extended region to look at, comprising the nearest and most massive star-forming regions of the Galaxy, with a wealth of possible cosmic accelerators, among the many SNRs and PWNe. It extends from 64°to 84°in Galactic longitude l and from -3°to 3°in Galactic latitude b. We simulated a possible survey of the Cygnus region with 50 pointings, at the same Galactic latitude ($b = 0$), spaced by 0.4°in Galactic longitude, from (l, b) = (64, 0) to

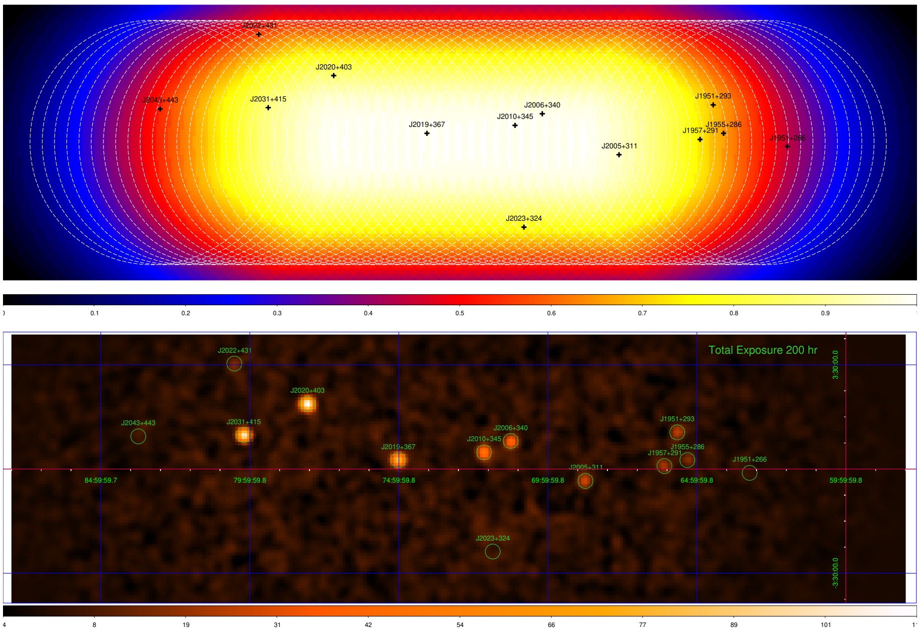

Figure 1: A simulated survey the Cygnus region. Upper panel: colour-based normalised exposure map of the whole field. Each pointing is shown as a circle of radius 4°, uniformly spanning the Galactic longitude from $l = 64$ to $l = 84$. Position and spectra of simulated field sources from [7]. Lower panel: count maps assuming for each pointing an exposure of 4 hr.

$(l, b) = (84{,}0)$. We simulated three different pointing exposures: 1, 2, and 4 hours, to assess the detection efficiency and parameter constraints as a function of the total observing time (50, 100, and 200 hours, respectively). This strategy maximises the exposure at the centre of the field, whereas the boundary regions of the survey are much less covered. An exposure map normalised at 1 for the maximally exposed region, computed at reference energy of 10 TeV, is shown in Fig. 1. For this simulation the list of TeV sources, with their spectra and morphology, are taken from the most recent HAWC catalogue [7]. For the 13 simulated field sources, 9, 10 and 11 sources are significantly detected (Test Statistic (TS) > 25) in 50 hr, 100 hr and 200 hr of total exposure, respectively. Two sources with TS < 9 (3HWC J1951+266 and 3HWC J2043+443) went undetected even in the 200 hr survey because their effective exposure (corrected for the off-axis effective area and number of pointings including these source) was considerably lower than that of the other sources (see upper panel of Fig. 1). For the detected sources, the relative positional errors are of the order of $1'$ or less, thus indicating that a census of a VHE population at the sensitivity presently reached by HAWC could be obtained with the ASTRI-MA using just few tens of hours of exposure.

