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GRB 221009A observations with LST-1 at VHE gamma rays

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On October 9th, 2022, the brightest gamma-ray burst (GRB) since the first GRB observation in the late sixties was detected by the Fermi-GBM and Swift-BAT telescopes (GRB 221009A). The outstanding characteristics of this GRB triggered extensive follow-up observations of the source across all wavebands, including at very-high-energy (VHE) gamma rays with the Large-Sized Telescope prototype (LST-1) of the upcoming Cherenkov Telescope Array Observatory (CTAO). In this contribution, we present the analysis and results of the LST-1 observation campaign in October 2022, focusing on the data taken under nominal observing conditions and above 200 GeV.

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1. Introduction

Gamma-ray bursts (GRBs) are bright transient events characterised by a prompt phase at X-rays and gamma rays, and a subsequent afterglow decaying phase, emitting across the electromagnetic spectrum from radio to gamma rays. Only a limited number of long GRB have been detected at very-high-energy (VHE, $E > 100$ GeV) gamma rays by Cherenkov telescopes with important implications for the physics behind them [1–4]. However, our comprehension of the underlying physical processes at play remains limited.

GRB 221009A is the brightest long GRB detected up to date. Its exceptional bright emission was first detected by Fermi-GBM and Swift-BAT telescopes on Oct. 9 (t_0 = 59861.55346065 MJD [5]) and followed up extensively across all the electromagnetic spectrum, including in VHE gamma rays. Remarkably, GRB 221009A was the first GRB detected above 10 TeV as reported by LHAASO [6].

CTAO is the upcoming observatory to be sensitive to VHE gamma rays. The CTAO sensitivity to short-timescale variability and transient events at VHE gamma rays will be one of its notable strengths [7]. CTAO will be constituted by three telescope types. Among them, the largest one, with a mirror of 23 m diameter, is the Large-Sized Telescope (LST). LSTs are designed to operate at the lowest energies of the CTAO energy range (triggering events down to 20 GeV) and with a fast reposition speed (180 deg in less than 30 s) [8, 9]. LSTs are ideally suited telescopes for follow-up observations of transient sources.

The first LST, LST-1, is already built on the northern site of the CTAO array on the Roque de los Muchachos Observatory (La Palma, Spain). LST-1 is in the commissioning phase and has been taking gamma-ray data since Nov. 2019, with several GRBs observed since then [10]. The first Large-Sized Telescope (LST-1) of the upcoming Cherenkov Telescope Array Observatory (CTAO) followed up GRB 221009A.

In this work, we report the GRB 221009A observations with LST-1 during the follow-up in Oct. 2022. In Section 2, the GRB 221009A observations with LST-1 are described. We explain the data analysis in Section 3 and the preliminary results are presented in Section 4. Finally, we summarize our conclusions in Section 5.

2. GRB 221009A observations with LST-1

The observation conditions for this GRB with Cherenkov telescope facilities were remarkably challenging due to the very high night-sky-background (NSB) conditions induced by the moonlight during the full moon phase. Despite the unfavourable observation conditions, LST-1 started observations about one day after the trigger time ($t - t_0$ = 1.33 d). The observation campaign with LST-1 was extended until late November and carried out under different observing conditions.

Between Oct. 10–13, spanning 1 to 4 days post-burst, a total of 3 hours of data was acquired under strong moon conditions. The LST-1 data in this period was taken with reduced high-voltage (HV) to decrease the number of triggered fake events due to the very high NSB. Later, a total of 15 hours of data under nominal observations (i.e. dark observations) were obtained between Oct. 15–28, which corresponds to 6–19 days after the burst trigger. In this work, we focus on the observations in Oct. 2022, in particular, the observations obtained under nominal dark conditions. More information regarding the moon analysis will be provided in a dedicated forthcoming publication.

3. Data analysis

To analyse the GRB 221009A observations we use `cta-lstchain` [11] and `Gammapy` [12], the official analysis pipeline and tools of LST and CTAO. The standard source-independent analysis approach is used [9]. MC simulations tailored to the GRB 221009A observation in dark conditions are employed to train the Random Forests (RFs) and estimate the instrument response functions. RFs are used in the classification and regression steps to estimate the direction, energy and type of the incident particle responsible for the recorded image.

A 1-D analysis is performed with `Gammapy`. The spectral energy distribution (SED) of GRB 221009A is computed in the energy range $E = [0.2, 10]$ TeV. This work does not include the SED below 200 GeV, which is still under investigation. The energy flux is determined in the same energy range as the SED.

4. Preliminary results

GRB 221009A is not detected at a statistically significant level with LST-1 using the whole 15 h of dark data between days 6 and 19 after the burst. Consequently, we assume a power-law spectral shape to describe the GRB 221009A emission in this energy range. We fix the spectral index of the power-law model and compute upper limits (ULs) at a 95% confidence level to constrain the GRB 221009A emission during the LST-1 observations. Hereafter, an intrinsic spectral shape $\propto E^{-2}$ is assumed. The spectral ULs with LST-1 for the whole dark observation period (Oct. 15 to 28) are shown in Fig. 1.

