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Large zenith angle observation of the PeVatron candidate SNR G106.3+2.7 with the LST-1 and the MAGIC telescopes.

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Imaging Atmospheric Cherenkov Telescopes (IACTs) are ideal for investigating the nature of moderately extended gamma-ray sources at very high energy thanks to their optimal angular and energy resolution compared to ground array detectors. The Supernova Remnant SNR G106.3+2.7 is one of the most promising Galactic hadronic PeVatron candidates. We carried out observations using the Large-Sized Telescope prototype (LST-1) of the Cherenkov Telescope Array Observatory (CTAO) and the two neighboring IACTs of the MAGIC experiment at large zenith angle (LZA) to enhance the effective area at energies above tens of TeV. Data reconstruction and analysis are challenging due to the increased atmospheric depth and strong dependency on the zenith angle of the image properties. Therefore, specialized LZA reconstruction and analysis tools have been developed. We present a joint analysis of data from several telescope combinations, based on currently available statistics, including a preliminary study of the energy-dependent morphology and spectral models.

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1. Introduction

SNR G106.3+2.7 is a supernova remnant (SNR) recently confirmed to be a PeVatron by LHAASO, which measured emissions up to ~600 TeV[1, 2]. In radio it has the shape of a comet, characterized by a head with higher brightness and a fainter elongated tail [3]. The head region is colliding with a dense HI cloud and appears to contain the energetic pulsar (PSR) PSR J2229+6114 and its associated pulsar wind nebula (PWN), also known as the Boomerang Nebula. The tail region is expanding in a low density HI cavity, located in the vicinity of a dense molecular cloud [4].

Due to LHAASO's poor angular resolution and the complex nature of the SNR, the origin of the Ultra High Energy (UHE, E $\geq$ 100 TeV) emission remains unknown. If the gamma-rays with energy above 100 TeV are associated with the head region, the PeVatron nature of the region could be associated with efficient leptonic acceleration in the PSR or PWN. If this signal instead originates in the tail region, it would indicate the presence of PeV hadrons accelerated in the SNR and possibly interacting with the nearby dense molecular cloud. The source, discovered in the early 90's [5], has been subject to extensive multi-wavelength (MWL) campaigns [6–11]. So far, no MWL spectral analysis was able to determine the leptonic or hadronic nature of SNR G106.3+2.7. Hadronic emission models tend to be favored, but the leptonic scenario has not been ruled out. Recently, MAGIC presented results which indicate energy dependent emission morphology at Very High Energy (VHE, E $\geq$ 1 TeV) [12]. We aim to investigate these results with equivalent angular resolution but increased detection efficiency at energies above 10 TeV, which is achieved with Large Zenith Angle (LZA) pointing and with joint LST-1 and MAGIC observations.

2. LZA observation with LST-1 and MAGIC

SNR G106.3+2.7 is undergoing a multi-year observation campaign with LST-1 and the MAGIC telescopes, both located at the Observatorio del Roque de los Muchachos, La Palma (Canary Islands, Spain). LST-1, the Large-Sized Telescope prototype for the Cherenkov Telescope Array Observatory (CTAO), is optimized for gamma rays from $\sim$ 20 GeV to a few TeV. MAGIC (Major Atmospheric Gamma Imaging Cherenkov Telescopes) is an array comprising two IACTs operational since 2003 and 2009, covering an energy range from $\sim$ 50 GeV up to $\gtrsim$ 100 TeV.

The final dataset will be a combination of mono LST-1, stereo MAGIC and joint stereo LST-1+MAGIC datasets. The joint stereo LST-1+MAGIC dataset is obtained with a simultaneous pointing to the source and a joint data reconstruction. Images are connected by a software trigger, which requires at least two telescope images per event. The source is observed in wobble mode, with two pointings positioned in a way to study both the head and the tail regions. The pointing is in the zenith range 55°-75°, which allows for an increase in the effective area by a factor 3 at 10 TeV and up to 7 at 50 TeV. The angular resolution is below 0.1° for energies sufficiently above the analysis threshold, which depends on the zenith pointing.

3. Data analysis

The mono LST-1, stereo MAGIC and joint stereo LST-1+MAGIC datasets are reconstructed with their respective pipelines: lstchain, MARS and magic-cta-pipe [13–15]. The Random Forests

used for reconstruction were trained on Monte-Carlo data simulated along the source declination line with a dense grid of pointings in order to reduce biases arising from rapidly varying shower parameters at large zenith angles. The high level analysis was performed with gammapy [16].

