

Galactic transient sources with the Cherenkov Telescope Array Observatory

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ABSTRACT

A wide variety of Galactic sources show transient emission at soft and hard X-ray energies: low-mass and high-mass X-ray binaries containing compact objects, isolated neutron stars exhibiting extreme variability as magnetars as well as pulsar wind nebulae. Although most of them can show emission up to MeV and/or GeV energies, many have not yet been detected in the TeV domain by Imaging Atmospheric Cherenkov Telescopes. In this paper, we explore the feasibility of detecting new Galactic transients with the Cherenkov Telescope Array Observatory (CTAO) and the prospects for studying them with Target of Opportunity observations. We show that CTAO will likely detect new sources in the TeV regime, such as the massive microquasars in the Cygnus region, low-mass X-ray binaries with low-viewing angle, flaring emission from the Crab pulsar-wind nebula or other novae explosions, among others. Since some of these sources could also exhibit emission at larger timescales, we additionally test their detectability at longer exposures. We finally discuss the multi-wavelength synergies with other instruments and large astronomical facilities.

Key words: gamma-rays:general – transients – binaries: general – pulsars:general – stars:novae – stars:magnetars

1 INTRODUCTION

Timing astronomy and variability studies have proven to be a powerful tool to study extreme astrophysical processes at very high energies (VHE, $E > 100$ GeV). The improvement of the Imaging Atmospheric Cherenkov Technique (IACT) over the past decade has revealed new transient phenomena with variability timescales from seconds to several weeks. The last generation of IACTs have discovered several classes of transient TeV sources such as gamma-ray bursts (GRBs) (MAGIC Collaboration et al. 2019; Abdalla et al. 2019), flaring blazars associated with high-energy neutrino sources (IceCube Collaboration et al. 2018) or Galactic novae (H. E. S. S. Collaboration et al. 2022; Acciari et al. 2022), among others, unveiling new types of VHE emitters with highly variable fluxes (Carosi & López-Oramas 2024).

The Cherenkov Telescope Array Observatory (CTAO) will be the next generation ground-based observatory for VHE astronomy. It will allow the detection of gamma rays in the 20 GeV–300 TeV domain, with two observatory sites, one in the Northern hemisphere (CTAO-N; Observatorio Roque de los Muchachos, La Palma, Spain) and another in the Southern one (CTAO-S; Paranal, Chile). It will provide an improved sensitivity with respect to the current generation of IACTs of about an order of magnitude (Cherenkov Telescope Array Consortium et al. 2019). Of special importance will be the sensitivity of CTAO to short-timescale phenomena¹.

CTAO will have 10^4 – 10^5 better sensitivity than the LAT instrument onboard the *Fermi* satellite for the detection of short-duration transient events (Funk et al. 2013).

The low energy threshold of ~ 20 GeV of the largest telescopes of the array, the Large-Sized Telescopes (LSTs; CTA-LST Project et al. 2023) is key for the detection of new transient sources at the lower end of the VHE regime. This capability, together with the fast slewing response of the LSTs, which can be re-pointed in about 20 seconds, will allow a swift reaction to transient events. The Medium and Small Sized telescopes (MSTs and SSTs) will also be key to understand the emission of this sources at higher energies. Finally, since the CTAO observatory will consist of two arrays located in two hemispheres, it will provide a better and more continuous coverage of many transient events accessible from both sites.

The core program of CTAO will consist of different *Key Science*

Projects (KSPs) which were considered to address the science questions of CTAO (see Cherenkov Telescope Array Consortium et al. 2019 for more details). The *Transients* KSP is proposed to encompass the follow-up observations of several classes of targets such as GRBs, gravitational waves (GWs), high-energy neutrinos, core-collapse supernovae (CCSNe) and Galactic transients.

In this paper, we focus on Galactic sources hosting compact objects whose emission is not periodic and/or that display unexpected flaring events, outflows or jets as described in the Galactic transients section of the Transients KSP as defined in Cherenkov Telescope Array Consortium et al. (2019). Extragalactic transient events such as GRBs, core-collapse SNe or GWs will be addressed in separate publications. We discuss the capabilities of CTAO to detect new transient phenomena at VHE from sources of Galactic origin, ranging from microquasars, to pulsar-wind nebulae (PWNe) flares, to novae, transitional millisecond pulsars or magnetars among others. Some of these sources could also exhibit persistent emission, hence we additionally test the detectability at longer exposures in some specific cases. Since the nature of the source classes of study and hence the physical processes are different, the simulated timescales of the expected VHE emission also vary. We have used timescales ranging from as low as 10 min to few hours for transient detection and up to 50–200 h to test persistent emission in certain sources of interest. For our simulations, we have used the software packages *ctools*² (Knödlseder et al. 2016) and *Gammapy*³ (Donath et al. 2023; Aguasca-Cabot et al. 2023) with the official CTAO observatory instrument response functions (IRFs).⁴ For a full description of CTAO observatory IRFs and configurations see Maier et al. (2023).

The source classes of our interest are described in the following Subsections 1.1–1.5. We present the sensitivity of CTAO to Galactic transient detection in Section 2 and population studies in Section 3. The simulations, analysis results and discussion for each type of transient are collected in Section 4. Section 5 describes the synergies

² *ctools* is a software specifically developed for the scientific analysis of gamma-ray data, see <http://CTAO.irap.omp.eu/ctools/index.html>

³ *Gammapy* is an open-source Python package developed for gamma-ray astronomy, see <https://gammapy.org/>

⁴ The IRF version *prod3b-v2* is the one used throughout the manuscript, unless otherwise specified. The newest *prod5* version corresponding to the *Alpha Configuration*, which corresponds to the first stage of CTAO observatory construction has also been tested in some science cases and are specified in the text.

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¹ For CTAO performance, see: <https://www.CTAO.org/for-scientists/performance/>

with multi-wavelength and multi-messenger astronomical facilities. The summary and final conclusions are listed in Section 6.

1.1 Microquasars

Microquasars are binary systems with a compact object (NS or a BH) orbiting around and accreting material from a companion star. The matter lost from the star can lead to formation of an accretion disk around the compact object and a relativistic collimated jet (Mirabel & Rodríguez 1998).

At the moment more than 20 microquasars are known in the Galaxy (see i.e. Corral-Santana et al. 2016). Observations demonstrated correlations between the mass of the compact object, radio (5 GHz) and X-ray (2–10 keV) luminosities (e.g. Falcke et al. 2004), strengthening the link between active galactic nuclei (AGNs) and microquasars. In AGNs, jets are known to be places of efficient particle acceleration and produce broad band non-thermal emission. The resulting radiation can extend from radio up to the VHE band. According to TeVcat⁵ more than 65 AGNs have been already detected by current IACTs. If similar jet production and particle acceleration mechanisms operate in microquasars and AGNs, this might imply that microquasars should be sources of VHE γ -ray emission as well.

Up to now, only three microquasars have been detected in the high-energy (HE, $E > 100$ MeV) domain: Cygnus X-1 (Bulgarelli et al. 2010; Sabatini et al. 2010, 2013; Malyshev et al. 2013; Zanin et al. 2016; Zdziarski et al. 2017), Cygnus X-3 (Tavani et al. 2009; Fermi LAT Collaboration et al. 2009; Zdziarski et al. 2018), and SS 433 (Bordas et al. 2015; Sun et al. 2019; Rasul et al. 2019; Xing et al. 2019; Li et al. 2020), all of them hosting a massive companion star. In the case of low-mass microquasars, the only one that has displayed a strong hint of gamma-ray emission (at high energies) was the binary V404 Cyg during its 2015 outburst (Loh et al. 2016; Piano et al. 2017). Steady VHE emission was first detected from the interaction regions between the jet and the surrounding nebula for the time in SS 433 (Abeysekara et al. 2018a; H. E. S. S. Collaboration et al. 2024). Other microquasars have been recently reported to be sources of persistent of TeV and PeV emission (for details see i.e. Alfaro et al. 2024; LHAASO Collaboration 2024). Regarding flaring emission, the strongest hint reported was the 4.1σ transient signal (post-trial) found at VHE in Cygnus X-1 (Albert et al. 2007). The expectations for the detection of both massive microquasars and low-mass X-ray binaries (LMXBs) with CTAO are presented in Sections 4.1–4.2.

The relevance for studying binary systems in the VHE regime has already been addressed by Paredes et al. (2013); Chernyakova et al. (2019). In this paper, we do not focus on gamma-ray binaries displaying periodic orbital variability and likely powered by non-accreting pulsars, but only on systems powered by accretion and displaying jets, to better investigate the potential VHE emission of this specific class of binaries. We discuss high-mass microquasars (Section 4.1) separately to low-mass X-ray binaries (Section 4.2).

1.2 Transitional millisecond pulsars

Transitional millisecond pulsars (tMSPs) are a class of neutron star binaries that has emerged in the last decade with the discoveries of three confirmed systems: PSR J1023+0038 (Archibald et al. 2009a; Patruno et al. 2014a), XSS J1227-4853 (de Martino et al. 2010; Bassa et al. 2014) and IGR J1824-2452 in the globular cluster M28 (Papitto

et al. 2013). Additionally, a handful of candidate tMSPs have been recently discovered in the X-ray and GeV ranges (see review by Papitto & de Martino 2022). tMSPs alternate between a radio-loud MSP state (RMSP, showing radio pulsations and no sign of an accretion disk) and a sub-luminous LMXB state (forming an accretion disk and showing X-ray pulsations). These sources are the direct link between the LMXB and the radio MSP phases in which neutron stars are spun up to ms periods during the LMXB-phase. Sudden transitions between the two states occur on a timescale of a few days to weeks, and are accompanied by drastic changes across the electromagnetic spectrum. The transition from the RMSP to LMXB state is accompanied by brightening of optical, UV (Patruno et al. 2014b; Takata et al. 2014), X-ray and gamma-ray (Stappers et al. 2014) emission with the disappearance of radio pulsations. The origin of these transitions is still debated and, for this, intense multi-wavelength campaigns are on-going to understand the phenomenology in both the RMSP and LMXB states. tMSPs were so far not detected in the VHE regime. The constraints to the VHE emission from tMSPs during the LMXB state are discussed in Section 4.3.