The dark observations are divided between mildly distant (subset one, $t - t_0 = [6, 9]$ d) and distant (subset two, $t - t_0 = [12, 19]$ d) observations from the burst to compute the energy flux. We present the observed energy flux with LST-1 in the range $E = [0.2, 10]$ TeV in Fig. 2. The LST-1 ULs constrain the flux to be below about 2% and 4% of the Crab energy flux for the first and second subsets, respectively. Moreover, the ULs from HAWC and H.E.S.S. with different energies are shown in Fig. 2 for comparison. We note that the LST-1 ULs are at lower energies than the other ones.

5. Conclusions

The observation campaign with LST-1 provides a deep monitoring of the afterglow emission of GRB 221009A in Oct. 2022. The data analysis under extreme moon conditions for the first observation days with LST-1 is still ongoing. For the observations in nominal conditions six days after t_0, GRB 221009A is not detected with LST-1. The afterglow energy flux is constrained in the energy range between 0.2 TeV and 10 TeV below $\sim 2 \times 10^{-12}$ TeV cm^{-2} s^{-1}. The analysis of the data obtained one day after the trigger, which is the closest to the burst trigger taken by any Imaging Atmospheric Cherenkov Telescope (IACT) at VHE gamma rays, together with the low-energy dataset below energies $E < 200$ GeV for the period 6–19 days burst trigger will be provided in a forthcoming publication.

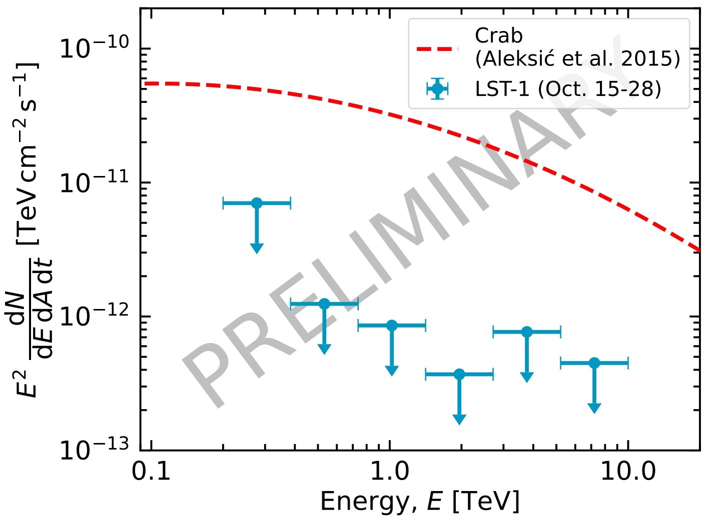

Figure 1: Observed GRB 221009A SED using all LST-1 data in dark conditions in light blue. In addition, the dashed red line shows the Crab spectrum from [13] as a reference.

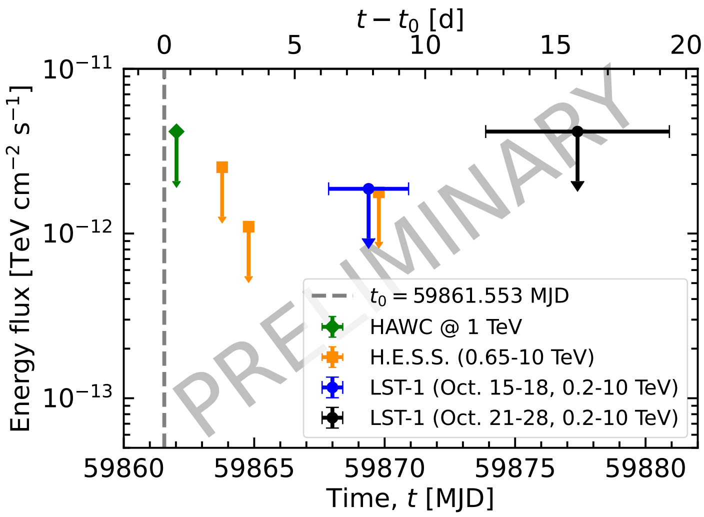

Figure 2: Observed energy flux for LST-1 dark observations (using observations on Oct. 15–18 and 21–28 in blue and black, respectively) between 0.2 TeV and 10 TeV. Also, the 95% ULs from HAWC (green; [14]) and H.E.S.S. (orange; [15]) are shown. Moreover, the dashed line marks the Fermi-GBM trigger time (t_0; [5]). Notice that the H.E.S.S. energy-flux ULs are between 0.65 TeV and 10 TeV, while the HAWC UL is at 1 TeV.

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