In this work, we present preliminary results obtained with 42.6 hours of the mono LST-1 dataset, in the energy range 3-100 TeV. We first present skymaps of the source in several energy bins, then we perform the spectral modeling of the source (1D analysis) in the same regions of interest (ROIs) used by MAGIC or LHAASO, and finally we perform a spectral and morphological modeling of the source (3D analysis) over the whole FoV. Additionally, we perform a joint 1D analysis of this dataset with the middle zenith angle dataset (120 hrs) used for the MAGIC 2023 publication [12], which permits to show the coherence of recent LZA results with data taken with different pointing conditions and in a different energy range.

3.1 Background model estimation

The study of extended sources demands to correctly estimate the residual hadronic background to be subtracted from the detected signal. For that, it is necessary to estimate the background instrument response function (IRF), which describes the telescope acceptance for gamma-like protons over the field of view (FoV), which is 4.5° of diameter for LST-1 and 3.5° for MAGIC. At LZA the rapidly changing atmosphere depth implies an inhomogeneous acceptance in the FoV also in the case of a single telescope. The background IRF estimation was performed with the BAccMod package[1] by creating an acceptance model from the stacked data properly masked in the source region. More precisely, each dataset was binned in zenith, and a 3D acceptance model (energy, pointing altitude and azimuth) was produced for each zenith bin by stacking the counts and normalizing them to get the background rates in FoV coordinates. For the LST-1 mono dataset specifically, we handled the lack of statistics by fitting an analytical function to the data. The spatial acceptance is described by a 2D gaussian function with two linear gradients along the altitude and azimuth axis to account for the zenith dependent variation over the FoV. The background IRF was then used in the ring background method [17] provided by gammapy. This method allowed us to get a good background model from 3 to 100 TeV for the LST-1 dataset, and from 0.5 to 20 TeV for the MAGIC 2023 dataset.

3.2 Spectral analysis (1D analysis)

The spectral analysis was performed considering ON regions from published results: the head and tail ROIs from MAGIC 2023, and the r_{39} extension of the LHAASO WCDA source [2, 12]. The emission spectrum was modeled with a power law (PL) function given by $\frac{dN}{dE} = N_0(\frac{E}{3\,TeV})^{-\Gamma}$. The spectral points were computed requiring a minimum of 2σ significance.

3.3 Spectral and spatial analysis (3D analysis)

The 3D analysis was performed by fitting a set of spatial models (point-like, 1D or 2D Gaussian, disk, and ellipse) and spectral models (PL, PL with exponential cut-off (ECPL), and log-parabola (LP)). Considering the possibilities of the absence of a source or the presence of one or two sources,

[1] https://github.com/mdebony/BAccMod

we fitted a total of 256 model combinations. The source models were initialized with the parameters of the head and/or tail results from MAGIC.

The best fit models were selected by using the Wilk's theorem. The best non-nested models were then ranked according to the Akaike Information Criterion (AIC) [18, 19]. First, we computed the significance for each set of nested models to create a significance matrix $\mathbf{S} = (s_{ij})$, where s_{ij} is the entry giving the significance of the model M_j when tested as an alternative to the null model M_i. Then, the models were filtered with a 3σ significance threshold: a model M_j was rejected if a null model M_i existed such as $S_{ij} < 3\sigma$, or if an alternative model M_k existed such as $S_{jk} \geq 3\sigma$. The AIC score was then computed for each remaining non-nested model. The best-fit model was determined as the one with the minimum AIC score. Models presenting a score difference $\Delta\mathrm{AIC} \leq 2$ were considered compatible. Any model with $\Delta\mathrm{AIC} > 2$ is considered rejected. The spatial residuals of each model were checked for final validation.

3.4 Analysis parameters

We masked the source with two 0.4° circle regions centered on the MAGIC head and tail positions. This mask was applied for the acceptance and the ring background modeling. The ring kernel had a 0.12° internal radius and a 0.5° external radius. The significance was computed with a 0.12° correlation radius.

4. Results

4.1 Energy-dependent morphology

Fig. 1 shows the significance map of the Boomerang SNR region obtained with 42.6 hours of LZA observation with LST-1, from 3 to 100 TeV. We see an extended region with more than 5σ significance extending over the whole SNR region, with a global maximum peak at 7.3 σ in the tail region. Looking at the energy-dependent morphology, we can study the 3-6 TeV, 6-10 TeV, 10-50 TeV and 50-100 TeV energy bins. In these energy bins, we have a PSF ranging from 0.11° to 0.08°. A shift of the high-energy emission is observed from the head towards the tail, consistent with the one seen by MAGIC 2023. Hints of signal are also observed above 50 TeV in the outer tail region.

4.2 Spectral analysis (1D analysis)

Results from LST-1 are consistent with both the MAGIC and the LHAASO spectral studies. The increased statistics at higher energy coming from the LST-1 data, seems to soften the MAGIC spectral shape in the tail region. Furthermore, the addition of MAGIC 2023 data allows to better constrain the fit at lower energies.