1.3 Pulsar wind nebulae

Pulsar wind nebulae (PWNe) are bubbles or diffuse structures of relativistic plasma powered by a central highly-magnetized rotating neutron star. They represent one of the largest Galactic populations at VHE. Recently, several PWNe have been suggested to be PeV particle (leptons) accelerators, with the detection of gamma rays at $E > 100$ TeV (Cao et al. 2021, 2023). The Crab nebula is the standard candle at VHE and both the nebula and the pulsar have been intensively studied. Pulsations have been measured up to TeV energies (Ansoldi et al. 2016) and the nebula spectrum has been detected up to 100 TeV by IACTs (MAGIC Collaboration et al. 2020) and recently extended to PeV (Lhaaso Collaboration et al. 2021). Unexpectedly, the Crab nebula displays rapid flaring emission over daily timescales at HE as reported by AGILE and Fermi-LAT (Tavani et al. 2011; Abdo et al. 2011). The enhanced fluxes measured over different flaring episodes were a factor three-to-six times larger than the standard flux. These episodes of enhanced HE emission have been detected up to 10 GeV (as reported by Tavani et al. 2011) and can last up to few weeks. A detection of the synchrotron tail at higher energies or a additional inverse Compton component in the TeV domain could be expected. So far, no signs of variability have been reported at VHE (Mariotti 2010; Ong 2010; H. E. S. S. Collaboration et al. 2014; van Scherpenberg et al. 2019). The characterization of the expected VHE emission to be putatively detected by CTAO is shown in Section 4.4.

1.4 Novae

Novae are thermonuclear runaway explosions on the surface of a white dwarf star in binary systems involving a white dwarf accreting matter, often through an accretion disc, usually from a late-type star (Gallagher & Starrfield 1978). They are detected as transient events exhibiting huge and sudden increase of brightness. Though novae have been studied both observationally and theoretically for many decades, a comprehensive understanding of nova physics is still lacking (Iben 1982; Yaron et al. 2005; Bode & Evans 2008; Kato et al. 2014; Chomiuk et al. 2021). Particle acceleration in novae was predicted before the launch of the Fermi Gamma-ray space telescope (see Tatiseff & Hernanz 2007). Shortly after, GeV emission from the outburst of the symbiotic binary system V407 Cygni, comprised of a white dwarf and an evolved red giant companion, was first detected. Subsequently, classical novae with main sequence donor stars

⁵ <http://tevcat2.uchicago.edu/>

were also detected (Abdo et al. 2010a; Ackermann et al. 2014).⁶ More recently, VHE emission in novae has been predicted and searched for in a handful of sources (see e.g. Aliu et al. 2012; Ahnen et al. 2015), with the first detection at VHE gamma rays occurring in 2021 in the recurrent nova RS Ophiuchi (RS Oph, Acciari et al. 2022; H. E. S. S. Collaboration et al. 2022; Abe et al. 2025).

Since the first detection at HE gamma rays from nova Cygni 2010, 19 novae⁷ have been detected in this energy band (only RS Oph at VHE) with a rate of about one outburst detection per year. All novae so far detected at HE have been bright in the visible band (≤ 10 mag), and the vast majority are nearby sources with distances within 5 kpc (Franckowiak et al. 2018). Non-thermal emission is expected to arise from leptonic and hadronic interactions by particles accelerated in radiative expanding shocks (Abdo et al. 2010a; Hernanz & Tatischeff 2012), which can originate from the interaction of the ejecta during the initial stage of the outburst and the circumbinary material, or with the fast wind produced by nuclear burning in later stages of the outburst (Abdo et al. 2010a; Ackermann et al. 2014; Martin et al. 2018). The VHE signal reported by Acciari et al. 2022; H. E. S. S. Collaboration et al. 2022; Abe et al. 2025 is suggested to be of hadronic origin, due to protons accelerated in the nova shock.

Based on observations of novae in the nearby M31 Galaxy, as well as binary population synthesis models for the Milky Way, a rate of approximately 30 nova events per year is expected (see Section 4.5). However, a significant proportion of these will be obscured by intervening dust in the Galactic plane, preventing multi-wavelength follow-up observations. The number of nova events that will be detectable at HE and VHE gamma rays will be further constrained by properties of the system, such as the shock velocity and the target material density. This dependence on the parameter space and prospects for detection of novae at VHE will be characterised for CTAO in Section 4.5.

1.5 Magnetars

Magnetars are isolated neutron stars in which the main energy source is the magnetic field (e.g. Mereghetti et al. 2015; Kaspi & Beloborodov 2017, for reviews). They are observed as pulsed X-ray sources, with typical spin periods of a few seconds and strong spin-down rates (typically 10^{-12} – 10^{-10} s s⁻¹) (Harding et al. 1999), and/or through the detection of short bursts and flares in the hard X-ray/soft gamma-ray range. This led to their historical subdivision in the Anomalous X-ray Pulsars and Soft Gamma-ray Repeater classes (Mereghetti 2008), but it is now clear that these are just two different manifestations of the same underlying object: a strongly magnetized neutron star powered by magnetic energy, as proposed by Paczynski (1992) and Duncan & Thompson (1992).

About 30 magnetars are known so far. With the exception of two sources in the Magellanic Clouds, all of them lie in the Galactic Plane. The majority of the magnetars are transient X-ray sources that have been discovered when they became active, with an increase of their X-ray luminosity (from a quiescent level of $\sim 10^{33}$ erg s⁻¹ up to $\sim 10^{36-37}$ erg s⁻¹), accompanied by the emission of luminous and rapid bursts. This means that the total Galactic population of magnetars is larger than the currently observed sample, and more sources of this class will be known at the time of CTAO observations.

Furthermore, magnetar-like behavior has recently been observed in some sources originally presumed to be of a different kind, such as rotation-powered (radio) pulsars (Gavril et al. 2008; Göğüş et al. 2016), and even in the gamma-ray binary LS I +61 303 (Torres et al. 2012; Weng et al. 2022).

For what concerns the persistent emission, magnetars have not been detected above few hundred keV (Abdo et al. 2010b; Aleksić et al. 2013). Their X-ray emission typically comprises a soft thermal component that dominates in the 1–10 keV range and a hard power-law component that is believed to originate from multiple resonant scattering in the magnetosphere. The upper limits (ULs) in the MeV range (Li et al. 2017) indicate a turn-off of this component implying that their detectability is below the CTAO capabilities, unless a different spectral component is present at higher energies. On the other hand, magnetar bursts and flares (in particular the so called Giant Flares) are potentially very interesting targets for CTAO, with the only disadvantage of their unpredictable time of occurrence. Giant flares are extremely energetic and bright events, reaching isotropic peak luminosities as high as a few 10^{47} erg s⁻¹ for a fraction of a second. However, they occur very rarely: only three have been seen from local magnetars in 40 years. The high luminosity of their short (< 1 s) initial peaks implies that they can be detected, with properties resembling those of short GRBs, up to distances of tens of Mpc by current hard X-ray instruments. Indeed, a few candidate extragalactic giant flares have been identified (Mazets et al. 2008; Frederiks et al. 2007; Svinkin et al. 2021; Roberts et al. 2021). Of particular interest regarding CTAO's perspective to detect giant flares is the case of the flare located in the Sculptor galaxy (NGC 253, at 3.5 Mpc) for which *Fermi*-LAT observation led to the detection of two high-energy photons with energies of 1.3 GeV and 1.7 GeV, likely produced via synchrotron mechanism (Fermi-LAT Collaboration et al. 2021). However, no emission from a magnetar has been yet detected at TeV energies (Abdalla et al. 2021; López-Oramas et al. 2021). For further discussion, see Section 4.6.

2 SENSITIVITY OF CTAO TO TRANSIENT DETECTION IN THE GALACTIC PLANE

CTAO will have unprecedented sensitivity over a broad energy range and will devote a large amount of time to sources in the Galactic plane, both with a dedicated Galactic Plane Survey (GPS) (for details on the pointing strategy and expected results see CTA Consortium 2023) and with pointed observations on specific targets. These are ideal capabilities for the discovery of new Galactic transients at TeV energies.

It is then important to characterize the sensitivity of CTAO in the Galactic plane. The differential sensitivity of CTAO for detecting a new source is defined as the minimal flux of a source, multiplied by the mean energy squared within the given energy interval, such that the source is detectable at the 5σ significance level. It is defined within a given energy range, and for a given observation interval or exposure. We assume a test point source power-law spectral model,

$$F(E) = P_f \left(\frac{E}{E_0} \right)^{-\gamma} \quad (1)$$

where we set the pivot energy, $E_0 = 1$ TeV, and the spectral index, $\gamma = 2.5$, using typical values for Galactic VHE sources. The prefactor, P_f is varied as part of the sensitivity calculation, in order to find the minimal flux value for a 5σ detection. In order to be compatible with previous analyses (e.g. Fioretti et al. 2019), we also require that the source emits at least 10 gamma-ray photons. In addition,

⁶ Gomez-Gomar et al. (1998) (and references therein) predicted gamma-ray emission from novae but of nuclear origin, in the keV–MeV domain.

⁷ According to <https://asd.gsfc.nasa.gov/Koji.Mukai/novae/latnovae.html> (as of February 2024).

