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Observation of Active Galactic Nuclei with the Large-Sized Telescope prototype of the Cherenkov Telescope Array

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Cherenkov Telescope Array (CTA) will be the next generation gamma-ray observatory. It will consist of three different sizes of telescopes, with a collective improvement of about an order of magnitude in sensitivity, compared with the current generation gamma-ray telescopes. Large-Sized Telescopes (LSTs) will be the most sensitive at energies from tens of GeV up to a few TeVs, and will be the best suited to observe gamma-ray sources such as Active Galactic Nuclei (AGN). The first Large-Sized Telescope prototype (LST-1), inaugurated in 2018 and currently in commissioning phase, has accumulated more than one thousand hours of data to date. From 2020 to 2022, we have detected various gamma-ray sources, and prominent among them are several well-known AGN, like Mrk 421, Mrk 501, 1ES 1959+650, 1ES 0647+250, PG 1553+113, etc. We report on light curves and energy spectra reconstructed out of these observations down to energies of tens of GeV, which is very close to the energy threshold of LST-1.

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1. Introduction

The exact mechanisms of gamma-ray emission from astrophysical sources like Active Galactic Nuclei (AGN) are not fully understood. Cherenkov Telescope Array (CTA) will be the next generation gamma-ray observatory located on two sites, the Roque de los Muchachos observatory in the Canary Island of La Palma, Spain and Paranal, Chile. It aims to detect gamma-ray sources using arrays of Imaging Atmospheric Cherenkov Telescopes (IACTs) of different sizes with an improvement of about an order of magnitude in sensitivity compared with the current generation IACTs. Four Large-Sized Telescopes (LSTs) alongside nine Medium-Sized Telescopes (MSTs) will be deployed at the northern site in La Palma. LSTs are equipped with 23 m diameter mirror dishes and the camera composed of 1855 photomultiplier tubes, where signals are recorded by a readout system with a 1 GHz sampling rate. The telescopes will be most sensitive at energies from tens of GeV up to a few TeVs and the best suited to observe gamma-ray sources such as AGN. LSTs also have an ability to reposition to any point in the sky within 20 seconds, which is ideal condition for observing fast transient sources.

The first Large-Sized Telescope prototype (LST-1), inaugurated in 2018 and currently in the commissioning phase, has accumulated more than one thousand hours of data to date. From 2020 to 2022, we have detected various gamma-ray sources, and prominent among them are several well-known AGN, like Markarian 421 (Mrk 421), Markarian 501 (Mrk 501), 1ES 1959+650, 1ES 0647+250, PG 1553+113, etc. These are all known TeV blazars (a type of AGN with jets aligned with the line-of-sight), and we detected them with more than 5σ up to a redshift $z \sim 0.45$. In this contribution, we report on light curves and energy spectra of these 5 sources down to energies of tens of GeV, which is very close to the energy threshold of LST-1.

2. Observation and data analysis method

For the analysis presented in this contribution, we use data collected from July 2020 to May 2022 under dark night conditions. The events are reconstructed with the CTA LST-1 standard method described in [1]. We performed source-independent (standard) and source-dependent methods for spectrum analyses. In the source-dependent method, the source position is assumed in random forest training on Monte Carlo simulations (MCs) and energy resolution improvement is expected at lower energies [1]. This is also to check systematic uncertainty by analysis methods.

To train the event reconstruction algorithms with random forests, we used MCs for gamma-rays and protons, following the trajectory along the source declination line (the training MC). To compute instrument response functions (IRFs), we used MCs for gamma-rays simulated in a grid of cosine of zenith and the orthogonal component of the geomagnetic field values (the test MC). Data products (DL3) were produced using all-sky MC with IRFs being calculated using the nearest node (and also interpolated IRFs) corresponding to the position of the telescope during the observation.

We fit the observed spectrum with exponential cutoff power-law (ECPL) function[1] for Mrk 421 analysis. It is defined as $\phi(E) = \phi_0(E/E_0)^{-\Gamma}\exp(-(\lambda E)^{\alpha})$, where ϕ_0 and Γ are the flux at the reference energy E_0 and the spectral index, respectively. λ parameter is related to the spectrum cutoff energy. α is fixed as 1 in this analysis. The E_0 is obtained by fitting the data points using

[1] https://docs.gammapy.org/0.20/modeling/gallery/spectral/plot_exp_cutoff_powerlaw.html

Table 1: Summary of source observation conditions. Source redshifts are derived from [5–9]. Preliminary detection significances using total data in observation time periods are described. The significances are calculated from θ^2 distribution according to Eq. (17) in Li & Ma (1983) [10], with a θ^2 cut at 0.04 deg^2 and without an energy cut in the analysis.

