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Novae at gamma rays with the LSTs of CTAO: present and future

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Abstract

The Cherenkov Telescope Array Observatory (CTAO) is the next-generation ground-based gamma-ray observatory. CTAO will be located at both the northern and southern hemispheres. The northern site will be at the Observatorio del Roque de Los Muchachos on the Canary Island of La Palma, Spain, while the southern site will be established in Paranal, Chile. The Large-Sized Telescope (LST) is the largest telescope type of CTAO. Designed to detect gamma rays from tens of GeV to a few TeV, LSTs are ideally suited for observations of transient sources. The first LST (LST-1) is located at the northern site and, despite being in commissioning phase, is already taking data from various sources, including galactic transients. In particular, galactic novae are of high interest to the LST Collaboration. The detection of 2021 RS Oph nova at hundreds of GeV gamma rays with LST-1 and other Cherenkov telescopes marked a milestone for our understanding of novae. Such a breakthrough has unveiled that efficient particle acceleration up to TeV energies takes place in these systems. In this contribution, we will present an overview of novae at gamma rays and the results of the analysis of LST-1 observations of RS Oph, put in context with other gamma-ray data. Moreover, we will discuss future observations of these systems with CTAO.

1 Introduction

The etymology of nova refers to the appearance of a new star in the sky (from Latin abbreviation *stella nova*) [1]. Such (sudden) increase in brightness originates in a thermonuclear runaway explosion on the surface of a white dwarf in a binary system. The companion star transfers mass onto the compact object. Depending on the spectral type of the companion star, the systems that undergo nova explosions can be categorized into two types: cataclysmic variables, where the white dwarf accretes matter from a main sequence star, and symbiotic binaries, involving an evolved star such as a red giant star. The bright explosions ($L \sim 10^4$–$10^5\,L_\odot$) with ejection of material that occur in cataclysmic variables are named classical novae, while the term symbiotic novae is used to refer to the cases in which a evolved star is present.

Despite the large amount of energy released during a nova explosion, reaching a few 10^4–$10^5\,L_\odot$, the binary system survives the event. It is thought that nova systems outburst more than once during their lifetime, contributing to the synthesis of elements and constituting a possible channel for type Ia supernovae if the white dwarf gains enough matter to reach the Chandrasekhar mass. When we have records of multiple nova outbursts from the same system, this source is observationally categorized as a recurrent nova. See [2] for a recent review.

Novae show signs of non-thermal emission across the electromagnetic spectrum, from radio to gamma rays. Very recently, the first detection of gamma rays above 100 GeV (very-high-energy, VHE) in the 2021 nova event in RS Ophiuchi (RS Oph) shows evidence that this system, and maybe other novae, can efficiently accelerate particles up to TeV energies and subsequently produce the observed gamma rays [3, 4]. The high frequency and fast evolution of novae make them good laboratories for testing particle acceleration models.

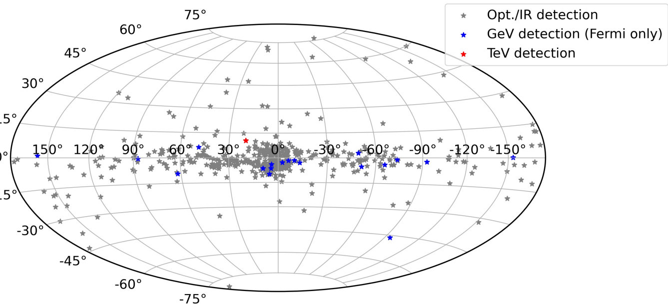
The Cherenkov Telescope Array Observatory (CTAO) is the future ground-based facility sensitive at gamma-ray energies between tens of GeV to hundred TeV. CTAO will be located in the northern and southern hemispheres (CTAO-N and CTAO-S, respectively). Constituted by different telescope arrays of various sizes to cover the wide energy range, the largest telescope type is the Large-Sized Telescope (LST). The first out of four LSTs in CTAO-N, LST-1, is under commissioning and is already taking scientific data. LST-1 participated in the detection of RS Oph at VHE gamma rays [5, 6]. In these proceedings, we provide in Sect. 2 an overview of novae explosions in gamma rays. We present the results of the analysis of observations of RS Oph taken with LST-1 in context with other gamma-ray data in Sect. 3. In Sect. 4, the perspective of novae detections with the full array of CTAO is discussed. Summarising conclusions are provided in Sect. 5.