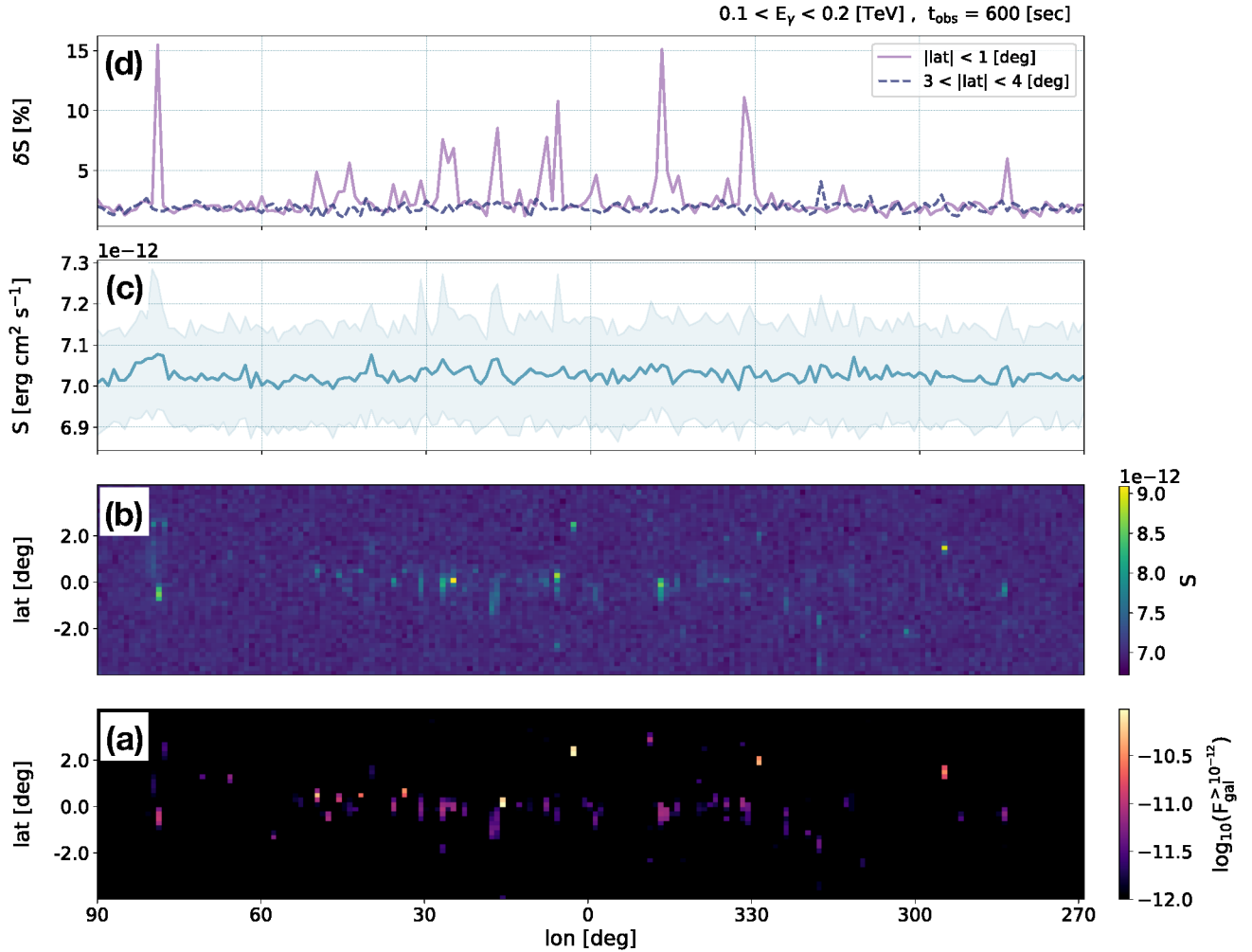


Figure 1. Differential flux sensitivity, S , of the Southern CTAO array within 100–200 GeV for 10 min observation intervals, considering different putative source locations along the Galactic plane. *Panel (a)* shows a simulation of $F_{\text{gal}}^{>10^{-12}}$, the Galactic emission (Galactic diffuse emission and a simulated population of Galactic sources) above a threshold of $10^{-12} \text{ erg cm}^2 \text{ s}^{-1}$, which is derived for different Galactic longitudes, lon , and latitudes, lat . *Panel (b)* shows the corresponding CTAO sensitivity. In *panel (c)* we present the median of S for different longitudes within the range, $-4 < \text{lat} < +4 \text{ deg}$, where the shaded uncertainty region represents the 1σ variance of S . Finally, *panel (d)* shows the relative 1σ variance, δS , (compared to the median) derived for two ranges in latitude, as indicated. The variance away from the Galactic plane ($3 < |\text{lat}| < 4 \text{ deg}$) represents the intrinsic statistical uncertainty of the sensitivity calculation. The variance in the inner Galactic region ($|\text{lat}| < 1 \text{ deg}$) includes the intrinsic uncertainty, as well as the additional effect of the Galactic foregrounds, which are concentrated in this region.

we validate that this number of events is larger than 5% of the corresponding contribution from backgrounds (cosmic rays; electrons) and foregrounds (other coincident gamma-ray sources).

We explore the performance of CTAO in the Galactic plane region for various short observation intervals. For illustration, the sensitivity of the Southern array is shown in Fig. 1, considering different putative source locations. In this example, we estimated the performance for short observation intervals of 10 minutes within the energy range 100–200 GeV, exploring the detection potential of new sources in the low-energy range of CTAO. We use a publicly-available Galactic sky model, based on observations of known gamma-ray sources and interstellar emission from cosmic-ray interactions in the Milky Way

(CTA Consortium 2023).⁸ We simulate our putative transients on top of the emission derived from this sky model, such that the latter constitutes an additional background to the search.

As may be inferred from Fig. 1, upward fluctuations of the sensitivity (requiring brighter transient emission for detection), are correlated with the steady emission from Galactic sources. In the selected energy range, the flux of the simulated Galactic foreground is mostly below the level of a few $10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$. This is of the same order as the nominal sensitivity of the observatory in the absence of

⁸ Galactic sky model available at <https://zenodo.org/records/10008527>

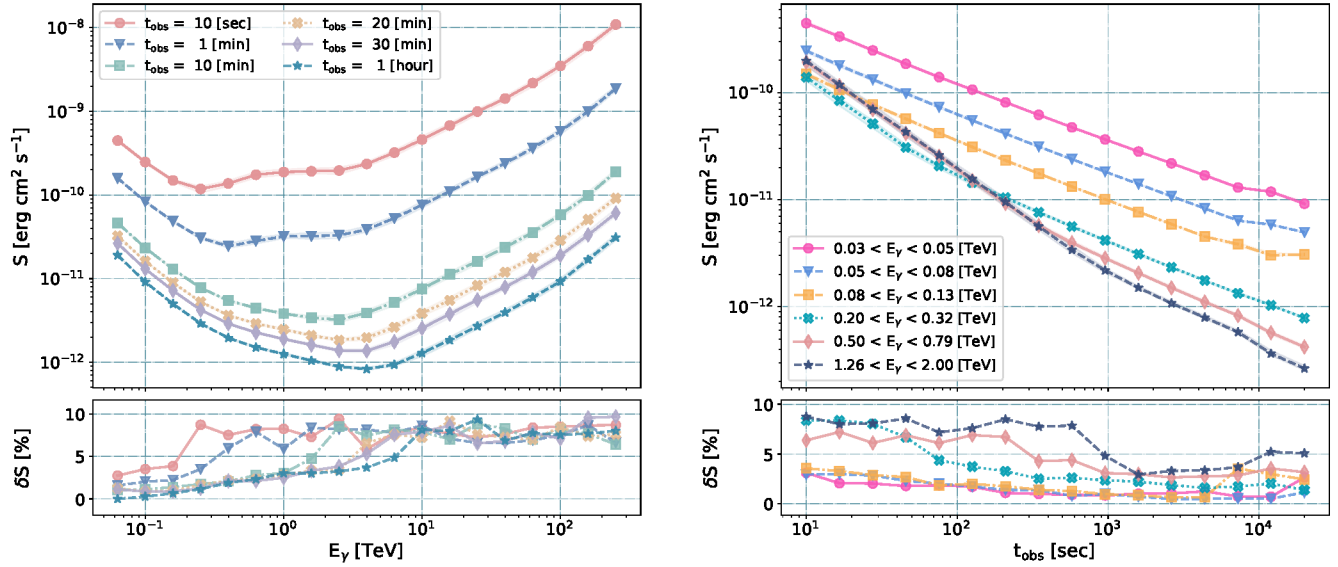


Figure 2. The differential flux sensitivity, S , of the Southern CTAO array for different energy ranges, $0.03 < E_\gamma < 200$ TeV, and observation intervals, $10 < t_{\text{obs}} < 2 \cdot 10^4$ sec. The sensitivity is derived as the median value for various putative source positions, considering an area of 4 deg^2 close to the Galactic centre. The bottom panels show the relative 1σ variance of the sensitivity, δS , compared to the median. The variance accounts for both the intrinsic statistical uncertainty of the sensitivity calculation, and the degradation of performance due to the presence of steady sources.

foregrounds. Correspondingly, the overall degradation in sensitivity to transients is not expected to be significant.

In order to verify this, we calculated δS , the relative variation of the sensitivity (compared to the median value) for different Galactic longitudes. The steady foreground sources are concentrated in the inner Galactic region. We therefore derived δS for two regions in latitude, in order to enhance or suppress their effect. Away from the Galactic plane we find $\delta S \sim 2\text{--}3\%$ which amounts to the intrinsic statistical uncertainty of the sensitivity calculation. In the more crowded inner region, the variation is of the order of $5\text{--}15\%$. This represents a mild increase in the flux threshold for a new transient source to be discovered, though only when coinciding with strong Galactic emitters.

