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ASTRI Mini-Array follow-up of LHAASO and HAWC sources

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In recent years the number of known sources emitting in the multi-TeV regime (from tens to hundreds of TeV) has increased significantly thanks to facilities like LHAASO and HAWC. These observations have the potential to change our understanding of particle acceleration processes in our Galaxy. However, many of the observed sources are still unidentified or poorly constrained due to the limited angular resolution of these instruments, preventing us from performing a detailed study of the sources. The ASTRI Mini-Array is an array of nine Cherenkov telescopes under construction at the Teide Astronomical Observatory in Tenerife, Spain. It will operate in multi-TeV regime with unprecedentedly good angular resolution (~ 0.05 deg @ 10 TeV) and large field of view (~ 10 deg in diameter). Here we present the simulations and the spatially-resolved spectral analysis of a set of sources for which the ASTRI Mini-Array will allow us to identify the astrophysical objects emitting at these extreme energies.

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1. The ASTRI Mini-Array

LHAASO observations have shown that the gamma sky is rich in sources also in the UHE region of the spectrum ($E > 0.1$ PeV). The first catalog of LHAASO sources [1] contains 90 sources, most of which are along the plane of the Galaxy between $l = 10°$ and $l = 200°$. Although some of these have clearly identified counterparts (e.g. Crab, or SNR G106) many of them are unidentified, as they have no known counterpart, or have more than one. A good understanding of the astrophysical phenomena capable of accelerating particles at these enormous energies requires a detailed characterization (both morphological and spectral) of the sources seen by LHAASO.

The ASTRI Mini-Array [2, 3] is an array of small Cherenkov telescopes optimized for high-energy observation ($E > 1$ TeV). It is characterized by an excellent angular (0.05° at 10 TeV) and spectral resolution (12% at 10 TeV) and a large field of view (~ 10° in diameter) which will allow the coverage of large sky areas. The ASTRI Mini-Array will observe from the Teide observatory (Tenerife), located at a latitude very similar to that of LHAASO.

The follow-up of LHAASO sources will be one of the main goals of the ASTRI Mini-Array. In the following paragraphs, we present a sky region in which the ASTRI characteristics (large field of view and good angular resolution) will allow us to study in detail the sources detected by LHAASO. The following simulations and analyses make use of the GAMMAPY software library [4] and of the ASTRI Mini-Array Instrument Response Functions [5]

2. The sky region of LHAASO J1956+2845

LHAASO J1956+2845 is one of the twelve ultrahigh-energy γ-ray sources detected by LHAASO in 2021 [6]. It has a specific flux of $(2.5 \pm 0.5) \times 10^{-17}$ photons TeV^{-1} cm^{-2} s^{-1} at 100 TeV and emits up to a maximum detected energy $E_{\rm max} \approx 420$ TeV. In the first LHAASO catalog, published in 2023 [1], a more complex morphology of this sky region emerged. Within a radius of 5 degrees from LHAASO J1956+2845 there are three point sources (1LHAASO J1952+2922, 1LHAASO J1954+2836u, and 1LHAASO J2002+3244u), three extended sources with $\sigma \approx 0.15 - 0.30$ degrees (1LHAASO J1954+3253, 1LHAASO J1959+2846u, and 1LHAASO J2005+3050) and three very diffuse sources with $\sigma \gtrsim 0.75$ degrees (1LHAASO J1951+2608, 1LHAASO J1956+2921, and 1LHAASO J2005+3415*). Figure 1 shows the models we used to represent this sky region. The upper panels show the 1–25 TeV (left) and 25–300 TeV (right) sky maps, with all the 1LHAASO sources labeled in black, LHAASO J1956+2845 represented as a magenta circle, and the 3HWC sources represented as blue circles. As the figure shows, all the 1LHAASO sources have an HAWC counterpart (1LHAASO J2005+3415* is probably a merging of multiple sources), with the exception of 1LHAASO J1954+3253 and 1LHAASO J2002+3244u. The lower panel shows the 1–300 TeV sky map together with the middle-aged pulsars [7] (black dots) and the middle-aged radio supernova remnants [8] (white contours). The detail of these sources are discussed in the following and summarized in Table 1.