2 Novae at gamma rays

The first detection at high-energy gamma rays (HE; $E \geq 100\,\mathrm{MeV}$) occurred in 2010 during the outburst of the symbiotic binary V407 Cyg [7], which confirmed the predictions of particle acceleration and gamma-ray emission in such evolved systems [8]. Later on, following the unexpected detections at HE gamma rays from cataclysmic variables in outburst, classical novae were added as a new source class of HE gamma-ray emitter [9, 10].

In sixteen years of continuous monitoring of the HE sky with *Fermi*-LAT (2008–2024), 20 novae have been detected at HE gamma rays. This implies a detection rate at these energies of about one nova per year[1]. This rate is low compared with the estimated nova rate in the Milky Way of $48^{+3}_{-8}\,\mathrm{yr}^{-1}$ and about an order of magnitude lower than the observed one in the optical [11, 12]. The distribution of historical novae[2] is shown on the left panel of Fig. 1. Novae detected at HE gamma rays (blue stars) follow a similar distribution as the historical novae (grey stars): they concentrate towards the galactic plane and bulge.

We show on the right panel of Fig. 1 the maximum apparent magnitude for all novae during the lifetime of *Fermi*-LAT until June 2024. Observationally, HE novae are bright. In particular, they are located at the bright edge of the peak apparent magnitude distribution, which might indicate an observational bias rather than a consequence of different source intrinsic properties [13].



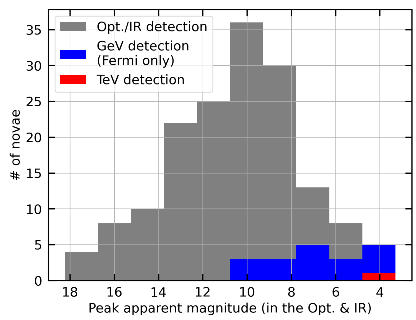


Figure 1: Left: Skymap in galactic coordinates of all historical novae as of June 2024. Stars highlighted in blue correspond to novae detected only at GeV, while the red one is RS Oph detected at TeV. Right: Distribution of the maximum apparent magnitude in the optical and infrared for novae between June 2008–2024. The same colour palette as the left plot is used. V959 Mon is excluded because its maximum apparent magnitude was not observed due its close distance to the Sun.

3 RS Oph

RS Oph is a binary system at a distance of about 2.45 kpc[3] composed of a red giant star and a white dwarf that undergoes recurrent nova outbursts taking place every 9 to 26 years [14]. The evolved companion star overfills the Roche lobe, transferring matter onto the compact object with a mass close to the Chandrasekar limit. The 2021 outburst of RS Oph was observed extensively with Cherenkov telescopes as the High Energy Stereoscopic System

[1]List of *Fermi*-LAT detected novae: `https://asd.gsfc.nasa.gov/Koji.Mukai/novae/latnovae.html`.

[2]Data were extracted on 25 June 2024 from `https://github.com/Bill-Gray/galnovae`.

[3]Different methods to estimate the distance of RS Oph yield estimates ranging from 1.4 kpc up to 4.3 kpc.

(H.E.S.S.), the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) and LST-1 at VHE gamma-ray energies succeeding in the first detection of a nova explosion in this energy band. Significant VHE detections were obtained only within the first days after the outburst. VHE observations were obtained contemporaneously with *Fermi*-LAT, which significantly detected RS Oph in its 2021 outburst for a total of 45 days [15].

In Fig. 2, we show the spectral energy distribution (SED) of RS Oph from 50 MeV to about 1 TeV for days with coincident data from the three Cherenkov telescope facilities. The SEDs show signs of curvature, with a pronounced decay above a few tens of GeV. The temporal evolution of the emission during the first days after the explosion is characterised by a decay in the HE band, while the emission increases at VHE gamma rays.