We show the median sensitivity for various combinations of energy ranges and observation intervals in Fig. 2. Here we consider an area of 4 deg^2 next to the Galactic centre, where the steady emission is relatively strong. The observed variation in sensitivity is mild, of the order of $1\text{--}10\%$.

As a test, the presence of possible source variability is assessed in Section 4.1.1. Other topics such as the study of Galactic Centre sources and interstellar emission through observations of the Galactic Centre region and GPS and the prospects for the CTAO and its scientific results are covered in other KSPs (see [Cherenkov Telescope Array Consortium et al. 2019](#); [CTA Consortium 2023](#))

We conclude that the performance of CTAO in the Galactic plane is consistent with the corresponding nominal extragalactic sensitivity. (That is, the sensitivity in the absence of significant emission from other gamma-ray sources.)

3 DETECTABILITY OF TRANSIENTS OF UNKNOWN ORIGIN

Apart from the transient sources of clearly identifiable type, others of unknown nature could also be serendipitously observed e.g. during a scan of the GPS. The detailed study of serendipity and corresponding observational strategies for CTAO will be addressed in a dedicated separate publication. However, to assess capabilities of CTAO for the detection of Galactic transient sources of unknown origin, a population of generic sources can be used. A full study of such populations requires considering various models of sources, population sizes and observational setups, and therefore will be presented separately. Here, we illustrate the methodology with a specific, simplified example. We simulate the populations of 100 generic transients. We consider the relatively short observation time of 1 hour (compatible with the strategy defined in [CTA Consortium 2023](#)) during which it would be possible to detect the source and make a decision about further observations.

We simulated the variability of each source using the following lightcurve model:

$$F(t) = \frac{2F_0}{\exp\left(\frac{t_0-t}{T_r}\right) + \exp\left(\frac{t-t_0}{T_d}\right)}$$

where T_r and T_d stand for time rise and time decrease and t_0 is the time at which $F = F_0$; we normalize the lightcurve to $F = 1$ at its maximum. Such a lightcurve describes the flux of a transient during its growth, at peak and when it falls, allowing the simulation of observations at each of these stages. We assume T_r , T_d and t_0 to be in ranges $1 - 86400$ s, $86400 - 604800$ s and $T_d - T_r$ respectively.

We used the model of [Yusifov & Küçük \(2004\)](#) for the radial distribution of sources. For simplicity, we did not take into account the visibility constraints, assuming that all sources are visible to either array at the time of observation.

For each population, the parameters defining the spectrum and the

Table 1. Simulated populations. We consider sources with different spectral shapes and parameters.

Population	Spectrum	Prefactor ($\text{ph cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$)	Spectral index
1	power-law	$10^{-14} - 10^{-09}$	[-3.50, -1.50]
2	power-law	$10^{-18} - 10^{-13}$	[-3.50, -1.50]
3	log-parabola	$10^{-14} - 10^{-09}$	[-3.50, -1.50]
4	power-law (Alpha)	$10^{-14} - 10^{-09}$	[-3.50, -1.50]

Table 2. Energies (TeV) assumed in the simulations depending on the array location, configuration and zenith angle. Different energy ranges were assumed depending on the geomagnetic field (average, North, South) for CTAO-N Alpha Configuration, as produced in the dedicated IRFs (Observatory & Consortium 2021).

Site	20°	40°	60°
CTAO-N	0.03-200	0.04-200	0.11-200
CTAO-S	0.03-200	0.04-200	0.11-200
			0.06-200 (A)
CTAO-N (Alpha)	0.03-200	0.04-200	0.12-200 (N)
			0.08-200 (S)
CTAO-S (Alpha)	0.04-200	0.06-200	0.18-200

lightcurve of each source are assigned randomly for each of them, assuming a log-uniform distribution for the prefactor and a uniform one for other parameters. The pivot energy for all sources is 1 TeV.

Four simulated populations are summarized in Table 1. They include different spectral shapes and parameters. For the log-parabola model we assume the range of curvature $[-0.25, 0.25]$. Note that populations 1 and 4 are two different populations sharing only the spatial distribution of the sources. For each population we employed the 0.5 h IRFs for both CTAO-N and CTAO-S, and also tested the Alpha configuration in the case of population 4. Both IRF sets contain three zenith angle observation options at 20°, 40° and 60°; and they also account for the azimuth dependence coming from the geomagnetic field pointing direction: North, South or an average over the azimuth direction.

For each source, we simulate the photon events list for 1 hour both for the CTAO-N and CTAO-S sites with a 5.0° ROI centered at a source, without any other sources within it, accounting only for the IRF background as seen in Fig. 1 and Fig. 2. The energy ranges used for both configurations at each site are collected in Table 2. The energy dispersion effect has been also taken into account (according to the IRFs). We then performed an unbinned maximum likelihood fitting. The test statistic (TS) equal or higher than 25 is used as criterion for a source detection. The TS for different values of prefactor and spectral index are shown in Figs. 4 and 5 respectively.

The results for all populations and observation configurations are presented in Fig. 3-6. Since the simulated lightcurves have different timescales and to have an idea at which lightcurve stage the observation takes place and how it affects the detectability of a source, we present in Fig. 6 the test statistic versus the value of lightcurve averaged over the observation time for each source in the simulated populations. We found that in the case of having a power-law spectra and fluxes in the range of $10^{-14} - 10^{-09} \text{ ph cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$, 73 – 83% of sources for 20° and 40° zenith angles and 65 – 74% of sources for 60° zenith angle will be detected, while for the population with fluxes $< 10^{-13} \text{ ph cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$, CTAO will not detect

any source during 1 hour of observation. In most cases CTAO-S performs marginally better than CTAO-N, with the larger difference for the North magnetic field configuration. Adding a curvature to the spectrum does not affect the detection rate in a statistically significant way. Using the Alpha Configuration (which corresponds to a first construction phase) slightly decreases the detectability, which is expected due to the reduced number of telescopes and the lack of LSTs in the CTAO-S Alpha configuration (Maier et al. 2023).

In the case of ROIs not centered in a source, we present in Fig. 7 the dependence of the detection probability on the source distance (in degrees) from the ROI center, with a clear decrease in detectability for the offsets $> 3^\circ$.

Finally, to roughly estimate how source visibility affects the presented observation probabilities, we compute, as an example, the number of detected sources for 1-h long observations starting at 2:00 UTC on three different nights taking into account the visibility constraints at each observatory site. For sources with zenith angle ranges of $[0^\circ, 33^\circ]$, $[33^\circ, 54^\circ]$ and $[54^\circ, 66^\circ]$, we employed the IRFs corresponding to zenith angles of 20°, 40° and 60° respectively (observations were not considered for zenith angles exceeding than 66°). Each source was evaluated using the IRF appropriate for its azimuth. The results are presented in Table 3. We see that while the detection probabilities without these constraints are high, there is a significant reduction in detection probabilities when visibility constraints are taken into account.

4 SOURCE DETECTION WITH CTAO

Galactic transients that exhibit MeV-GeV emission are specially interesting to be studied with CTAO, since it is already known that non-thermal mechanisms leading to gamma-ray production are at work. We aim at understanding whether these sources of interest can also emit VHE radiation, which can be produced by the same HE mechanisms and be detected as a spectral extension, or be created by an additional component at TeV energies.

4.1 High-mass microquasars

The microquasars of the Cygnus region, Cyg X-3, Cyg X-1 and the system SS 433 are the only microquasars that have been detected in the HE regime, hence they can be considered as potential targets for the CTAO observatory. After the discovery of persistent gamma-ray emission from SS 433 above 20 TeV by HAWC (Abeysekara et al. 2018a), the latest LHAASO detection (LHAASO Collaboration 2024) and specially the first detection by an IACT (H. E. S. S. Collaboration et al. 2024), the CTAO observations of these microquasars will be crucial to shed light on the physical mechanism responsible for the VHE emission in this type of binary systems, by investigating the limits of extreme particle acceleration in the jet.

The importance of observing this subclass of binary systems with CTAO has been previously discussed in Paredes et al. (2013). In particular, a detailed study on a possible detection of a TeV flare from Cyg X-1 was presented in that paper, showing conclusions similar to our findings (see Sect. 4.1.3.1). In this section, we show simulations on the first microquasar detected in the VHE regime, SS 433, and estimate the detectability both of transient and persistent emission from Cyg X-3 and Cyg X-1. Even if the detection of persistent emission is not the scope of this paper, we perform this additional exercise to complement the expectations to detect microquasars with CTAO. For the case of the microquasars in the Cygnus region, we carried out several CTAO observation simulations by using the latest prod5-v0.1