2.1 1LHAASO J1954+2836u, 1LHAASO J1959+2846u and 1LHAASO J1956+2921

1LHAASO J1954+2836u, 1LHAASO J1959+2846u and 1LHAASO J1956+2921 are spatially coincident with the previously detected LHAASO J1956+2845. 1LHAASO J1954+2836u is a

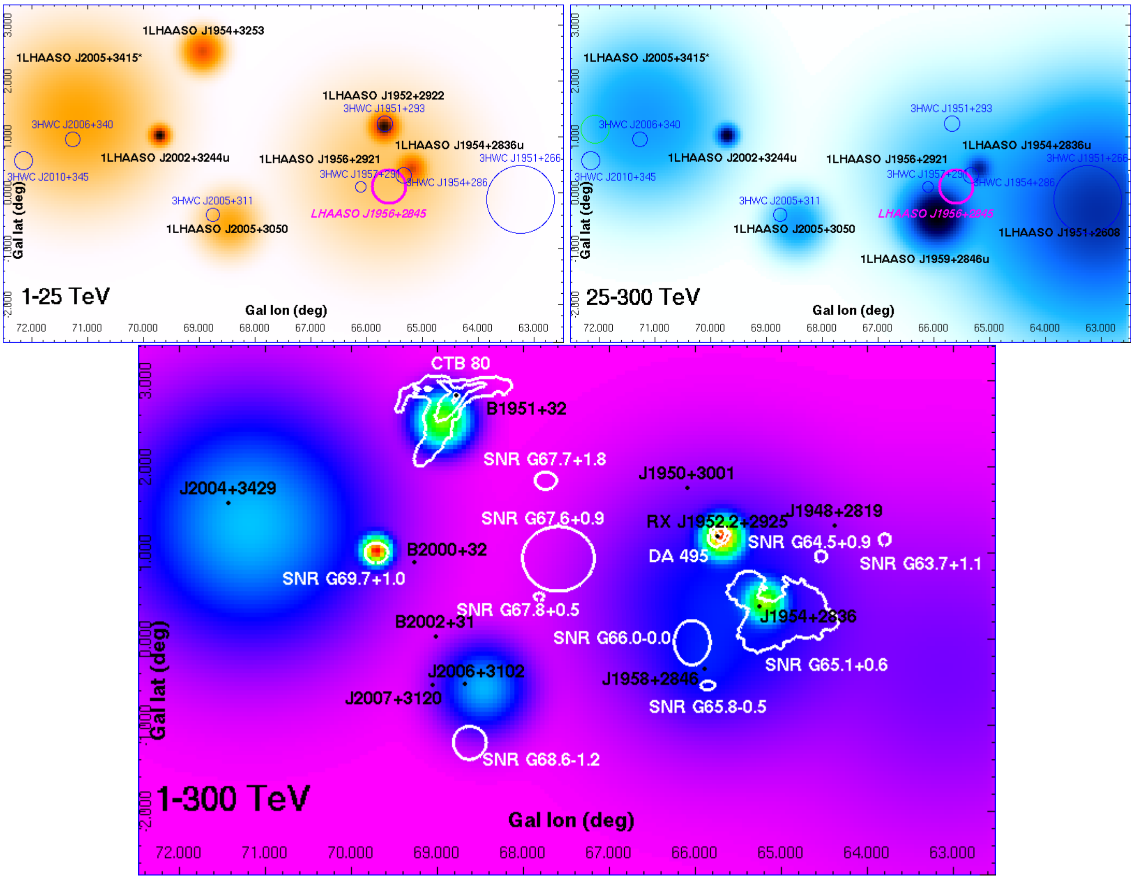

Figure 1: Sky map modelled according to the first LHAASO catalog [1], in the energy ranges 1–25 TeV (upper left panel), 25–300 TeV (upper right panel), and 1–300 TeV (lower panel). In the upper panels, the 1LHAASO and the 3HWC sources are indicated, as well as the location of LHAASO J1956+2845 (magenta circle). The lower panel also shows the middle-aged supernova remnants (white contours) and pulsars (black dots).

