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The ASTRI Mini-Array Science Case

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Abstract: ASTRI is a Flagship Project financed by the Italian Ministry of Education, University and Research, and led by INAF, the Italian National Institute of Astrophysics. Within this framework, INAF is currently developing an end-to-end prototype of a Small Size Telescope in a dual-mirror configuration (SST–2M) for the Cherenkov Telescope Array (CTA), scheduled to start data acquisition in 2014. Although the ASTRI SST-2M prototype is mainly a technological demonstrator, it will perform scientific observations of the Crab Nebula, Mrk 421 and Mrk 501 at $E \geq 1$ TeV. A remarkable improvement in terms of performance could come from the operation, in 2016, of a SST–2M mini-array, composed of a few SST–2M telescopes to be placed at final CTA Southern Site. The SST mini-array will be able to study in great detail relatively bright sources (a few $\times 10^{-12}$ erg cm^{-2}s^{-1} at 10 TeV) with angular resolution of a few arcmin and energy resolution of about 10–15%. Thanks to the stereo approach, it will be possible to verify the wide field of view (FoV) performance through the detections of very high energy showers with 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 selected targets, and to perform the first CTA science at the beginning of the mini-array operations. Prominent sources such as extreme blazars (e.g., 1ES 0229+200), nearby well-known BL Lac objects (e.g., MKN 501) and radio-galaxies, galactic pulsar wind nebulae (e.g., Crab Nebula, Vela-X), supernovae remnants (e.g., Vela-junior, RX J1713.7−3946), micro-quasars (e.g., LS 5039), and 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.

Keywords: ASTRI, Imaging Atmospheric Cherenkov Telescopes, CTA, High Energy Astrophysics

1 Introduction

ASTRI ("Astrofisica con Specchi a Tecnologia Replicante 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, [1, 2]). 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 at the INAF "M.C. Fracastoro" observing station in Serra La Nave (Mount Etna, Sicily) [3], and scheduled to start data acquisition in 2014. A detailed description of the ASTRI Project, the Prototype structure, mirrors, camera, and scientific performance are provided in [4, 5], [6], [7], and [8], respectively. Although the ASTRI SST–2M will mainly be a technological prototype, it will perform scientific observations of the Crab Nebula, MRK 421, and MRK 501. Preliminary calculations show that in the maximum sensitivity range (≥ 1 TeV) we can obtain a 5σ detection of a source at a flux level of 1 Crab in a few hours, while in the energy range ≥ 10 TeV a flux level of 1 Crab at 5σ can be reached in a few tens of hours. Because of strong flux and spectral variations of the two Markarian sources, estimates of exposures are more uncertain. In case of large flares, with fluxes up to 5–10 Crab Units (see, e.g., [9]), detection could be reached on a much shorter time-scale.

2 The mini-array in a nutshell

A remarkable improvement in terms of performance -and expected scientific results- could come from the operation in 2016 of a mini-array, composed of a few SST–2M telescopes and to be placed at the final CTA Southern Site. This could constitute the first *seed* of the future CTA Project. The SST-2M mini-array will verify the following array properties:

- the array performance in terms of reliability and cost at the chosen site;
- the trigger algorithms;
- the wide field of view performance to detect very high energy showers with the core located at a distance up to 500 m;
- the hardware/software configurations for the array;
- the data-handling chain.

Moreover, through deep observations of a few selected targets, it will allow us to compare the actual performance with the Monte Carlo expectations, and to perform the first CTA science, by means of a few solid detections during the first year.

A preliminary set of tests on the scientific performance of the SST–2M mini-array (with different geometrical configurations and under a few simplifying assumptions) is reported in [10]. These Monte Carlo simulations allowed us to estimate that the mini-array will be able to study relatively bright sources, as discussed in [11]. The expected scientific cases shown in the present paper are based on the most updated simulations of a SST–2M mini-array performed by the ASTRI Monte Carlo group in synergy with the CTA Monte Carlo group, and whose results are discussed in [12]. The main figure of merit is the sensitivity, expressed as the minimum detectable flux in 50 hrs of observations. With an energy threshold of ~ 1 TeV, the ASTRI mini-array, in a 7-unit layout, has a sensitivity similar or better than that of H.E.S.S. in the energy range (a few – 100) TeV (see Figure 6 in [12]). The other two key parameters, the angular and energy resolution, can be as good as 0.08 deg and 15% respectively at 10 TeV. Since energies higher than few tens of TeV are widely unexplored, dedicated analysis techniques may provide room for further improvement in that regime.