Source	Observation date	Redshift	Observation time before/after cut (h)	Detection significance (σ)
Mrk 421	2020 Dec. 12 - 2022 May 23	0.031	68.5 / 31.9	53
Mrk 501	2020 July 10 - 2022 May 22	0.034	67.2 / 39.7	21
1ES 1959+650	2020 July 11 - 2022 May 5	0.048	21.3 / 11.8	13
1ES 0647+250	2020 Dec. 16 - 2020 Dec. 21	0.45±0.05	8.8 / 8.2	7
PG 1553+113	2021 Apr. 8 - 2022 May 23	0.433	12.2 / 9.9	16

power-law spectral model with the given reference energy and calculating the decorrelation energy of the fit [2]. The gamma-ray flux is absorbed during propagation due to the interaction with the extragalactic background light (EBL) via pair production [3]. The fitting function was folded with the EBL model of Domínguez (2011) [3].

For variable sources (Mrk 421, Mrk 501 and 1ES 1959+650), an average spectrum over the full time period is not very meaningful. One may utilize the Bayesian block algorithm [4] to identify time periods of similar spectral emission. We produced a night-wise flux light curve above 100 GeV, applied systematic uncertainty of 6% of the flux values in quadrature to the statistical uncertainty [1], and use a false alarm probability of 3σ to separate the light curve to each block. A flare event was observed in a certain block of Mrk 421 light curve and we performed a detailed analysis of the data during the highest flux state, which is shown in section 3.

Detailed information about the data collection in each source can be found in Table 1.

3. Results of Mrk 421

Mrk 421 was observed over 34 nights between 2020 December 12 and 2022 May 23 for a total observation time of 31.9 h under good conditions. The observations were performed within a zenith angle range from 9° to 52°. Fig. 1 (left) shows the pointing direction of observation data runs, training and testing MCs described in section 2.

The distribution of θ^2, which is the difference between assumed and reconstructed source position in the camera, of gamma-like events is shown in Fig. 1 (right). We observe events from circular region around the source position (ON events) and neighboring circular regions in the same FoV (Background events) to get background-normalized signal events. It shows a clear excess of ON events compared with background events.

The flux light curve in the data period is plotted in Fig. 2. It shows variability on one-day timescales and the flux is mainly less than Crab Nebula flux. There was a flaring event reaching ~3 times of Crab Nebula flux on 2022 May 18. The dataset was separated to 12 blocks by the Bayesian block analysis.

Fig. 3 (left) shows the spectrum energy distribution (SED) on 2022 May 18. The SED was measured down to tens of GeV and can be fitted by ECPL function folded by the EBL model.

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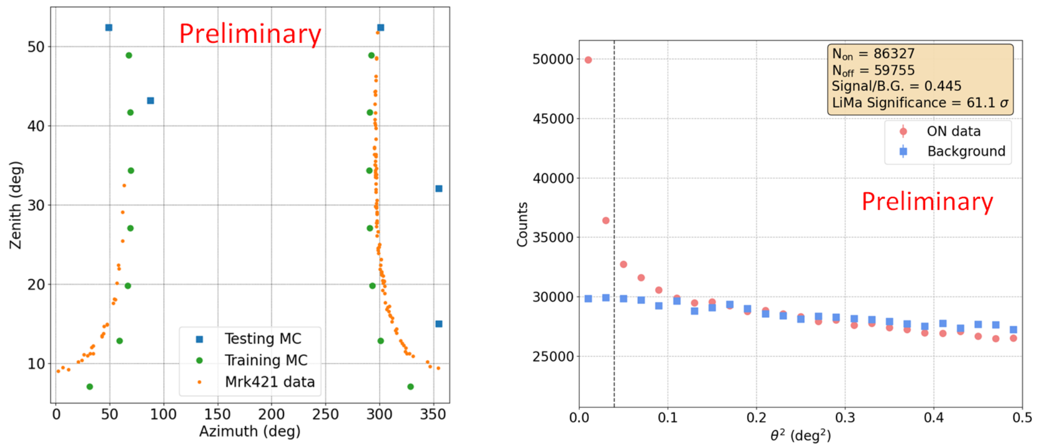