point source with a broad-band spectrum from 1 to 300 TeV, while 1LHAASO J1959+2846u is extended and only hard (> 25 TeV). They both have a significant TS above 100 TeV (TS_{100} = 44.9 and TS_{100} = 74.0, respectively), and a compelling HAWC counterpart [9]. These two sources are spatially coincident with two *Fermi* pulsars (PSR J1954+2836 and PSR J1958+2846), that have $\dot{E}$ of 1 and 0.3 $\times 10^{36}$ erg s^{-1} and τ_c of 70 and 20 kyr, respectively. The distances, estimated using the empirical 'pseudo'-distance relation for γ-ray pulsars [10], is about 2 kpc for both sources. They have a typical cut-off power-law spectrum in the 0.1–100 GeV energy range and no evidence for emission above 100 GeV [11]. Uncostraining upper limits for the presence of PWNe were also reported [12]. PSR J1954+2836 is probably associated to SNR G65.1+0.6, a middle-aged supernova remnant (size $\sim 90' \times 50'$) with radio and γ-ray emission in the southern shell region [13–15]. VERITAS shows a 3.5σ excess that can be compatible with the SNR and the PSR position [16]. 1LHAASO J1954+2836u can thus be the 100 TeV counterpart of this SNR (see also [15]). On the contrary, SNR G65.8–0.5 and SNR G66.0–0.0 are found at 0.16° and 0.39° away from the position of 1LHAASO J1959+2846u, with a radio size of $\sim 10' \times 6'$ and $\sim 30' \times 25'$, respectively

[17]. For this LHAASO source, the interpretation of the TeV halo emission powered by PSR J1958+2846 is more likely.

It is not clear yet if LHAASO J1956+2845 is powered by the sum of the ultra-high-energy 1LHAASO J1954+2836u and 1LHAASO J1959+2846u, and what is the role of the diffuse source 1LHAASO J1956+2921 (σ = $(0.99 \pm 0.07)^{\circ}$), that could be due to cosmic rays escaping from the close by sources or to the local enhancement of the target gas.

2.2 1LHAASO J1952+2922 and 1LHAASO J1954+3253

1LHAASO J1952+2922 is a point source at about 1° from LHAASO J1956+2845, with a rather soft spectrum; these characteristics are roughly in agreement with the findings of other VHE facilities [9, 16]. This source is coincident with DA 495 (G65.7+1.2), a PWN that emits also in radio [18], X-rays [19], and possibly γ-rays [11]. A soft unresolved source with a blackbody temperature of 1 MK consistent with a neutron star, dubbed RX J1952.2+2925, was discovered by *Chandra* at the center of the nebula [20]. Given that the pulsations have not been detected so far, we cannot have reliable measurements of the age and the energetic of the neutron star and its nebula; independent estimates based on the broad-band emission give $\tau \approx 20-200$ kyr and $\dot{E} \approx 5 \times 10^{34} - 10^{37}$ erg s^{-1}.

1LHAASO J1954+3253 is an extended source detected between 1–25 TeV. In this energy range, no source has ever been detected within $\sim 2.5^{\circ}$ from its position (see e.g. [21–23]). The source is spatially coincident with the composite SNR G69.0+2.7, also known as CTB 80. It is a middle-aged (50 – 80 kyr) supernova remnant [14] with a complex radio morphology showing three extended radio arms and a radio [24] and X-ray [25] compact nebula near the location of the pulsar PSR B1951+32 ($\dot{E}$ = 3.7×10^{36} erg s^{-1} and τ_c = 107 kyr). The pulsar emits radio, X- and γ-rays [26]. The whole system is about 3 kpc distant [27]. In addition to the pulsar emission, *Fermi* data reveals an excess in the northern part of the SNR [11, 28]; the reported flux between 0.1–0.3 TeV is consistent with the extrapolation at lower energies of the 1LHAASO J1954+3253 spectrum ([28], see also Figure 2, left panel). However, the association is yet to be confirmed because the LHAASO source is about 0.5° away from the *Fermi* excess of the SNR and about 0.3° from the pulsar and its nebula.

2.3 1LHAASO J2002+3244u and 1LHAASO J2005+3050

1LHAASO J2002+3244u is a point source throughout the all LHAASO energy range, with TS_{100} = 28.1. Remarkably, it does not have a counterpart of other VHE facilities [22, 23, e.g.]. It is spatially coincident with SNR G69.7+1.0, a radio supernova remnant with a diameter of ~ 16' [29], that was recently detected also in the γ-rays by *Fermi* [11] (see Figure 2, right panel). At about 0.45° there is the radio pulsar B2000+32, but an association seems unlikely due to the distance of the pulsar (6.4 kpc, inferred from the dispersion measure [30]).