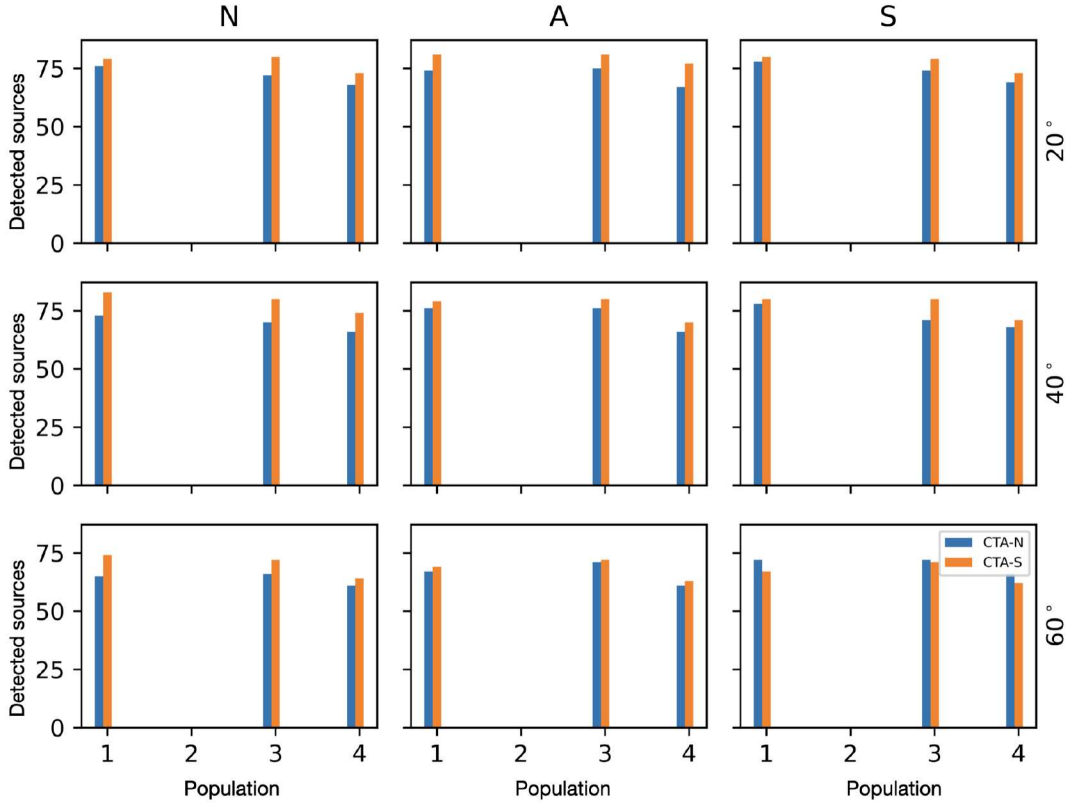


Figure 3. Number of detected sources in populations 1 to 4 for CTAO-N (blue) and CTAO-S (orange), including the Alpha configuration in population 4. From left to right: different configurations of the geomagnetic field (North, average and South). From top to bottom: different zenith angles (20° , 40° and 60°).

Table 3. Number of detected sources in populations 1, 3 and 4 including the visibility constraints for observations taking place from 2:00 to 3:00 UTC.

Population	IRF zenith angle	2025-05-22						2025-08-22						2025-11-22					
		CTAO-N			CTAO-S			CTAO-N			CTAO-S			CTAO-N			CTAO-S		
		N	A	S	N	A	S	N	A	S	N	A	S	N	A	S	N	A	S
1	20°	0	3	1	0	0	0	0	3	0	11	24	2	0	0	0	0	0	0
	40°	0	17	10	0	14	13	0	13	0	15	4	7	0	1	0	0	0	0
	60°	0	4	11	0	13	1	0	6	0	3	1	2	0	1	0	0	0	0
3	20°	0	4	1	0	0	0	1	0	0	9	25	1	0	0	0	0	0	0
	40°	0	15	8	0	14	16	0	11	0	11	4	11	1	1	0	0	0	0
	60°	0	2	12	0	14	0	1	7	0	3	1	4	0	1	0	0	1	0
4	20°	0	2	1	0	1	0	1	2	0	13	23	2	0	0	0	0	0	0
	40°	0	17	12	0	12	12	0	9	0	13	2	6	0	0	0	0	0	0
	60°	0	2	12	0	12	0	0	5	0	1	2	2	0	0	1	0	1	0

IRFs to check if these two systems could already be detected in the first years of operation of CTAO. Almost all the simulations have been carried out in the lowest range of energies for the CTAO observatory, where the bulk of the emission from these binary systems is expected. For each set of observations, besides the emission from the microquasars, we simulated the main field sources of the Cygnus region: 2HWC J2006+341 (Araya & HAWC Collaboration 2019), VER J2016+371, VER J2019+368 (Aliu et al. 2014b), Gamma Cygni SNR (Ackermann et al. 2017; Abeysekara et al. 2018b), TeV J2032+4130 (emission model as detected by MAGIC before the periastron passage of November 2017, Abeysekara et al. 2018c). This approach

also applies to the case of the LMXB V404 Cyg located in the same region (see subsection 4.2.1).

4.1.1 SS 433

SS 433 is a binary system containing a supergiant star that is overflowing its Roche lobe with matter accreting onto a compact object, either a BH or a NS (see e.g. Margon 1984; Fabrika 2004). Two jets of ionised matter, with a bulk velocity of approximately one quarter of the speed of light in vacuum, extend from the binary, perpendicular to the line of sight, and terminate inside the supernova remnant W50 (e.g. Fabrika 2004). The lobes of W50 in which the

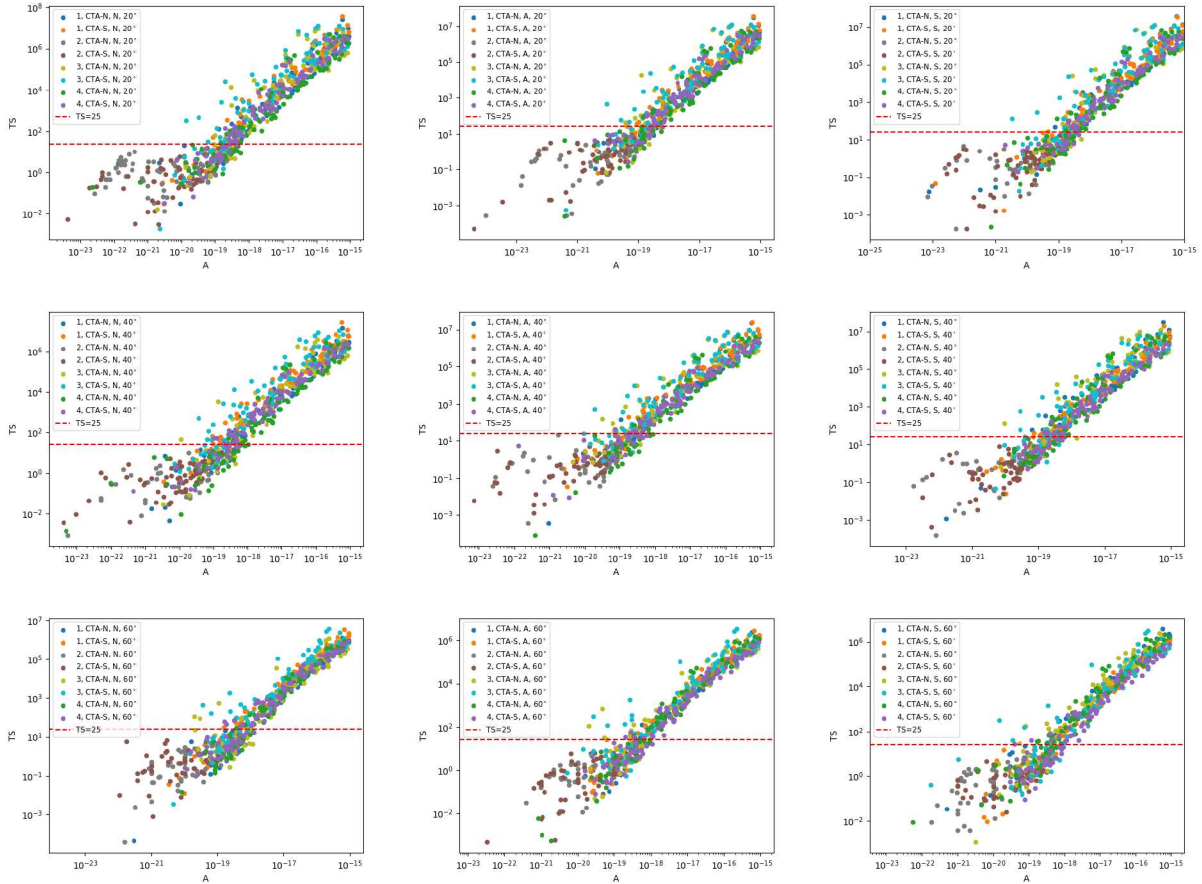


Figure 4. Test statistic for different values of prefactor in the simulated populations. From left to right: different configurations of the geomagnetic field (North, average and South). From top to bottom: different zenith angles (20°, 40° and 60°). The red dashed line marks $TS = 25$.

jets terminate about 40 parsecs from the central source, are accelerating charged particles, as it follows from radio and X-ray observations, consistent with electron synchrotron emission (Geldzahler et al. 1980; Brinkmann et al. 2007).

At TeV energies SS 433 was detected by both the High Altitude Water Cherenkov (HAWC) Observatory (1017 days of measurements, Abeysekara et al. (2018a)) and H.E.S.S. (200 hours of observations, H. E. S. S. Collaboration et al. (2024)). These observations demonstrate presence of two regions of gamma-ray emission of leptonic nature at the positions of the eastern and western jets. The reported H.E.S.S. fluxes at 1 TeV ($(2.30 \pm 0.58) \times 10^{-13} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ and $(2.83 \pm 0.70) \times 10^{-13} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ for the eastern and western jets correspondingly) are inline with HAWC data. Quality of the H.E.S.S. data also allow to study the energy dependence of the source morphology, demonstrating that while the gamma-ray emission above 10 TeV appears only at the base of the jets, the lower-energy gamma rays have their peak surface brightness at locations further along each jet, reflecting an energy-dependent particle energy loss timescale.

Analysis of the *Fermi*-LAT data led to the discovery of the significant HE gamma-ray emission from the region around SS 433 (see Bordas et al. 2015; Sun et al. 2019; Rasul et al. 2019; Xing et al. 2019; Li et al. 2020). However, the analysis is model dependent and can lead to very different conclusions on the position and extension of the source. In Rasul et al. (2019), authors report evidence at 3σ level for the modulation of the γ -ray emission with the precession period of the jet of 162 days. This result suggests that at least some

of the gamma-ray emission originates close to the base of the jet. Li et al. (2020) detected HE emission in the vicinity of SS 433 which shows periodic variation compatible with the precessional period of the jets.

