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LST-1 observations of GRB 221009A: Insights into its late-time VHE afterglow

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Gamma-ray bursts (GRBs) originate from explosions at cosmological distances, generating collimated jets. GRB 221009A, exploded on 9 October 2022, has been established as the brightest GRB to date. Its bright and long emission was extensively followed up from radio to gamma rays. LHAASO firmly detected the onset of the afterglow emission at energies up to ~13 TeV within about an hour after the burst, starting just a few minutes after the trigger. While this VHE emission component can be accounted for in a narrow jet scenario, such an interpretation cannot reproduce the broadband emission observed at later times, which exceeds the theoretical expectations. This discrepancy can be settled if more complex models are considered, providing the first strong evidence for a structured jet in a long GRB. Unfortunately, the VHE emission after a few hours is poorly constrained, as sensitive VHE observations by Cherenkov Telescopes were prevented due to strong moonlight conditions. The first Large-Sized Telescope (LST-1) of the future Cherenkov Telescope Array Observatory began observations about one day after the burst under high night sky background conditions. These observations are the first ones performed on GRB 221009A by a Cherenkov telescope, revealing a hint of a signal with a statistical significance of about 4σ during the observations performed at 1.3 days after the burst. The monitoring campaign continued until the end of November 2022, making it the deepest observation campaign performed on a GRB with the LST-1. In this contribution, we will present the analysis results of the LST-1 observation campaign on GRB 221009A in October 2022.

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1. Introduction

Gamma-ray bursts (GRBs) were first detected in 1967 with the Vela satellites [1]. These events are characterised by intense emission (milliseconds to thousands of seconds) in the hard X-ray to soft-gamma-ray range (tens of keV to several MeV). The majority of the emitted energy during this phase occurs in the sub-MeV to MeV band and is commonly referred to as the prompt emission. A long-lived, multi-wavelength afterglow emission was first observed in 1997 [2]. This fading afterglow emission can persist for several months following the burst discovery and has been detected across the electromagnetic spectrum from radio to very-high-energy gamma rays (VHE; $E > 100$ GeV) [e.g. 3].

GRBs originate from catastrophic events at cosmological distances that launch relativistic jets. A GRB is detected from Earth when one of the jets is pointing towards us. The observed afterglow emission is interpreted as non-thermal radiation produced by the interaction of relativistic particles with the surrounding medium. The physical origin of GRBs is broadly divided into two categories. Long-duration ($T > 2$ s) GRBs are associated with the core collapse of massive stars, while short-duration ($T < 2$ s) GRBs are connected to the coalescence of two compact objects [4, 5].

The non-thermal high-energy emission is usually attributed to synchrotron self-Compton processes. The first VHE gamma-ray detection from a GRB was reported for GRB 190114C [6, 7]. To date, five GRBs have been detected in this band [8–11]. Among these, GRB 221009A stands out as the brightest GRB ever detected, earning the nickname of the brightest-of-all-time (BOAT) GRB. It was initially discovered on 9 October 2022 by several space-borne satellites, including *Swift* and *Fermi* [12–14]. An extensive follow-up campaign continued across the electromagnetic spectrum over a broad period of time. In the VHE band, the Large High Altitude Air Shower Observatory (LHAASO) was serendipitously covering the sky region where GRB 221009A occurred, succeeding in detecting the onset afterglow emission [11, 15].

On 9 October 2022, the presence of the bright Moon prevented rapid follow-up observations by imaging atmospheric Cherenkov telescopes (IACTs). The first Large-Sized Telescope (LST-1) of the future Cherenkov Telescope Array Observatory (CTAO) started observation 1.33 days after the burst, constituting the first observation by this class of detectors.

In this work, we report the observations with LST-1. Section 2 describes the observation campaign with LST-1. The analyses of the observations are described in Sect. 3, while the results are shown in Sect. 4. Concluding remarks are provided in Sect. 5.

2. Observations

LST-1 began observations 1.33 days after the burst, on 10 October 2022, with Moon illumination at 99%. Similar night-sky-background (NSB) conditions were present during the second day of data taking, 3.33 days post-burst, on 12 October 2022. Observation on 11 October 2022 were not possible due to camera problems. These observations were conducted with reduced high voltage during a period when data acquisition is normally halted due to the bright moonlight. Subsequent observations were obtained under nominal operations in low NSB[1] conditions until the end of

[1] Diffuse NSB below 2.3 photoelectrons.

Table 1: Observations of GRB 221009A with LST-1 in October 2022. For each observation day, we list the day of the evening before data taking, the starting date, the starting time offset with respect to the burst trigger [T_0; 16], the observation time after the data selection, the zenith angle range of the observations, and the NSB conditions that affected the data.

Start day	Start date [MJD]	$T - T_0$ [d]	Time after data selection [h]	Zenith range [°]–[°]	NSB conditions
10 Oct. 2022	59862.88	1.33	1.75	31–54	High
12 Oct. 2022	59864.89	3.33	1.42	34–52	High
15 Oct. 2022	59867.85	6.30	0.80	25–52	Low
16 Oct. 2022	59868.88	7.32	2.35	34–65	Low
17 Oct. 2022	59869.85	8.30	2.41	28–60	Low
23 Oct. 2022	59875.86	14.30	2.01	34–61	Low
25 Oct. 2022	59877.89	16.33	1.18	45–59	Low
26 Oct. 2022	59878.87	17.32	1.42	42–58	Low
Total observation time after data selection [h]			13.34		

October, within the same lunar cycle as the initial observations. The campaign continued into the following lunar cycle, extending through the end of November 2022. Here we report the observations under high and low NSB conditions in October 2022, which are summarised in Table 1.