1LHAASO J2005+3050 is an extended source; within 0.23° from its centroid there is 3HWC J2005+311, that has a similar spectral shape [9]. This TeV source is spatially coincident with the *Fermi* pulsar J2006+3102 ($\dot{E}$ = 2×10^{35} erg s^{-1} and τ_c = 100 kyr, $d \approx 6$ kpc [29]), while the nearest radio supernova remnant is SNR G68.6–1.2, that is 0.67° away. For this source, the TeV halo interpretation is favored.

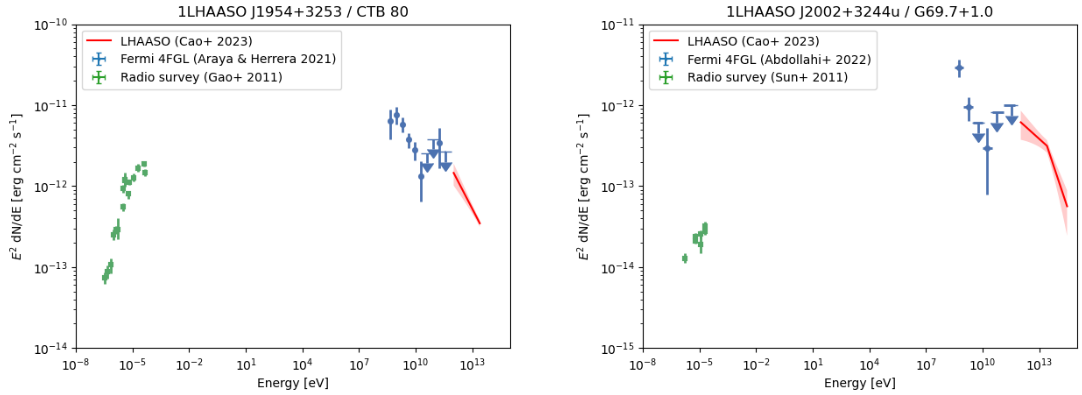

Figure 2: SED of the two supernova remnants for which, before the 1LHAASO catalog, there were no TeV counterparts: 1LHAASO J1954+3253 / CTB 80 (left panel) and 1LHAASO J2002+3244u / G69.7+1.0 (right panel). The plotted data are taken from [1, 11, 14, 28, 29].

2.4 1LHAASO J1951+2608 and 1LHAASO J2005+3415*

1LHAASO J1951+2608 and 1LHAASO J2005+3415* are very diffuse sources for which there is no obvious association. The previous is spatially coincident with the extended HAWC source 3HWC J1951+266, while the latter is probably the merging of 3HWC J2006+340 and 3HWC J2010+345. The astrophysical objects present in the field are the pulsar J2004+3429 and the compact radio/optical nebula G70.7+1.2, as well as *Fermi* unidentified sources; possible associations are discussed in [31].

2.5 Our simulations

We simulated the ASTRI Mini-Array observation of 300 and 500 hr on the sky region around LHAASO J1956+2845 (a single pointing of the ASTRI Mini-Array can cover a region 10 degrees wide, thanks to its large field of view). The 9 sources were modeled as reported in the first LHAASO catalog [1]: we assumed a Gaussian disk as morphology, with σ reported in Table 1, and a broken power law as spectrum with $E_{\rm break}$ = 25 TeV, Γ_1 and Γ_2 reported in Table 1. In fact, the first LHAASO catalog [1] provides for each source two different spectra, corresponding to the measures of the WCDA and KM2A detectors, that are sensitive between 1–25 TeV and above 25 TeV, respectively. The test statistic (TS) map of the 500 hr observation is shown in the first panel of Figure 3.

We used the GAMMAPY source detection algorithm with the simulated morphologies and spectra, which identified 5 sources out of 9. The residual map shows that 2 additional sources must be included in the model (second panel of Figure 3). For all the sources included in the model, the maximum detected energy together with the TS is reported in Table 1 for both 300 hr and 500 hr of observing time. We note that the only 2 sources that are not detected in our set of simulations are those with a KM2A counterpart only, due to the worse ASTRI Mini-Array sensitivity above 30 TeV [2].