The GC can be observed only at high zenith angles, thus rising the lower threshold for γ detection, while boosting the effective area for the highest energies. Of the many sources that crowd the GC region, we studied more in detail the VHE emission from the Globular Cluster Terzan 5. Globular Clusters (GlCl) harbour the richest population of neutron stars (NS) per unit volume in the Galaxy. Many GlCls revealed emission in the HE, with typical cut-offs around few GeV [8], but only the GlCl Terzan 5 has been detected in the TeV range (though the best-fit position lied at

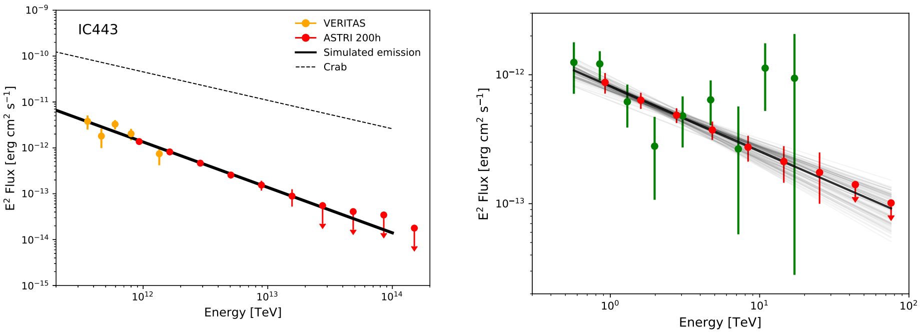

Figure 2: Simulated ASTRI-MA spectra for the SNR IC443 (left panel) and the GC Terzan 5 (right panel). ASTRI-MA dimulated points in red. Data from VERITAS in orange [14]; data from HESS in green [9].

few armin from the GlCl centre [9]). Its VHE spectrum is consistent with an unbroken power-law of index 2.5, for a TeV luminosity 1.5% Crab. Different scenarios have been discussed to explain this emission: either a combined effect of the milli-second pulsar population in the GlCl [10], or relic emission from a past NS-NS merging event [9, 11]. We simulated 200 hr observations with ASTRI-MA at 3 deg$^\circ$ offset (angular distance from the GC). Using the HESS best-fit model [9], ASTRI-MA can detect Terzan 5 up to 30 TeV (right panel of Fig. 2), constraining the presence of a cut-off in the spectrum if the break is at energies less than 12 TeV. Moreover, positional uncertainty on the TeV emission better constrained with ASTRI-MA by a factor of 2.

Among the many sources that will be observed within the *Pillars* programme, we highlight:

- *The SNR IC 433* (also known as G189.1 + 3.0) is a SNR of $\sim 20'$ angular radius, at $\sim 6^\circ$ from Geminga. The age of the SNR is still uncertain, though recent 3D hydro-dynamical simulations suggest an age of $\sim$ 8.4 kyr [12]. It is classified as a mixed-morphology SNR, i.e. a remnant with a shell-like morphology visible in the radio band and a centrally filled thermal X-ray emission. It shows γ-ray emission only up to few TeV, whose origin is ascribed to the interaction of the SNR with a nearby molecular cloud at both HE [13] and VHE [14]. A spectral curvature interpreted as due to the characteristic pion-bump [13] in the HE spectrum strongly suggests that IC 443 is a cosmic-ray hadron accelerator. For a simulated 200 hr ASTRI-MA observation at 3°offset, assuming a power-law of $\Gamma = 3.0$, we obtained significant detection of VHE emission up to tens of TeV (left panel of Fig. 2). A spectral cut-off if present below 10 TeV will be likely constrained.

- *The moderately bright PWN HESS J1813-178*: at 6 degrees angular distance from W 28, this source is a PWN with a particularly hard spectrum ($\Gamma = 2$). TeV emission is likely powered by the very energetic pulsar at the centre, PSR J1813-1749 (spin-down luminosity 7×10^{37} erg s^{-1}). The PWN age is in the range 3.3-7.5 kyr; a recent estimate on the PSR distance, up to 12 kpc [15], would make it one of the brightest TeV source in the Galaxy and, therefore, a particularly interesting target to be observed. The ASTRI Mini-Array can give a major contribution in clarifying the nature of this source, improving its detected spectrum up to, and above, 100 TeV. To test this expectation we simulated the spectrum from the models