Figure 1: (left) The pointing direction of data, training and testing MCs of Mrk 421 observation direction. Each plot for data corresponds to each run, which is 1 wobble observation. (right) θ^2 distribution of Mrk 421 total data with intensity larger than 300 photoelectrons, which corresponds to a peak gamma-ray energy of 110 GeV [11]. The cut 0.04 deg^2 is used to calculate the significance.

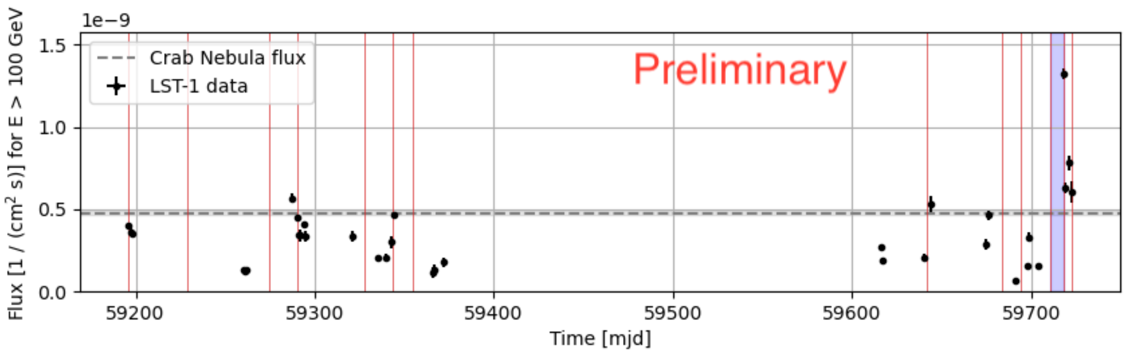

Figure 2: Mrk 421 light curve. Red vertical lines describe Bayesian block edges. Grey horizontal dashed line and shaded area show Crab Nebula flux and its error for reference, respectively [12]. Blue shaded block corresponds to the flare event on 2022 May 18.

The SEDs are comparable between the source-independent and source-dependent methods with extending up to several TeV. We obtained EBL-corrected spectra from the fit result of intrinsic spectrum model, which is ECPL function in this analysis. Table 2 shows preliminary EBL-corrected spectrum fit parameters of Mrk 421 data. The parameters of the flare event data on 2022 May 18 with source-independent and source-dependent methods and that of average spectra of total data (including the flare data) are shown. The spectral index and amplitude of flare data are 1.86 ± 0.05 and (9.06 ± 0.36) $\times 10^{-10}$ cm^{-2} s^{-1} TeV^{-1} at the reference energy E_0 = 0.40 TeV, respectively, for the source-independent analysis. The flare spectrum is harder than the average spectrum, where the index and amplitude are 2.23 ± 0.03 and (2.54 ± 0.06) $\times 10^{-10}$ cm^{-2} s^{-1} TeV^{-1} at the reference energy E_0 = 0.37 TeV, respectively, for the source-independent analysis.

The observed flux with energies larger than 100 GeV exhibited fast variations. Analyzed light