While we do not expect to detect variability in the VHE emission coming from the lobes, microquasars are known to have flaring emission on various timescales coming from its central source. To test the possibility of CTAO to detect a central source and its putative variability we simulate the local region of SS 433 with the diffuse background and the nearby MGRO 1906+06 source, where SS 433 consists of both the aforementioned lobes and a central point source.

Following the H.E.S.S. observations, we have modelled the eastern and western lobes as a combination of three hotspots with Gaussian profiles (with the parameters summarised in Table S4 of H. E. S. S. Collaboration et al. (2024)). Spectral models of the lobes were organised so that different hotspots appear in different energy bands. To represent the spectral model of each hotspot in agreement with H. E. S. S. Collaboration et al. (2024), we assumed that they follow a powerlaw distribution with a super-exponential cut-off at both high and low energies, to allow hotspots to arise at different energies:

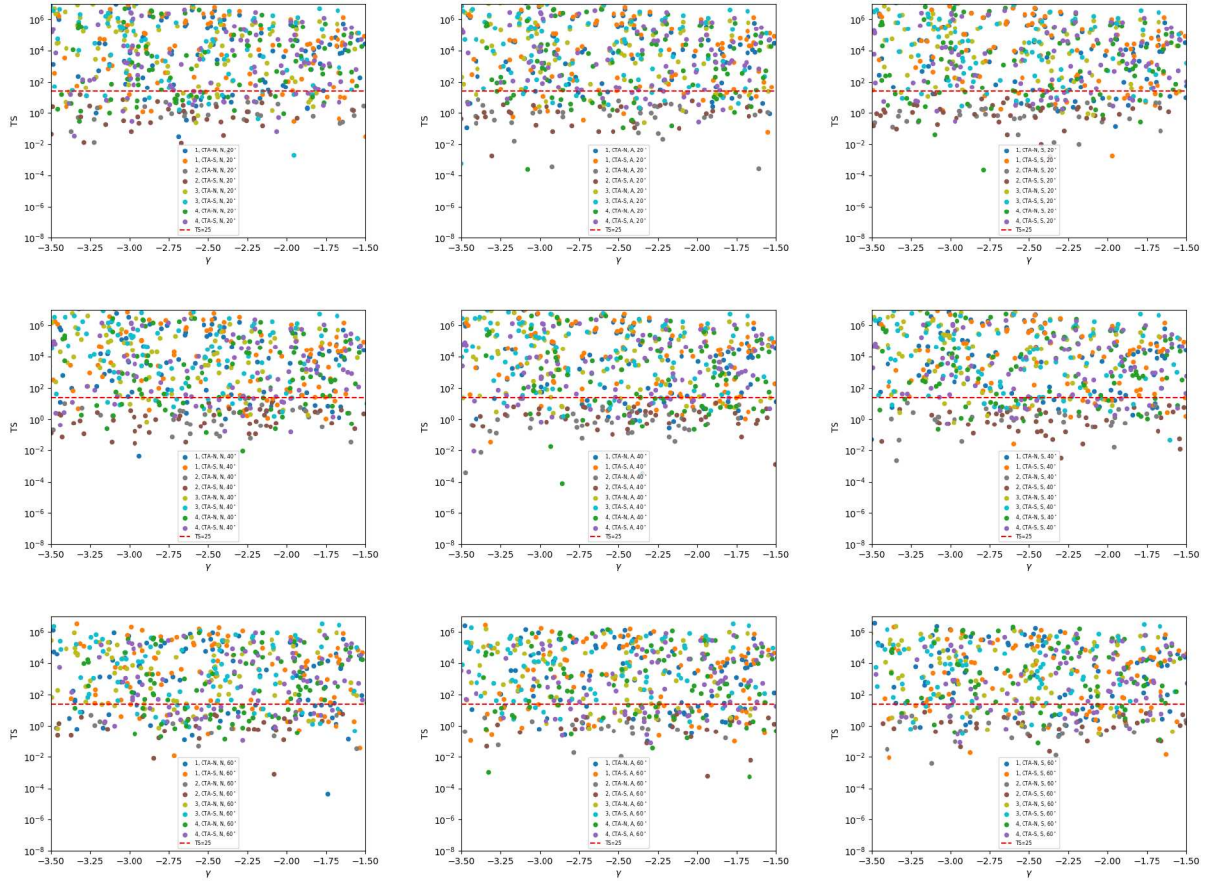


Figure 5. Test statistic for different values of spectral index in the simulated populations. From left to right: different configurations of the geomagnetic field (North, average and South). From top to bottom: different zenith angles (20°, 40° and 60°).

Source	ϕ_0 [TeV ⁻¹ cm ⁻² s ⁻¹]	Γ_1	Γ_2	Γ_3	E_{B1} [TeV]	E_{B2} [TeV]	β_1	β_2
Central Source	2.00×10^{-14}	2.00						
East 1	2.40×10^{-13}		2.18	10.0		2.00		1.00
East 2	1.00×10^{-14}	-2.10	1.00	2.80	2.50	7.00	0.10	0.01
East 3	1.00×10^{-16}	-2.10	1.04	4.00	10.0	100	0.50	0.01
West 1	3.00×10^{-13}		2.40	10.0		2.00		1.00
West 2	1.20×10^{-14}	-2.12	1.15	2.80	2.50	7.00	0.10	0.10
West 3	1.00×10^{-16}	-2.10	1.15	4.00	10.0	100	0.50	0.01

Table 4. Spectral model parameters

$$F(E) = \phi_0 \left(\frac{E}{1 \text{ TeV}} \right)^{-\Gamma_1} \left(1 + \left(\frac{E}{E_{B2}} \right)^{\left(\frac{\Gamma_3 - \Gamma_2}{\beta_2} \right)^{-\beta_2}} \right) \times \left(\frac{E}{1 \text{ TeV}} \right)^{-\Gamma_2} \left(\frac{E}{E_{B1}} \right)^{\left(\frac{\Gamma_2 - \Gamma_1}{\beta_1} \right)^{-\beta_1}}$$

The parameters chosen to represent the H.E.S.S. spectrum are given in Table 4. No low-energy cut-off was assumed for the e1 and w1 sources. The spectral model of the central source was obtained

directly from the H.E.S.S. ULs, and was modelled using a simple power law model with a flux falling below the H.E.S.S. UL value. As it is seen in Figure 8, 20 hours of CTAO observations is enough to clearly measure the energy dependent source structure as well as to detect the central source at the assumed flux level. The dependence of the central source relative flux errors on the exposure time is shown in Figure 9.

To study the CTAO possibility to detect possible variability of about 15% with the precession and orbital periods at the level proposed by [Rasul et al. \(2019\)](#) we have simulated a 500 hours obser-

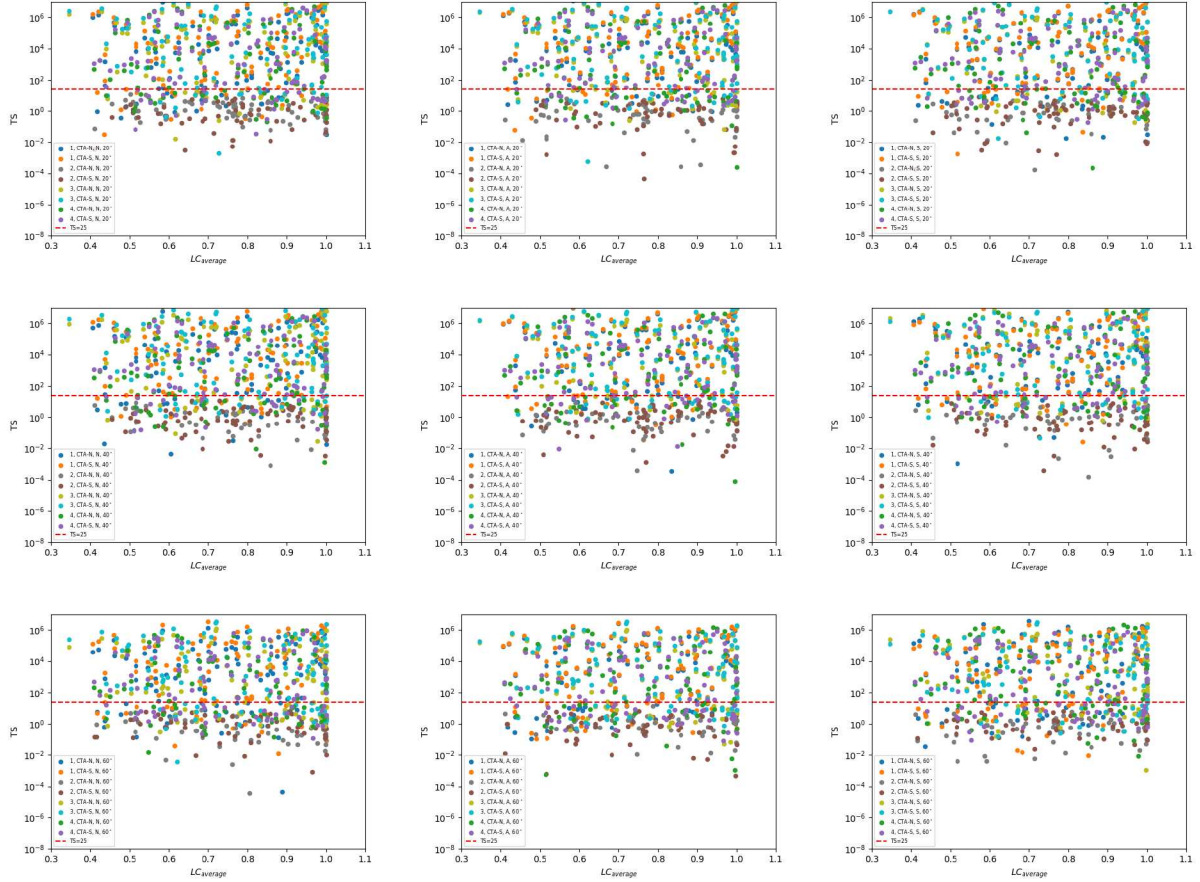


Figure 6. Test statistic for different values of the lightcurve averaged over the observation time in the simulated populations. From left to right: different configurations of the geomagnetic field (North, average and South). From top to bottom: different zenith angles (20° , 40° and 60°). The red dashed line marks $TS = 25$.

variation of the source uniformly distributed along the precessional period, assuming $F(\varphi) = (0.99 + 0.14 \sin(2\pi(\varphi + 0.84))) \times F$ and 500 hours observation of the source uniformly distributed along the orbital period, assuming $F(\varphi) = (1.07 + 0.18 \sin(2\pi(\varphi + 0.81))) \times F$. The expected variability is shown in Figure 10.