4.3 Spectral and spatial analysis (3D analysis)

The best-fit result from the 3D analysis on LST-1 data is a model consisting of two extended sources with PL spectral emissions. The first source is described by a 1D Gaussian spatial model located on the same axis as the MAGIC regions, at the outer end of the tail region, towards the molecular cloud. Its hard PL spectral emission is consistent with the one measured in the MAGIC tail region. The second source is a large disk-like source, overlapping the LHAASO WCDA

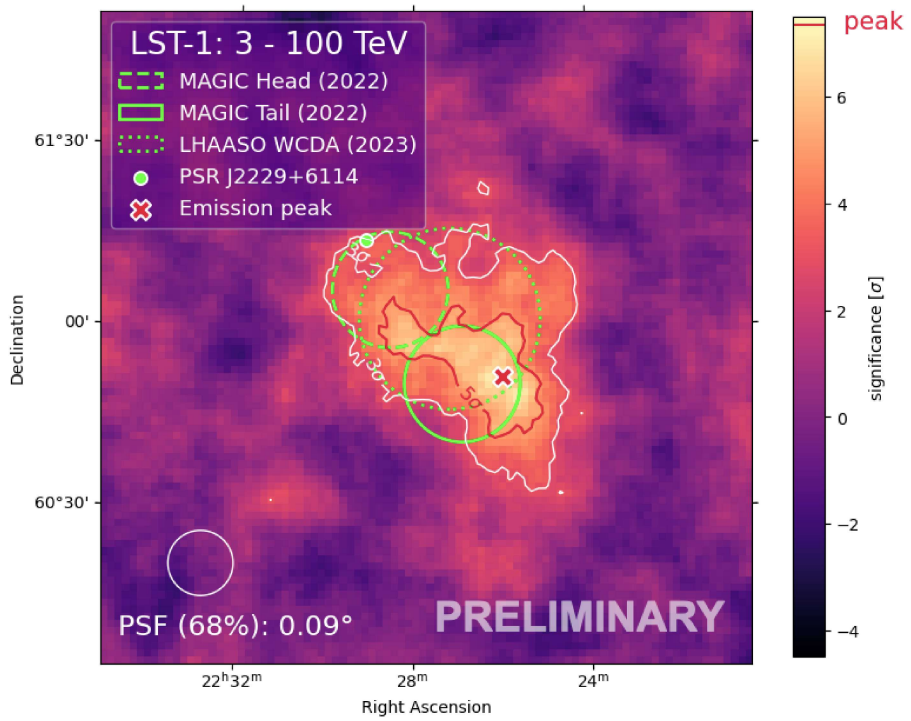

Figure 1: Significance map of the Boomerang SNR region obtained with 42.6 hours of LZA observation with LST-1. The position of the pulsar PSR J2229+6114, the head and tail ROIs from MAGIC and the LHAASO WCDA source radius are plotted in green for reference (dashed, full and dotted lines respectively). Significance contours at the 3σ (white) and 5σ (red) levels are overlaid. The global maximum significance peak (red cross) is at 7.3 σ in the tail region. The white circle shows the gaussian kernel consistent with our PSF 68% containment radius evaluated at the energy center of the stacked dataset.

emission region, the MAGIC head region and almost the whole MAGIC tail region. The soft PL spectral emission is consistent with the one from the LHAASO WCDA source.

Two other models were discarded by the AIC: a very similar one with a disk-like source on the tail region instead of a 1D Gaussian (ΔAIC$\simeq$ 5), and a single 2D Gaussian source model extending over the whole SNR region, with a PL spectrum consistent with LHAASO WCDA and KM2A (ΔAIC$\simeq$ 9). The spatial residuals were good for both of these models.

5. Conclusions

SNR G106.3+2.7 is undergoing a multi-year observation campaign at LZA with LST-1 and MAGIC telescopes. We performed a preliminary analysis on a total of 42.6 hours of LST-1 data taken with a zenith angle between 55° and 75°. We detected the source at 5 σ over the head and tail regions, with a global maximum emission peak in the tail. The energy-dependent morphology shows an apparent shift of the emission site towards the tail, with indications of emission above 50 TeV in the outer tail region. Both energy-dependent morphology and spectral analysis preliminary results were consistent with MAGIC and LHAASO's results. The spectral morphological analysis favored a model with two extended sources. The first source is a large disk-like source with a soft

PL spectral emission over the LHAASO WCDA, MAGIC head and part of MAGIC tail regions. The second source is a smaller 1D Gaussian source with a hard PL spectral emission, located in the outer tail region. The joint observation campaign is ongoing and joint LST-1 and MAGIC results will be available soon.

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