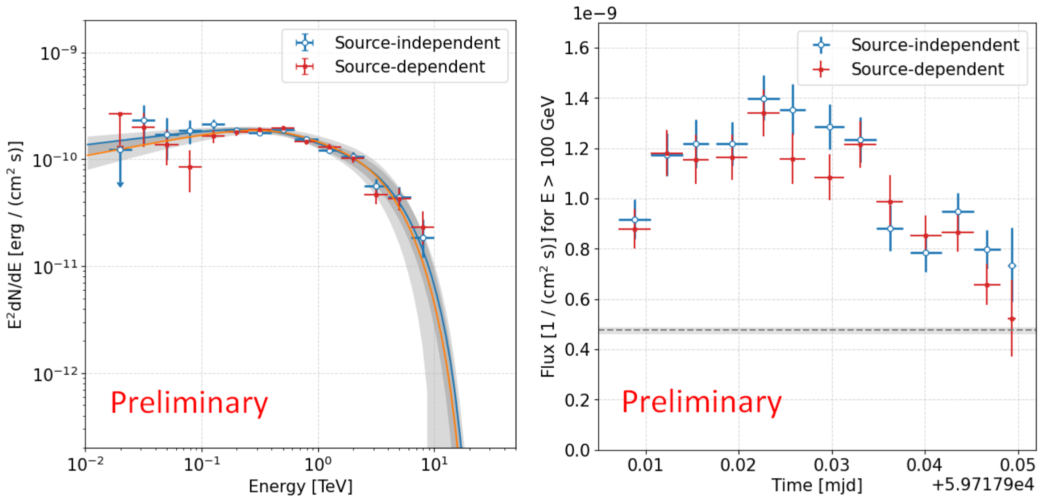

Figure 3: Plots for Mrk 421 data on 2022 May 18. Blue and red correspond to source-independent and source-dependent analyses, respectively. The energy-dependent cuts with efficiencies of 70% are used for event selection [1]. (left) Observed SED. The blue and orange lines show fit functions (ECPL function folded by the EBL model) of the source-independent and source-dependent analyses, respectively. Grey shaded area show errors of the fit lines. (right) Intra-night light curve with energies larger than 100 GeV. Grey shows the Crab Nebula flux as in Fig. 2.

Table 2: Preliminary EBL-corrected spectrum fit parameters of Mrk 421 observed data. Statistical errors are described.

Data	Method	E_0 (TeV)	Γ	ϕ_0 ($\times 10^{-10}$ cm^{-2} s^{-1} TeV^{-1})	λ (TeV)$^{-1}$
2022 May 18	Source-independent	0.40	1.86±0.05	9.06±0.36	0.29±0.06
2022 May 18	Source-dependent	0.41	1.79±0.07	8.63±0.57	0.36±0.10
Total	Source-independent	0.37	2.23±0.03	2.54±0.06	0.38±0.04
Total	Source-dependent	0.34	2.23±0.03	3.05±0.08	0.42±0.05

curve with a time binning of 5 min is shown in Fig. 3 (right). The flux changed within 0.7×10^{-9} cm^{-2} s^{-1} - 1.4×10^{-9} cm^{-2} s^{-1} for source-independent analysis in about 1 hour observation. The flux variability timescale study is in progress.

4. Results of other sources

Mrk 501 was observed between 2020 July 10 to 2022 May 22 for a total observation time of 39.7 h after data selection. The preliminary detection significance of total data is 21σ. The light curve showed variability on one-day timescales and the flux with energies larger than 100 GeV is mainly less than the Crab Nebula flux. The Bayesian block analysis identified 11 blocks among the whole time period, while there was not a flare event.

1ES 1959+650 was observed between 2020 July 11 and 2022 May 5 for a total observation time of 11.8 h after data selection. The preliminary detection significance of total data is 13σ. The observations were performed within a zenith angle range from 36° to 57°, thus we put additional cuts with effective area smaller than 10% of maximum value, since zenith angle is relatively high and low effective area at lower energy make larger systematics of background events contamination. The light curve showed variability with 4 Bayesian blocks, while no flare feature was observed.

1ES 0647+250 was observed between 2020 December 15 to 2020 December 20 for a total observation time of 8.2 h after data selection. The preliminary detection significance of total data is 7σ. PG 1553+113 was observed between 2021 April 7 to 2022 May 23 for a total observation time of 9.9 h after data selection. The preliminary detection significance of total data is 16σ. These sources did not show significant time variation in the whole observation time period. Since these sources are more distant than other 3 sources, the EBL effect to the spectra is larger. The SEDs of observed data were best fitted with power-law function folded by the EBL model.

5. Conclusion

In this work, we have reported the observation and data analysis of the blazars Mrk 421, Mrk 501, 1ES 1959+650, 1ES 0647+250 and PG 1553+113 with CTA LST-1. A flare from Mrk 421 was detected on 2022 May 18 and the spectra were analyzed down to tens of GeV, which is very close to LST-1 threshold. We performed source-independent and source-dependent analysis methods, and results were comparable between the two methods. Intra-night variability was seen at energies greater than 100 GeV for the flare.

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