To systematically study the CTAO sensitivity to detect different level of variability for various levels of the source flux we run batches of 5000 simulations for low exposure times of 30 mins and 60 mins, and batches of 1000 simulations for higher exposure times of 300, 600 and 6000 mins using the North and South site IRFs. The flux was calculated after every simulation and the total data was compiled into histograms for each exposure time to determine the error range of the detections. As SS 433 could be viewed from both the north and south hemispheres the results of error measurements from both sites were compared to determine which can produce more sensitive detections. Figure 11 shows the comparison of this flux error ratio depending on the integrated source flux above 1 TeV and exposure for both Northern (left) and Southern arrays. In this figure one can see also simulations for the values exceeding the H.E.S.S. upper limit on the central source ($\sim 10^{-13} \text{ ph cm}^{-2} \text{ s}^{-1}$). This was done to test the effectiveness of CTAO on dim transient sources to determine what level of variability can be observed with short exposures.

Based on the simulations run at different fluxes, sources with a photon flux $< 1 \times 10^{-13} \text{ ph cm}^{-2} \text{ s}^{-1}$ will require exposure times of more than 10 hours in order to detect flux variability at about 50%

level. However, for sources with a flux $\geq 1 \times 10^{-13} \text{ ph cm}^{-2} \text{ s}^{-1}$, CTAO may be able to detect variability as low as $\sim 10\%$ observing from 5 to 10 hours. At a photon flux $\geq 3 \times 10^{-12} \text{ ph cm}^{-2} \text{ s}^{-1}$ the 1 sigma ratio gets as low as $\sim 5\%$ with exposure times of an hour long, meaning that even low variability may be detectable from relatively bright sources with short observations.

To be sure that our results are applicable to the sources located in crowded regions we compared our results assuming that the source with the flux of $\sim 10^{-13} \text{ ph cm}^{-2} \text{ s}^{-1}$ was located either in the uncrowded region, like SS 433, or in the region with multiple nearby TeV sources, like LS 5039. It was found that the observed flux of the central source and its error agreed in these two cases within few percents and thus our results are valid for sources located in both crowded and uncrowded regions.

4.1.2 Cyg X-3

Cyg X-3 is a HMXB located at a distance of $\sim 9 \text{ kpc}$ (Reid & Miller-Jones 2023). The companion star is a Wolf-Rayet (WR) with a strong wind mainly composed of helium. The nature of the compact object is still unknown, although a black hole scenario is favored (Zdziarski et al. 2013; Antokhin et al. 2022). The orbital period is very short, $\sim 4.8 \text{ hours}$, indicating that the compact object is very close to the WR star, totally enshrouded in its stellar wind (orbital distance $\sim 3 \times 10^{11} \text{ cm}$). Recent observations with the Imaging X-ray Polarimetry

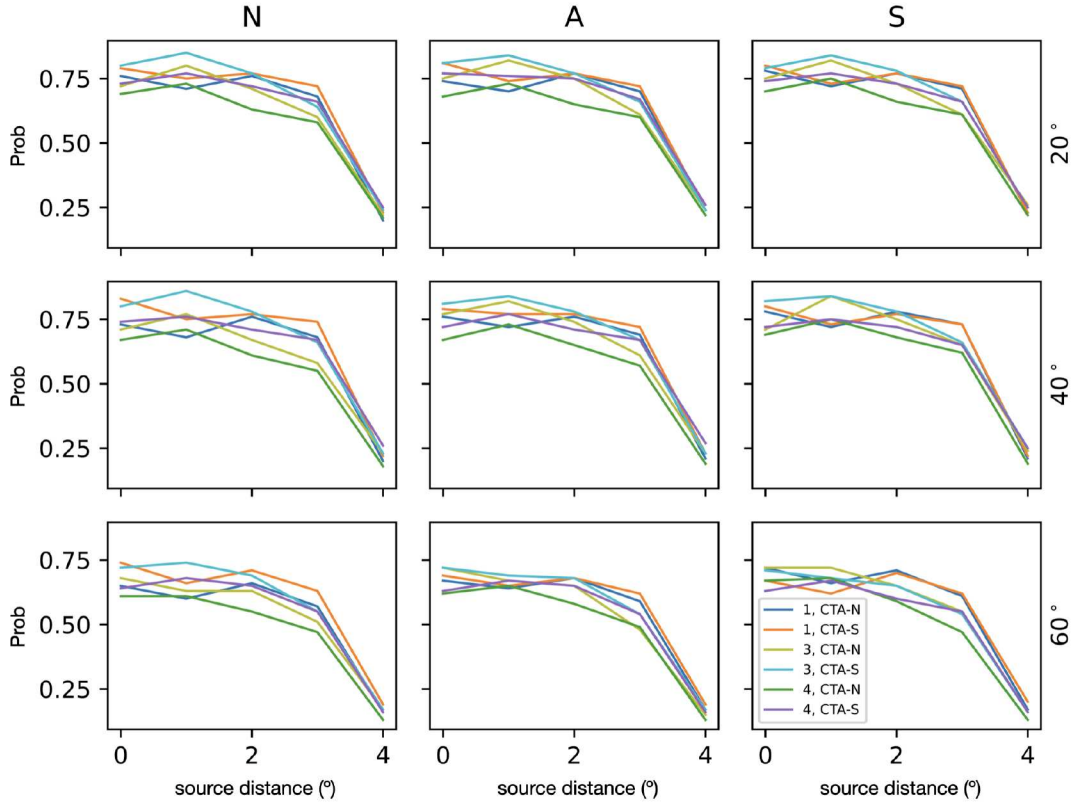


Figure 7. Dependence of the CTAO detection probability (vertical axis) on the source distance (horizontal, in degrees) from the ROI center. From left to right: different configurations of the geomagnetic field (North, average and South). From top to bottom: different zenith angles (20°, 40° and 60°).

Explorer (IXPE) show a high X-ray polarization degree from the system, during different spectral states, indicating the presence of collimated optically-thick outflows, which hide the central engine (Veledina et al. 2024a,b). The binary system is known to produce giant radio flares (flux > 10 Jy), produced by synchrotron processes from a relativistic jet oriented very close to the line of sight. Transient gamma-ray activity above 100 MeV was reported for the first time in 2009 by AGILE (Tavani et al. 2009) and *Fermi*-LAT (Fermi LAT Collaboration et al. 2009), and reported in several studies over the years, since its discovery (see Prokhorov & Moraghan 2023 for a recent study on the transient activities observed by *Fermi*-LAT). The flaring activity (typical duration: 1-2 days) was observed in coincidence with a repetitive pattern of multi-frequency emission (Piano et al. 2012): the gamma-ray flares have been detected (i) during soft X-ray spectral states (around minima of the hard X-ray light curve), (ii) in the proximity of spectral transitions, and (iii) a few days before giant radio flares. In particular, transient gamma-ray emission was found when the system is moving into or out of the quenched state, a spectral state – characterized by a very low (or undetectable) flux at radio and hard X-ray frequencies – that is known to occur a few days before major radio flares.

The quenching activity of Cyg X-3 turns out to be a key condition for the observed activity above 100 MeV. According to theoretical models, a simple leptonic scenario – based on inverse Compton (IC) scattering between electrons/positrons accelerated in the jet and seed photons from the WR companion – can account for the flaring gamma-ray fluxes and the 4.8 h modulation detected by *Fermi*-LAT during the transient activity (Dubus et al. 2010; Prokhorov & Moraghan 2023). A simple phenomenological picture, based on dominant leptonic processes in the jet, can account for the non-thermal

emission pattern: around the quenching, the jet would consist of plasmoids, ejected with high Lorentz factor. This transient jet would be responsible for the HE flare (for IC processes), produced in the proximity of the binary system ($10^{10} - 10^{12}$ cm), and it would subsequently produce the major radio flares (synchrotron processes), by moving out from the central engine (distances > 10^{14} cm). MAGIC repeatedly observed Cyg X-3, both during hard and soft spectral states, but never detected any significant VHE activity from the microquasar (Aleksić et al. 2010).

4.1.2.1 Cyg X-3: transient emission We carried out simulations by assuming two different theoretical models based on IC processes in the jet (Piano et al. 2012; Zdziarski et al. 2018), in order to test the possibility of a CTAO detection of transient VHE gamma rays from Cyg X-3.

We performed a binned analysis in the energy range 100 GeV – 1 TeV with *ctools*, by simulating observations with the Alpha Configuration of the Northern array of the CTAO observatory (IRF: North_z20), taking into account the energy dispersion. A multi-source input model with the main background TeV sources (see Section 4.1) and the CTAO instrumental background (CTA01rfBackground) has been considered.

