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The ASTRI Mini-Array: in the search for hidden Pevatrons

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Despite the enormous efforts done in very recent years, both theoretically and experimentally, the basic three questions about the cosmic rays origin remain without clear answers: what are their sources, how are they accelerated, how do they propagate? Gamma-ray astronomy plays a fundamental role in this field. Both relativistic protons and electrons can emit in the γ-ray band through different processes, but only the detection of hadronic γ-ray emission can probe the acceleration of cosmic rays. In particular, due to the Klein-Nishina suppression of inverse Comptonemission at the highest energies, the detection of γ-ray emission above 100 TeV was expected to provide firm proof of the acceleration of PeV hadrons. However, the recent results published by the LHAASO collaboration revealed the existence of several PeV sources likely related to PWNe, well known leptonic factories (e.g. the Crab Nebula for all). As a consequence, a γ-ray detection at PeV energies may no longer be the final proof of hadronic acceleration. However, the limited angular resolution of LHAASO makes associations uncertain and more detailed and deeper studies are needed. In this context, the ASTRI Mini-Array, with its unprecedented sensitivity and angular resolution at E>10 TeV, not only can extend the gamma-ray spectra of candidate Cosmic Ray factories but could help to distinguish emission regions from PWNe and other LHAASO sources, shedding light on the nature of the highest energy emission.

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1. The PeVatron Context and the role of ASTRI Mini-Array

Among the hottest topics in the very high-energy (VHE) astrophysics are cosmic particle acceleration and Cosmic Ray origin. One of the main investigation channels is non-thermal VHE γ-ray emission, either produced by electrons (bremsstrahlung or inverse Compton processes) or by protons (pion decay from p-p and p-γ interactions). The discosmic raysimination between the two main types of processes, leptonic or hadronic, is fundamental to understand particle acceleration phenomena and cosmic rays origin.

In the cosmic rays standard scenario, Galactic sources should be able to accelerate their light component (p and He) at least up to the "knee" energy ($\sim 10^{15}$ eV) (see [1–5] for recent reviews). Sources able to accelerate protons up to this energy will be referred to as “hadronic PeVatrons”. Recently, HAWC [6] and LHAASO [7] have detected several PeVatrons, most of them likely associated to pulsar wind nebulae (PWNe), like the Crab Nebula, and only a few to supernova remnants (SNRs). There is at least one LHAASO detected source, LHAASO J2032+4102, that seems to confirm 100 TeV emission from massive star clusters (MSCs) [5]. This follows the findings of H.E.S.S.[8, 9]) and then MAGIC [10] and HAWC [11] which detected emission around the Galactic Center (GC) and in other MSCs (e.g. Westerlund 1, Cygnus OB2) [12] with no evidence of a cut-off up to ~30 TeV, suggesting that MSCs in the GC may be responsible for the γ-ray emission. The hadronic or leptonic nature of their emission must be clearly disentangled to assess whether these sources are hadronic PeVatrons. Instead, despite the huge amount of available data, the contribution to cosmic rays acceleration is still largely uncertain.

In this context, the ASTRI Mini-Array will be fundamental thanks to its unprecedented sensitivity and spatial resolution at E > 10 TeV and its wide FoV. The ASTRI Mini-Array is being built at Teide observatory (Tenerife, Canary Sslands) thanks to an agreement between INAF and the *Instituto de Astrofisica de Canarias, IAC* [13]. The ASTRI Mini-Array includes Italian (universities of Perugia, Padova, Catania, Genova and the Milano Polytechnic, INFN sections of Roma Tor Vergata and Perugia,) and international partners (University of São Paulo with FAPESP in Brasil and the North Western University in South Africa) and it will have the first 3 telescopes operative within 2023 and it will be completed (all the nine telescopes) in 2025.

The ASTRI Mini-Array is expected to improve the MAGIC and VERITAS sensitivity in the Northern Emisphere for E > few TeV and to operate for a few years before the full completion of the Cherenkov Telescope Array Observatory (CTAO) North. In particular, its wide FoV ($\sim 10°$) with almost homogeneous off-axis acceptance will allow to survey a multi-target field and to enhance serindipitous discoveries. Its angular resolution (0.05° at 10 TeV) will be fundamental for a morphological reconstruction of extended sources like SNRs, PWNe and MSCs. Therefore, soon, the ASTRI Mini-Array will have a vast discovery space in the field of extreme γ-rays, up to 100 TeV and beyond [14–16].

