RS Ophiuchi nova outburst detection by the LST-1

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The recurrent symbiotic nova RS Ophiuchi experienced an outburst in August 2021 that was detected at optical and high-energy gamma rays. This triggered follow-up observations of the source at very-high-energy gamma rays with the first Large Size Telescope (LST-1) of the Cherenkov Telescope Array. RS Ophiuchi was observed for several nights after the outburst and it was clearly detected by LST-1. Here we report on the outcomes of this observation campaign of the first nova ever detected at very high energies.

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https://pos.sissa.it/
1. Introduction

The Large Size Telescope (LST-1) is the prototype of the largest telescopes of the next generation of Imaging Atmospheric Cherenkov Telescopes (IACTs) that will constitute the future Cherenkov Telescope Array (CTA). LSTs have a large collection area thanks to a 23 m diameter dish that will dominate the sensitivity of CTA at low energies [1]. Furthermore, their lightweight design with a fast re-position speed makes LSTs ideal instruments for transient follow-up studies.

Recurrent symbiotic novae are binary systems formed by a white dwarf and a red giant star. They undergo repetitive nova outbursts produced by thermonuclear runaway explosions in the white dwarf surface due to the accretion of matter from the companion star. Novae were detected for the first time at high energies in 2010 [2]. Their detection at very high energies (VHEs) did not happen until the outburst from RS Ophiuchi (RS Oph) in 2021 [3], which was deeply followed up by different IACT facilities such as MAGIC [4], H.E.S.S. [5] and LST-1. RS Oph is a recurrent symbiotic nova with an outburst period of about 15 years. This work reports the LST-1 and Fermi-LAT analysis during the first days of the 2021 RS Oph outburst.

2. LST-1 observations

LST-1 started the observations of RS Oph after the trigger alert from Fermi-LAT [6]. LST-1 observed RS Oph for several days after the outburst onset. The first observation started about a day after optical discovery, on August 9th, and the observation campaign lasted nearly a month. However, during this period, RS Oph could not be observed for several days due to the intense moonlight during the full moon phase and bad atmospheric conditions. In this work, we present the results using the observations recorded right after the outburst, selecting only those with good atmospheric conditions. The data that passed the selection criteria were recorded on August 9th, 10th and 12th. The total observation time for this observation subset is nearly 6.5 h. A summary of the LST-1 observations is presented in Table 1.

<table>
<thead>
<tr>
<th>Observation date [yyyy-mm-dd]</th>
<th>Time delay [d]</th>
<th>Effective time [h]</th>
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<tr>
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<tr>
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</tr>
<tr>
<td>2021-08-12</td>
<td>3.97</td>
<td>2.27</td>
</tr>
</tbody>
</table>

Table 1: Date, time delay between the outburst onset [3] and the beginning of the first observation, and exposure time for LST-1 observations with good atmospheric conditions during the first days of the outburst.

3. Data analysis

All LST-1 observations were made with the so-called wobble mode [7] with the single telescope trigger. The raw LST-1 camera images were processed with cta-lstchain [8], the data analysis pipeline developed to process LST-1 data. The energy and direction reconstruction, and particle classification of the incident particle are estimated through random forests (RFs), which are trained with Monte Carlo (MC) simulations of proton and gamma-ray events (more information in [9],
[10] and LST Collaboration, in preparation). In this work, the MC dataset used to train the RFs comprised simulated protons and gamma rays coming from a fixed sky position (at an azimuth of 180° and altitude of 50°) close to the RS Oph culmination in the sky at the LST-1 location. In order to have a better match between real data and MC simulations, random Poisson noise was added to match the Night Sky Background (NSB) of RS Oph observations. Also, the MC simulations were tuned to match the real Point Spread Function (PSF) of the LST-1.

The analysis method used in this work is based on the so-called source-dependent analysis, which uses the prior knowledge of the source position to estimate the physical properties of the primary particle. This source-dependent analysis is used to improve the performance of the single telescope observation mode at lower energies (see LST Collaboration, in preparation). Instead of using the typical \( \theta \) parameter to describe the direction of the event with respect to the nominal source direction, the source-dependent analysis uses the parameter \( \alpha \), which is the angle between the direction of the semi-major axis of the shower image and the direction to the assumed source position from the shower image center of gravity. A cut of 10° in \( \alpha \) was applied to the processed data. At the same time, a cut in the \( \text{gammaness} \) parameter is considered as well. It indicates how likely the primary event is a gamma ray using a score value between 0 and 1, where the highest value is given to the most gamma-like event. A score cut of 0.9 is used in the analysis.