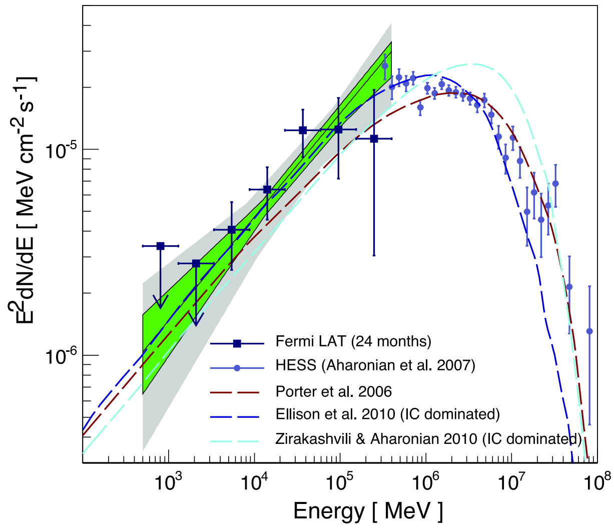

Fig. 1: Supernova remnant RX J1713.7−3946. See [17] for details.

3 Galactic targets and science

The CTA Southern site will provide an excellent view of most of the Galactic plane and of the Galactic Bulge. Several Galactic sources have been detected so far (see [13, 14]) above a few tens of TeV, including shell-type supernova remnants (SNR), pulsar wind nebulae (PWN, such as the Crab Nebula), binary systems, the Galactic Center, as well as a number of unidentied sources apparently emitting only above 100 GeV with no lower-energy counterparts.

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 [15] and [16]). The recent detection of this SNR by *Fermi* [17] and the combined study with H.E.S.S. (see Figure 1) show that the high-energy and very high-energy (VHE) emission could be interpreted in the framework of a leptonic scenario. Nevertheless, the majority of current models adopt a spherical geometry, while it is known that the gas distribution around the SNR is inhomogeneous [18] (and references therein). A clumpy circum-stellar medium (CSM) could produce an hadronic spectrum different from the prediction of a simple spherical model. A detailed comparison between the proton distribution in the CSM and the high-resolution gamma-ray image is therefore a useful test of the hadronic scenario. The improved sensitivity and angular resolution of the mini-array at energy above 10 TeV with respect to the current IACTs will allow us to investigate the VHE emission in the different regions of this source, studying their spectra.

Tycho's SNR is the best candidate as Pevatron [19], but it will not be accessible from the CTA southern site (it is located at $Dec(\mathrm{J2000}) \sim +64^{\circ}$ North). Interestingly, the Kepler's SNR, which will be accessible to CTA, is very similar to Tycho in many respects and it is expected to produce a similar gamma-ray spectrum. The H.E.S.S. telescope observed Kepler's SNR for 13 hrs and provided upper limits on the energy flux in the range 230 GeV – 12.8 TeV of 8.6×10^{-13} erg cm^{-2} s^{-1} [20]. Indeed, theoretical models [21, 22] predict that the high energy emission from Kepler's SNR should be only a factor 2–5 below the H.E.S.S. upper limits. Hence, the mini-array could be able to detect this young SNR by means of a deep observation, especially if conducted in conjunction with one (or even better two) medium size telescope units to be placed at the same CTA southern site, which could expand the energy range below a few TeV.

Recently, a lot of interest has been raised on gamma-ray sources produced by middle-age SNRs interacting with Molecular Clouds (MC). The detected gamma-ray emission confirmed that hadrons are indeed accelerated in SNRs [23, 24], even if the produced spectrum is not the one responsible for the CR flux observed at Earth. In spite of this, such systems can provide useful information on how particle escape from the remnant and propagate in their vicinity. Several sources like W 28, W 30, W 51C and IC 443 can be observed by the miny-array with better spatial and energy resolution than what has been done before.