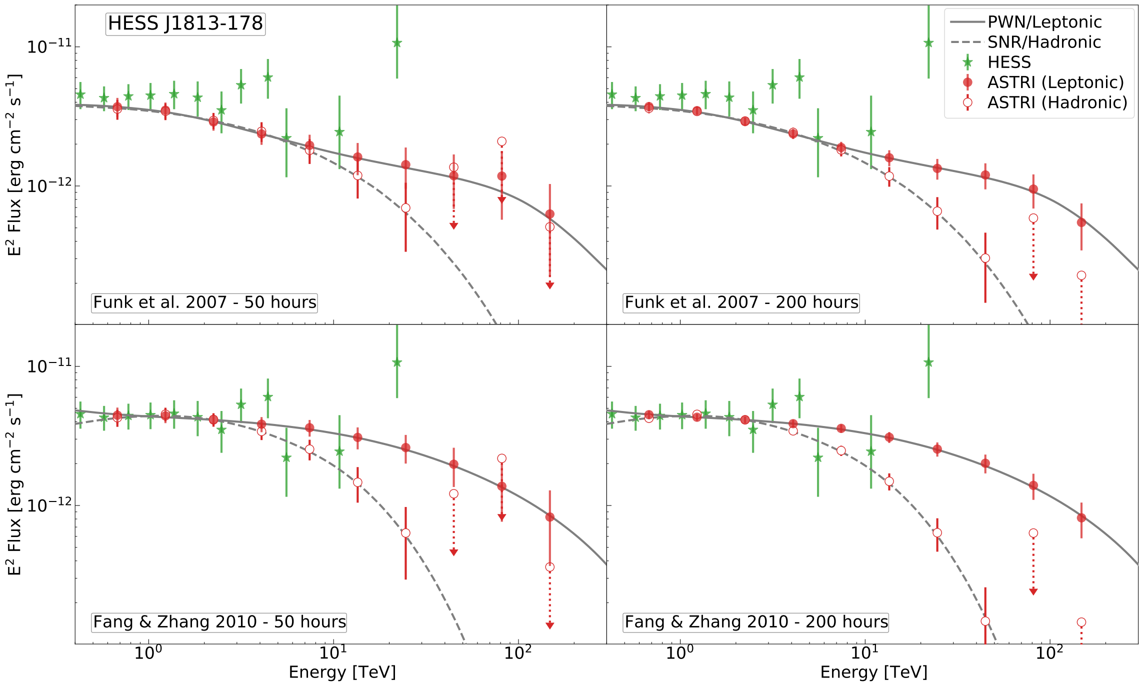

Figure 3: Simulated ASTRI Mini-Array spectral points (red filled circles for leptonic models, open red circles for hadronic models) for 50 hours (left panels) and 200 hours (right panels) of observing times, together with the input models (solid lines for leptonic models, dotted lines for hadronic models) and the available data from H.E.S.S. (green stars; [18]), for the leptonic and hadronic models from [19] (upper panels) and [20] (lower panels). The points with the dashed red error-bars are the upper limits found in the case of the hadronic models.

proposed in [16] and [17]. These papers both discuss a PWN leptonic and a SNR hadronic scenario to describe the MWL emission, with some differences in the assumed electron/proton injection spectra. Data points simulated with the [17] models result already well separated with 50 hours exposure, and it would be possible to select a preferred scenario over the other. In the case of the [16] models 50 hours are not sufficient to clearly distinguish them but we need at least of 200 hours of observations (Fig.3). Interestingly, we found that the source can be detected above 100 TeV already with 50 – 100 hours of observations in the case of leptonic origin of the emission, while in the hadronic scenario the maximum energy is well below this value (also increasing the observing time up to 500 hours).