3. Data analysis

We divided the observations according to the NSB conditions during the data taking. Observations on 10 and 12 October were analysed using a moon-adapted analysis scheme, while the rest of the data was analysed using the standard data analysis described in [17].

The moon-adapted analysis used refined camera calibrations employing an optimised charge-integration method and image cleaning adapted for an observation-by-observation analysis to account for the rapid evolving observing conditions with high NSB. These adaptations were considered after evaluating multiple combinations of charge-integration and image-cleaning algorithm. For instance, we tested different window configuration for the waveform signal integration [18]. Moreover, we investigated if the pulse shape of the signal between the observations in nominal and reduced high voltage significantly changed. Only minor variations, at a level of few percent were found, indicating that changes in the pulse shape are not expected to introduce significant systematic effects in the analysis. More detailed information about the analysis is described in [19].

4. Results

We obtain an excess of gamma rays centred towards the GRB 221009A position at a detection statistical significance of 4.1σ on 10 October 2022, while observations on subsequent days are compatible with background. Figure 1 shows the θ^2 distribution for 10, 12 and 15–27 October 2022. The reader is referred to [19] for more information about the analysis results.

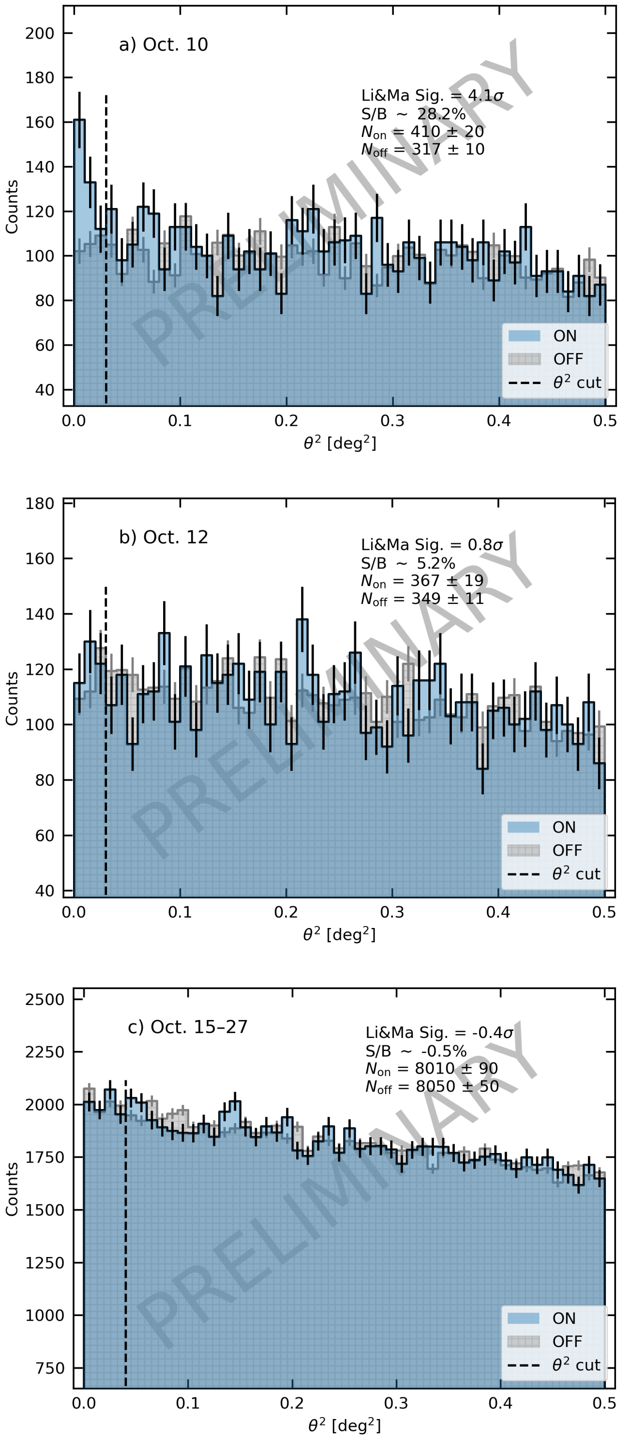

Figure 1: θ^2 distribution centred on the GRB 221009A position (ON) and the mean distribution from three control (OFF) regions. Panels a), b) and c) show the distributions using all the observations on 10, 12 and 15–27 October 2022, respectively (see Table 1). Error bars correspond to 1σ statistical errors.

5. Conclusions

LST-1 performed an extensive observation campaign on GRB 221009A. The first observations occurred 1.33 days after the burst, being the earliest observations of this burst published to date with an IACT. We obtain a hint of detection at 4σ significance on that day, while there is no excess over the expected background in the days after that one night. The dedicated analysis of these data and the final results are provided in [19].

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