PWN originate from the interaction of the relativistic wind of a pulsar with the surrounding medium and thus are excellent candidates for the study, among others, of particle acceleration and cooling in relativistic shocks. From its position on the southern hemisphere, the ASTRI mini-array will be able to observe two of the most notable examples of TeV-emitting PWN, that is Vela−X and HESS J1825−137. The former is a bright ($\sim$ 75% of the Crab flux) and extended ($\sim$ 1 deg) source, which shows no signs of spectral softening at increasing distance from its parent's pulsar. This is indicative that some re-acceleration mechanism is at work in this source [25]. On the other hand, the smaller ($\sim$ 0.2 deg) and dimmer ($\sim$ 15% of the Crab flux) HESS J1825−137 clearly shows such a spectral softening [26]. The observations of the mini-array will give stronger constraints on the maximum energy achievable by the relativistic particles at the termination shock, improving our understanding of the acceleration mechanism and on the properties of the surrounding medium.

At $\sim$ 1 deg from HESS J1825−137 lies the microquasar LS 5039. The detection of flux and spectral modulations in the VHE emission from this source might be indicative of a phase-dependent gamma-ray absorption via pair production [27]. The mini-array will be able to give important constraints on the spectrum of the observed TeV photons at phases different from the superior conjunction (where the softness of the spectrum will be a challenge for the detection capabilities of the mini-array), thus giving stronger constraints on the gamma-ray emission and absorption.

4 Extra-galactic targets and science

The ASTRI mini-array will be extremely important to investigate the VHE emission from extragalactic sources as well. Figure 2 shows the spectral energy distribution (SED) of the extreme blazar (E-HBL) 1ES 0229+200 [28] with superimposed the cascade spectra (E20 low IR and E19 low IR) initiated by the E^{-2} injection with $E_p^{max} = 10^{20}$ eV and 10^{19} eV protons, respectively, using the low-IR EBL model by [29], while the red-dashed curve (E19 best-fit) is the spectrum with $E_p^{max} = 10^{19}$ eV the best-fit EBL model. The brown dot-dot, dash-dash curve (E14 low IR) is the spectrum resulting from the cascade of $E_p^{max} = 10^{14}$ eV primary photons with index $\beta = 5/4$ produced at the source for the low-IR EBL model. Double dot-dashed and dotted curves show, respectively, the 5-σ differential sensitivity for 5 and 50 hr observations with CTA (configuration E, as reported in [1]). As discussed in [28] a clear detection of VHE emission above a few tens of TeV from such a blazar could provide a striking evidence for non-standard phenomena, either an anomalous transparency of the Universe at these energies [30, 31] or gamma-ray emission resulting from an electromagnetic cascade initiated by ultra-relativistic protons accelerated in the blazar jet and beamed toward the observer. A list of promising E-HBLs is currently under study [32] and will provide a fundamental "target list" for the future mini-array. The latter possibility would also demonstrate the possibility that relativistic jets are the accelerators of the still enigmatic UHECR.

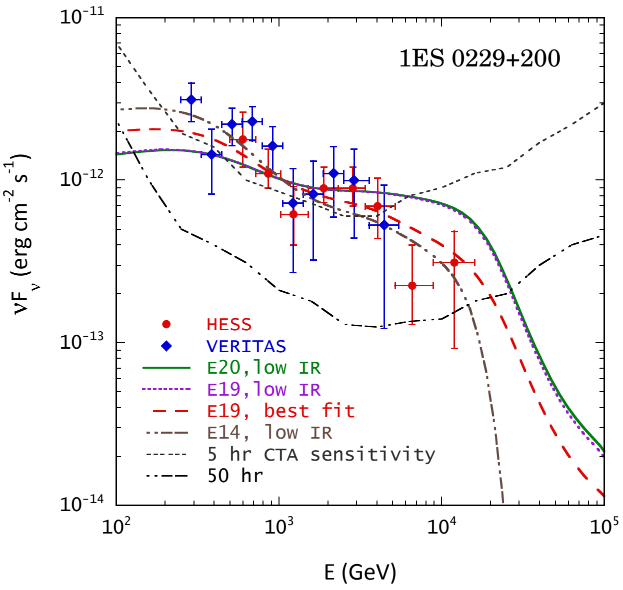

Fig. 2: Spectral energy distribution of the extreme blazar 1ES 0229+200 (see [28] for details). We expect for the SST–2M mini-array in a 7-unit layout a sensitivity at least comparable to (or slightly better than) the H.E.S.S. one above a few TeV.