Source name 1LHAASO	σ $^\circ$	Γ_1	Γ_2	$E_{\rm max}^{300}$ TeV	TS^{300}	$E_{\rm max}^{500}$ TeV	TS^{500}	Possible association
J1951+2608	1.00 ± 0.11	...	3.43 ± 0.17	...	...	...	...	...
J1952+2922	< 0.12	2.52 ± 0.10	...	14.1	20	14.1	22	DA 495†
J1954+2836u	< 0.12	2.22 ± 0.09	2.92 ± 0.14	64.2	4.5	64.2	9.4	G65.1+0.6‡
J1954+3253	0.17 ± 0.03	2.45 ± 0.09	...	14.1	18	30.1	4.6	CTB 80 †‡
J1956+2921	0.99 ± 0.07	2.03 ± 0.06	3.42 ± 0.12	30.1	5.3	30.1	7.7	...
J1959+2846u	0.29 ± 0.03	...	2.90 ± 0.10	...	...	...	...	PSR J1958+2846*
J2002+3244u	< 0.16	2.21 ± 0.11	2.70 ± 0.22	30.1	9.2	30.1	18	G69.7+1.0‡
J2005+3415*	0.74 ± 0.04	2.58 ± 0.05	3.79 ± 0.21	30.1	6.1	30.1	7.7	...
J2005+3050	0.27 ± 0.05	1.99 ± 0.10	3.62 ± 0.21	6.6	16.8	14.1	11.1	PSR J2006+3102*

Table 1: Summary of the sources in the sky region of LHAASO J1956+2845 reported in the first LHAASO catalog [1]. The 39% containment radius σ is that reported in their Table 1 (for sources observed by both the WCDA and KM2A detectors, the extension corresponds to that with higher significance level). Γ_1 and Γ_2 are the photon indices of the spectral broken power-law model with $E_{\rm break}$ = 25 TeV, that are also reported in Table 1 for the WCDA and KM2A instruments, respectively. The maximum detected energy $E_{\rm max}$ and its TS is for 300 and 500 hours of simulations by ASTRI Mini-Array instrument. The PWNs are marked with the † symbol, the ‡ indicate SNRs while the $*$ is for TeV-halos sources.

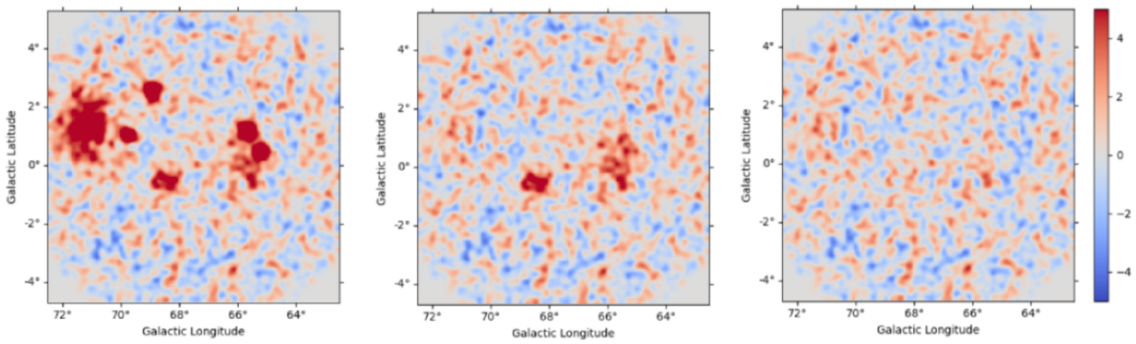

Figure 3: Residual map using as sky model: (left panel) the gamma diffuse and residual CRs background, (middle panel) backgrounds + sources automatically detected, (right panel) other two extended sources added.

3. Conclusions

The LHAASO and HAWC sources will be a great opportunity for the scientific observations of the future ASTRI Mini-Array.

The simulations and analyses presented in these proceedings focus on the region of the sky around LHAASO J1956+2845, where ASTRI, thanks to its wide field of view, will be able to collect data simultaneously from several sources, allowing us to get deep exposure on them. Most of these sources are unidentified, with possible counterparts including PWNe, TeV Halos and SNRs. The high-resolution observations of the ASTRI Mini-Arraywill help to association with known counterparts and therefore to the understanding of the physical processes that lead to such high energy radiations.

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