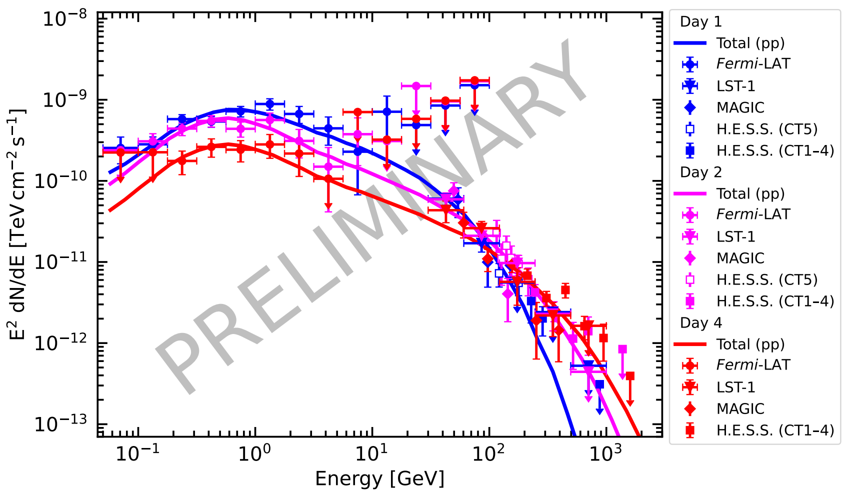


Figure 2: Evolution of the SED of RS Oph using *Fermi*-LAT (circles), LST-1 (triangles), MAGIC (diamonds) and H.E.S.S. (filled and empty squares) data for day 1, 2 and 4 after the outburst in blue, fuchsia and red, respectively. Also, the total emission of the best-fit hadronic model using all data for each day is shown as solid lines.

The preferred radiative mechanism to produce gamma rays is neutral pion decay via proton-proton interactions [4, 3, 15]. We show in Fig. 2 the best-fit emission model using all the gamma-ray data. The reader is referred to [6] for more information on the model used and obtained results. The temporal evolution agrees with findings in [4, 3, 15]: the protons require a finite acceleration time to reach TeV energies and subsequently produce gamma rays. We note, however, that more complex models involving a multi-particle population can also explain the observed emission [16, 17].

4 Perspective of novae detection with CTAO

RS Oph shares similar features with only a few other nova systems, the ones in which recurrent outbursts occur embedded in the wind of an evolved companion star, making these sources quite rare among the other systems with nova explosions, dominated by cataclysmic variables. It is unclear whether the distinct properties of RS Oph are required to produce gamma rays up to TeV energies or whether classical nova can also emit in the VHE band. Sensitive telescopes, like CTAO, will be pivotal to increase the chances of nova detections from dim sources, either due to their intrinsic nature or large distances to Earth. Furthermore, the improved sensitivity and higher energy resolution of CTAO compared with current facilities will be decisive for testing particle acceleration/radiation mechanisms in these time-dependent systems.

Simulations of RS Oph were performed accounting for the sensitivity of CTAO-N[4], assuming the RS Oph gamma-ray spectral profile obtained on the first day after the outburst [4]. For further information on these simulations, we refer the reader to [19]. In Fig. 3, we show the emission that CTAO-N would have observed with 1 hour of data taking, the same amount of time covered by MAGIC on the same day for RS Oph. The detailed obtained SED will allow us to characterize the emission with a much higher precision, enabling the test of current particle acceleration and emission models, or eventually triggering new theoretical developments.

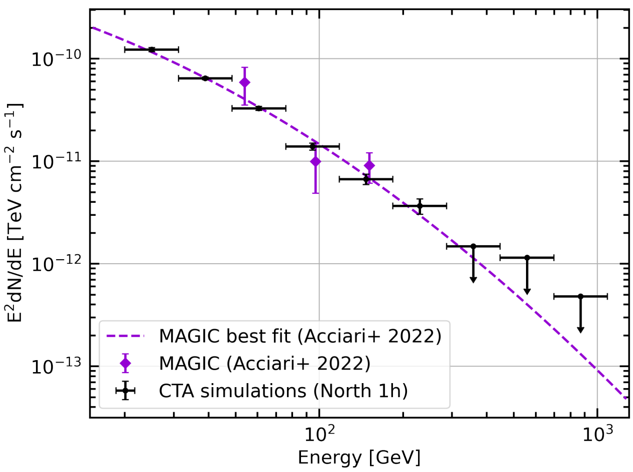


Figure 3: Simulated SED of RS Oph for day 1 after the outburst using CTAO-N for 1 hour observing time (black dots). In addition, the obtained SED from MAGIC using the same observation time (diamond data points) and the reference spectral shape (dashed line) are shown for reference in purple. Source [19].

[4]Using the official IRFs from `Prod5-v0.1` for the CTAO-N array. In particular, the closest IRFs to the RS Oph culmination in the CTAO-N site: `North-40deg-SouthAz` [18].

5 Conclusions

In less than 20 years since the first nova detection at HE gamma-ray energies, our understanding of the gamma-ray emission in novae has significantly improved, driven by multiple detections from different binary classes during bright outbursts. In particular, RS Oph is the brightest gamma-ray nova and the first one detected at TeV energies. Initially characterised by a soft spectrum in the VHE band, the gamma-ray emission is likely produced through hadronic processes in which protons require a finite acceleration time to reach TeV energies. The first telescope of CTAO participated in the detection of RS Oph at VHE gamma rays. The increased sensitivity of CTAO will be crucial in future novae detections, advancing our understanding of these sources and improving current models for particle acceleration in novae.

Acknowledgments

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