The LST-1 high-level data (gamma-ray candidates with reconstructed energy and direction) was processed with the official high-level data framework for CTA, Gammapy [11], to produce the energy spectra and light curve of RS Oph.

On the other hand, Fermi-LAT data was analysed with Fermi tools version 2.0.8\textsuperscript{1} and Fermipy version 1.0.1\textsuperscript{2}. The analysis considers a region of interest (RoI) of 20° centred on the RS Oph direction. The LAT 10 years source catalog was used together with the standard isotropic and galactic diffuse background from Pass 8 to model the RoI.

4. Results

To analyse the VHE gamma-ray emission of RS Oph, three reflected positions in the camera at 90, 180 and 270 degrees with respect to the source direction were used as control positions to assess the background emission. Using all the 6.4 hours of data from August 9\textsuperscript{th}, 10\textsuperscript{th} and 12\textsuperscript{th} observations, LST-1 detected RS Oph with a Li & Ma detection significance [12] of 7.5\( \sigma \) and a signal-to-noise ratio (S/N) of almost 5% (see Figure 1).

A power-law spectral model \( (\phi = \phi_0 (E/E_0)^\Gamma) \) was used to fit the spectral energy distribution (SED) of RS Oph at VHEs. The lower-energy bound used for the spectral fitting was 45 GeV, which is the energy value at the maximum of the distribution of survived MC gammas after weighting its distribution to the assumed RS Oph spectral index and using the same selection cuts applied to RS Oph data [13]. The best fit spectral model was obtained through a maximum likelihood fitting process stacking the data from August 9\textsuperscript{th}, 10\textsuperscript{th} and 12\textsuperscript{th} observations altogether. The best fit model has a soft spectral index of \( \Gamma = -3.3 \pm 0.2 \) and a normalization factor of \( \phi_0 = (4.5 \pm 0.8) \times 10^{-10} \text{TeV}^{-1}\text{cm}^{-2}\text{s}^{-1} \) at a reference energy of \( E_0 = 130 \text{GeV} \).

\textsuperscript{1}\url{https://fermi.gsfc.nasa.gov/ssc/data/analysis/}
\textsuperscript{2}\url{https://fermipy.readthedocs.io/en/latest/}
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Figure 1: LST-1 alpha plot displaying the angular distributions for the ON (angle between event major axis and the nominal source position) and OFF directions (angle between event major axis and the reflected directions). A cut in alpha at 10° (dashed line) is applied to compute the Li & Ma detection significance and S/N.

The SED at high-energy (HE) gamma rays from our dedicated Fermi-LAT analysis was computed using the same temporal window as the LST-1 observations. The SED obtained with LST-1 and Fermi-LAT is shown in Figure 2. The preliminary SED obtained with the LST-1 displays a smooth transition from the Fermi-LAT energy range to the LST-1 energy range.

Figure 2: RS Oph SED obtained with the LST-1 (blue) and the Fermi-LAT (back). The best fit model for LST-1 is shown as a blue line together with the spectral error band in gray. The spectral index and amplitude values of the best fit model and their associated errors are displayed on the lower left.

A zoom-in to the VHE range is displayed in Figure 3, where the SED points from MAGIC [4] and H.E.S.S. [5] are also included. The former was obtained using the data from the first four days of observations (August 9th to 12th), whereas the latter uses observations from August 8th and 13th, separately. The preliminary LST-1 SED shows a remarkably good agreement with the SEDs from the different IACT facilities that observed RS Oph at VHEs (Figure 3).
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Figure 3: RS Oph SED obtained with the LST-1 (blue), MAGIC (back) and H.E.S.S. (orange and green) telescopes. The best fit model for LST-1 is displayed as a blue line together with the spectral error band in gray. The spectral index and amplitude values of the best fit model and their associated errors are shown on the lower left.

5. Conclusions

LST-1 detected RS Oph with a detection significance of $\sim 7.5\sigma$ using a total observation time of 6.4 hours during August 9th, 10th and 12th. The preliminary spectral analysis reported in this work confirms that RS Oph had a soft spectrum during the first days after the outburst. LST-1 preliminary spectral results are compatible with the SEDs reported by the MAGIC and H.E.S.S. Collaborations [4, 5]. In addition, thanks to a large-effective area below 100 GeV, LST-1 is capable of studying the spectrum of RS Oph down to 45 GeV, allowing to observe a smooth transition between the Fermi-LAT energy range and the VHE domain.

The preliminary results presented in this work are obtained using a fixed MC production. However, a dedicated analysis using a refined MC production will be presented in a future publication.

Acknowledgements

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www.cta-observatory.org/consortium_acknowledgments

References


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