2. Candidates Galactic PeVatrons with ASTRI Mini-Array

In this paper, we present a summary of the ASTRI Mini-Array simulations of expected emission from some selected candidate hadronic PeVatrons. All the details and some cited figures can be found in [14].

Supernova Remnants - In the standard paradigm, SNRs are the main contributors of Galactic cosmic rays but the unquestionable evidence of freshly accelerated cosmic rays, hadronic γ-ray photons with E > 100 TeV, was not found in any SNR. However, Tycho SNR [17, 18] and SNR G106.3+2.7 [19] have realistic chances to be hadronic PeVatrons. Their γ-ray spectrum is $\propto E^{-2.3}$ without any clear evidence of a cut-off and, for Tycho, multi-wavelength studies clearly point towards a hadronic origin of this emission [20]. SNR G106.3+2.7 shows two separated emission regions but, although MILAGRO [21, 22], HAWC [23], Tibet AS γ [24], LHAASO [7] and MAGIC [25] detected γ-rays from the remnant's region (even up to ~100 TeV) these instruments cannot resolve which one of the two regions is responsible of the highest energy emission because of their low angular resolution. Only better effective area and sensitivity, as the ones of the ASTRI Mini-Array, can better constrain the spectrum at TeV energies, confirming or disproving the PeVatron nature of these two sources.

In Fig. 1 left panel and in Fig. 15 of [14], we show simulations of observation of these two hadronic PeVatron candidates with 500 and 200 hours of exposure, respectively. If Tycho should be a PeVatron source, then the ASTRI Mini-Array will be able to detect it (Fig.15 in [14]) and also to constrain its cut-off (we can exclude a cut-off below 4 PeV at 68% c.l.). For Boomerang SNR (Fig. 1) a detection with the ASTRI Mini-Array in 200 hr at E~100 TeV will constrain the proton maximum energy up to E~500 TeV with very small error bars. But the main strength of the ASTRI Mini-Array will be its angular resolution that will allow us to disentangle different components of the source region at different energies.

Galactic Center (and Massive Star Clusters) - The other strong hadronic PeVatron candidate is the GC region (comprises between ~ 1.5° in Galactic longitude and 0.2° in Galactic latitude). In this volume there are the central super-massive black-hole SgrA*, many star-forming regions, pulsars, SNRs, and many other astrophysical potential accelerators that could contribute to the TeV γ-ray excess detected by H.E.S.S. [8, 9], VERITAS [26] and MAGIC [10, 27]. This emission is perfectly correlated with the gas distribution and shows a hard PL spectrum without evidence of a cut-off at least up to 40 TeV, and lack of variability.

In Figure 17 of [14], it is evident that ASTRI Mini-Array will be able to extend the H.E.S.S. spectrum and, consequently, not only to detect possible particle PeV emission (γ-ray emission above 100 TeV) but also, with the same exposure time as H.E.S.S. (260h), to constraint the cut-off at E < 2 PeV with 95% c.l.. In addition, the excellent angular resolution of the ASTRI Mini-Array could help to identify the VHE source among several candidates and the very large Field of View (FoV) will allow to map the whole GC region (and other MSC) in a single observation.

The Crab nebula (and other PWNe) - Most of the LHAASO detected PeV sources [7] are likely related to pulsars, well known leptonic factories, and/or their nebulae, PWNe (the Crab Nebula for all), the only galactic sources where we expect to see electrons accelerated up to PeV energies [5]. Consequently, a γ-ray detection at these energies still cannot be considered the final proof of hadronic acceleration. Furthermore, the limited angular resolution of LHAASO at TeV scale makes associations uncertain and, thus, more detailed and deeper studies are needed. The Crab nebula, being detected also at PeV energies by LHAASO, is an extraordinary and surprising source for the VHE community. The current open question is if its emission is totally due to leptons or if there is also a hadronic component. In order to properly answer this question, the entire SED must be modeled and compared with all available data for different assumptions on the pulsar wind speed and composition [14].