- *The γ-ray binary LS 5039 and the micro-quasars SS 433:* γ-ray binaries represent a small fraction of all TeV confirmed sources. They consist of a compact objects (only 2 systems certainly host a NS) with an OB companion star. TeV emission produced either by interaction of a pulsar wind with the OB wind via shock acceleration or by Inverse Compton emission of relativistic particles in a jet. In all γ-binaries the TeV emission is strongly phase-dependent. As orbits are generally eccentric, the TeV emission traces the position of the shock front and of the absorbing medium along our line-of-sight. The TeV binary LS 5039 has the shortest orbital period (3.9 days) among the γ-ray binaries. A spin period of few seconds has been

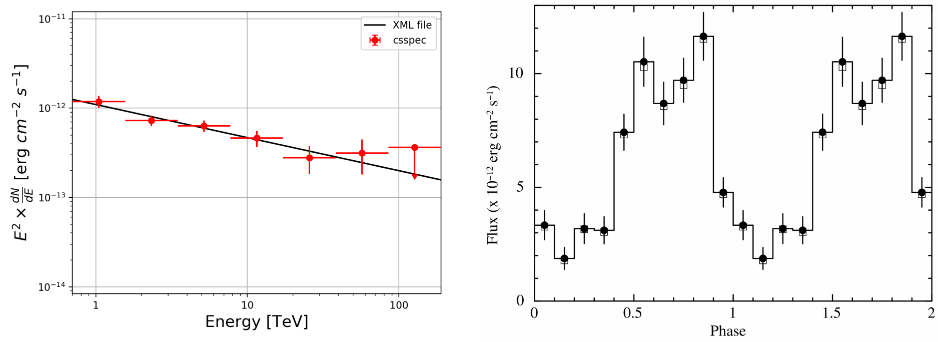

Figure 4: Left panel: the TeV spectrum of the $e1$ spot of SS 433 with 100 hr exposure, assuming a point-like morphology. Right panel: estimated fluxes and uncertainties of LS 5039 for 10 hr exposure in 10 phase-bins of its orbital curve.

claimed, though later disputed. Its TeV flux is highly modulated and the TeV spectral shape also changes according to the orbital phase: from a high luminosity (phase 0.45-0.9, $\Gamma = 1.85$, $E_{\rm cutoff}$ 9 TeV) to a low luminosity state ($\Gamma = 2.35$, $E_{\rm cutoff}$ 13 TeV). We tested the capabilities of the ASTRI-MA to detect a flux modulation of this type adopting a fixed exposure of 10 hr per phase bin (10 bins in total). The resulting folded curve shown in Fig.4 clearly demonstrates the feasibility of such study.

A small group of X-ray binaries (Cyg X-1, Cyg X-3 and SS 433) show HE emission up to GeV. SS 433 (likely a super-Eddington accreting source) with broad MWL emission is a key target to understand particle acceleration in XRB jets [21]. The jet produces two bright TeV spots ($e1$ and $w1$). Using HAWC recent results [22] we investigated the constraints that ASTRI-MA will be able to set on this source. SS 433 is 1.5° from pillar source VER J1907+063. In case of a point-like emission e1 source, ASTRI-MA spectrum in 100 hr would detect the emission up to 100 TeV.

- *TeV J2032-431*: located in the Cygnus region, it is the only known PWN in a binary system. Enhanced TeV emission has been observed during the latest peri-astron passage in 2011, but, as the orbital period is 50 yr, VHE emission is expected in the next decades to be dominated only by the PWN. It resides close to massive OB associations (Cygnus cocoon) where emission above 100 TeV has very recently been detected with HAWC [7] and LHAASO [23]. It is still uncertain whether, and to which degree, the emission is connected to TeV J2032 or it is entirely due to young stellar population winds. We simulated the PWN spectrum of TeV J2032 according to the baseline model obtained with MAGIC and VERITAS [24], i.e. a power-law of index Γ=2.06). The most important aspect regards the possibility to see a cut-off in the spectrum; this will clearly allow us to disentangle the PWN emission from other close-by accelerators. We verified that ASTRI-MA would detect a possible cut-off with 200 hr exposure only if $E_{\rm cut} < (60 \pm 13)$ TeV. As this threshold is far above the typical cut-off seen in other PWN of similar luminosity, we expect to definitively constrain its nature.

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This research made use of CTOOLS [5], a community-developed analysis package for IACT data. CTOOLS is based on GammaLib, a community-developed toolbox for the scientific analysis of astronomical gamma-ray data [25, 26]. This research made use of gammapy,[1] a community-developed core Python package for TeV gamma-ray astronomy [27, 28].

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