The study of the extra-galactic background light (EBL) in the far infrared energy band could be an important task, although not a simple one, for the mini-array. Possible candidates should be nearby, hard, intense blazars. Among those observable form the Southern Hemisphere, we can consider MKN 421 ($z = 0.03$) and possibly M 87 ($z = 0.0043$), the latter one being less intense than the former. MKN 421 and M 87 will be observable from the CTA southern site at high zenith-angles, requiring ad-hoc Monte Carlo simulations in order to fully study their VHE properties. If detected above 10 TeV, M 87 would be particularly important to investigate the VHE emission mechanisms in radio-galaxies. Observations of MKN 421 above 10 TeV could be crucial, especially during high or very-high states, not only for the EBL studies, but also for the intrinsic relevance of this source. These observations will allow us to investigate the intra-night variability of such intense and low-redshift class of objects above a few TeV [33] during periods of high-flux states, as shown in Figure 3.

5 The SST–2M mini-array wide field of view

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 4 shows the current TeV sources

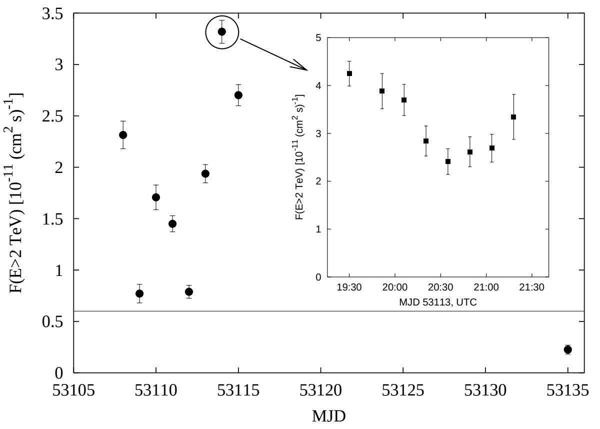

Fig. 3: MKN 421 daily light-curve at energy $E > 2$ TeV. The inset shows possible intra-night variability (time-bin of 14 min) during a particularly high flux-state (see [33] for details).

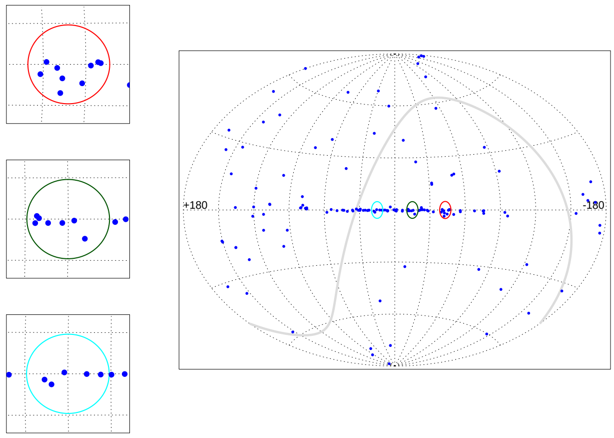

Fig. 4: Blue dots are the known TeV sources as listed in the TeVCat Catalogue. The grey line represents the Celestial Equator. The red, green and cyan circles are the ASTRI mini-array (optical) field of view during three possible pointings. The left panels are zooms centered on the ASTRI mini-array pointings. Different colors are for sake of clarity only.

as listed in the TeVCat[1] compilation. Red, green and cyan circles represent the 9.6° (optical) field of view diameter for three possible pointings along the Galactic 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. Moreover, detections of serendipitous strong flares (a few Crab units) from hard-spectrum sources will be possible as well. We also notice that several GeV sources detected by *Fermi*-LAT lie within the central region of each mini-array pointings.

6 Conclusion

The SST–2M mini-array, whose operations are planned to start since 2016, could constitute the first *seed* of the future CTA Project, and will be open to the CTA Consortium for both technological and scientific exploitation. A robust improvement could come from the implementation of one (or even better two) medium-size telescope at the same site. This would extend the energy range down to a few hundreds of GeV, lower the trigger threshold, and largely improve the science return.

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