The ASTRI Mini-Array sensitivity will allow us to constrain the hadronic contribution in the Crab Nebula (and similar sources): different hadrons' fraction and energies imply different behavior at the highest energies. In Figure 22 in [14] we show that with an exposure of 500h, ASTRI Mini-Array may play a fundamental role to constrain the hadronic contribution to the PeV γ-ray emission of the Crab.

Follow-up of LHAASO sources: LHAASO J1908+0621 - Among other PeVatron candidates, one of the most promising TeV sources is VER J1907+062 (MGRO J1908+06/2HWC J1908+063/LHAASO J1908+0621) [see e.g. 28]. After its discovery by MILAGRO [21], this VHE source with a very complex morphology was detected by HAWC up to ~ 100 TeV with no evidence of a cut-off [6, 29] and recently by LHAASO [7] up to ~ 500 TeV. In spite of a strong correlation between ^{12}CO emission and the SNR G40.5-0.5, likely connected with VER J1907+062, other possible counterparts cannot be excluded with the current data (see also [30]). Also the possible association of the emission with the PWN of PSR J1907+0621 has been considered [e.g. 31–33], but in fact there is no consensus on whether the emission is hadronic or leptonic.

The ASTRI Mini-Array, as showed in Figure 1 right panel, will be able to detect possible PeVatron emission from this source with 200 h of exposure, constraining the cut-off to E<0.96 PeV with 95% c.l.. An X-ray follow-up of this source and similar ones could be very important in order to constrain the γ-ray emission model and we are moving in this direction through X-ray observations proposals. Moreover, we are working on ASTRI Mini-Array simulations in order to resolve a possible energy-dependent morphology (using a 2-zone models) impossible with the resolution of the current instruments (Crestan et al. in preparation). ASTRI Mini-Array could firmly constrain the origin of the emission from the northern region of VER J1907+062 and thus assess its PeVatron nature.

3. Conclusions

The ASTRI Mini-Array will be a forerunner of the CTAO, with the first three telescopes operative within 2023 and all the nine telescopes will be ready within 2025. Our first simulations show how ASTRI Mini-Array will contribute in a fundamental way to the cosmic rays study thanks to its unprecedented performance at the TeV and multi-TeV energy bands. We are working on further simulations in order to assess the improvements that are expected thanks to the very good angular resolution of this instrument.

Taking into account all the well known occurrence of unfavorable conditions (bad weather, maintenance operations, Canary "calima"[1]), we expect to have on average ~1800 h/yrs available for observations, also thanks to the possibility to operate in the presence of the Moon [34]. The ASTRI Mini-Array has a great potentiality to answer the question "What are the sources of Galactic cosmic rays?" in the very near future.

[1]This is the name given by local people to the Saharan dust tha covers the islands, affecting air quality and visibility

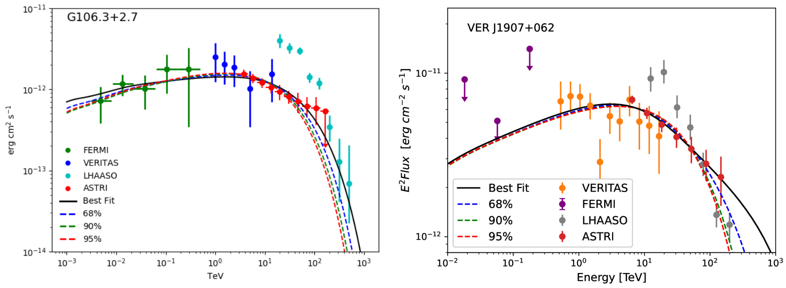

Figure 1: *Left panel* - G106.3+2.7: γ-ray data from Fermi-LAT (purple), VERITAS (orange), LHAASO (cyan) and ASTRI Mini-Array (red, 200h). The solid lines show the emission from a proton population with a best-fit cut-off energy of 350 TeV (black) and lower-limit cut-off energy of 250 (blue), 180 (green) and 160 (red) TeV at 68, 90 and 95% c.l., respectively.*Left panel* - VER J1907+062: γ-ray data from Fermi (purple dots), VERITAS (orange dots), LHAASO (grey points) and ASTRI Mini-Array simulations (100h, red dots). The blue, green and red lines show the broken power law fit with a cut-off energy of 1.67, 0.54 and 0.4 PeV, corresponding to 68, 90 and 95% c.l. respectively.

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