In the first case, we adopted a simple power-law spectrum (see Eq. 1) inferred from the leptonic Model A from Piano et al. (2012), where prefactor $P_f = 1.34 \times 10^{-21}$ ph cm $^{-2}$ s $^{-1}$ MeV $^{-1}$, index $\gamma = 4.5$ and pivot energy $E_0 = 1$ TeV. The leptonic model is based on IC scatterings between accelerated electrons in the jet and soft seed photons from the accretion disk (X-rays) and from the companion star (UV). We simulated 5 hour and 50 hour observations, and we investigated the resulting simulated data, by performing a binned

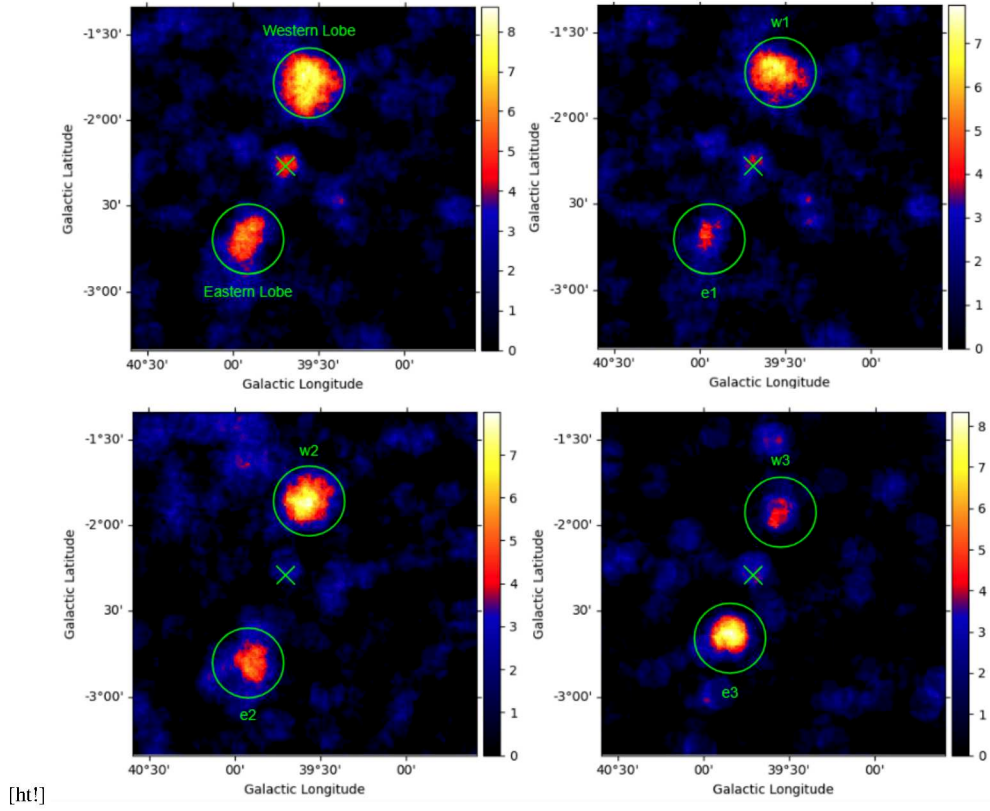


Figure 8. SS433 Simulations, taken with twenty total hours of exposure time spread across two precessional periods. Top right: 0.8-2.5 TeV. bottom left: 2.5-10 TeV. Bottom right: >10 TeV. Top left: total model from 0.8 TeV to 100 TeV. The position of the central source is marked with a cross.

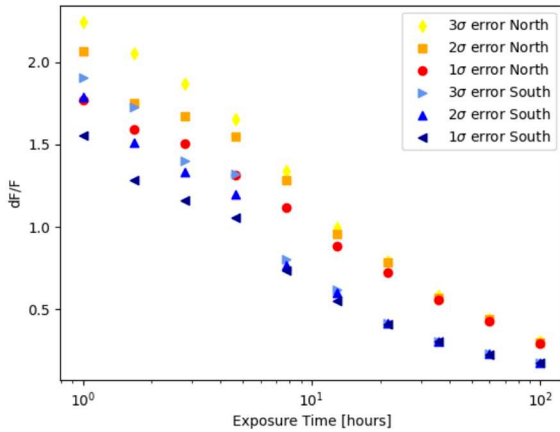


Figure 9. Comparison of the relative flux errors for the SS 433 central source at different exposure times for the Northern and Southern arrays.

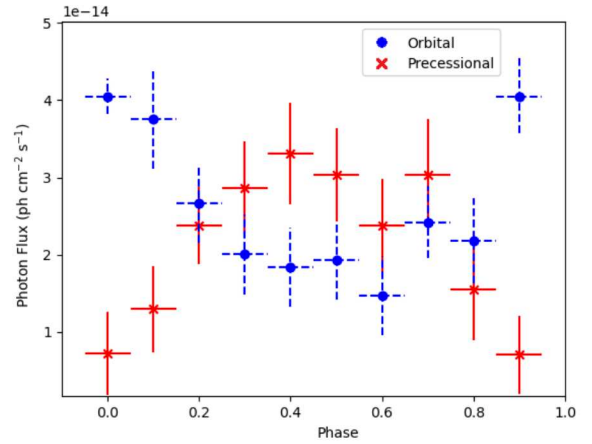


Figure 10. 500 hours observations of SS433 as observed with the Southern array folded with the precessional and orbital periods.

analysis. The resulting spectra are shown in Fig. 12, together with the X-ray “hypersoft” spectrum (Koljonen et al. 2010), the AGILE flaring spectrum (Piano et al. 2012) and the MAGIC flux ULs observed during the soft states (Aleksić et al. 2010). All the spectra (not simultaneous observations) are referred to the same spectral state of Cyg X-3 when the transient gamma-ray activity is detected at MeV-GeV energies (quenched state). We show the reference theoretical model and the input simulated power-law, together with the CTAO

simulated spectra. By assuming this input spectrum we found no detection with CTAO-N with 5-h observation and a weak hint of signal ($\sim 3\sigma$) for 50 hours of observation time.

In the second case, we assumed a different theoretical model, developed by Zdziarski et al. (2018) in order to fit the flaring spectrum from Cyg X-3 as detected by *Fermi*-LAT (cumulative spectrum of 49 1-day flares detected between August 2008 and August 2017). The theoretical model presented in their paper is similar to the one

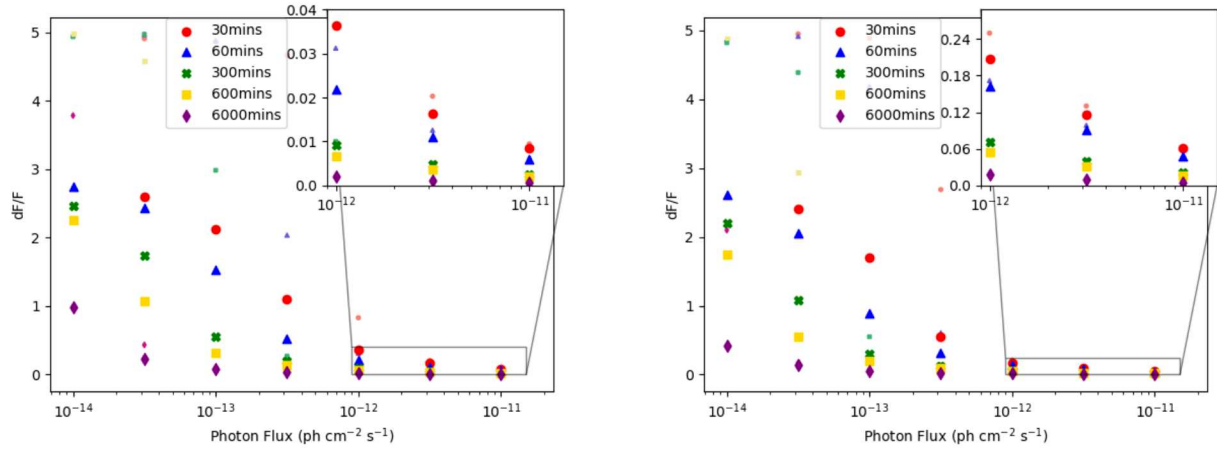


Figure 11. Dependence of the 1 and 3 σ relative flux error ratio on the photon flux for the Northern (left) and Southern (right) arrays. Different exposure times are given by different colours as indicated in the legend. 3 σ relative flux errors are shown with smaller and fainter symbols.

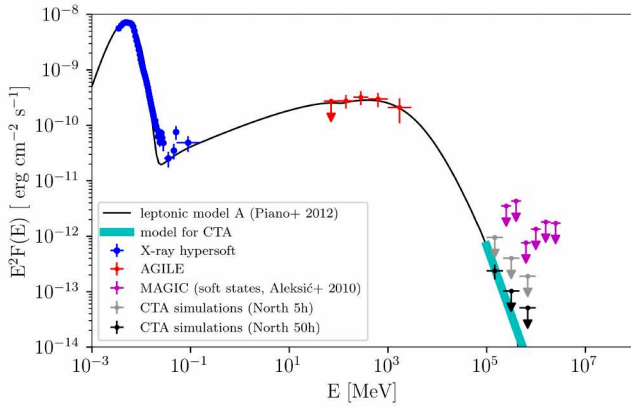


Figure 12. Multi-frequency spectral energy distribution of Cyg X-3. Black solid curve: leptonic model A (Piano et al. 2012). Cyan solid curve: CTAO input model for the simulation. Blue points: “hypersoft” X-ray spectrum (Koljonen et al. 2010), RXTE-PCA and RXTE-HEXTE data (~ 3 to ~ 150 keV). Red points: HE gamma-ray cumulative flaring spectrum (Piano et al. 2012), AGILE (50 MeV – 3 GeV). Magenta points: VHE gamma-ray flux ULs (95% C.L.) from Aleksic et al. (2010), MAGIC (199 GeV – 3.16 TeV). Gray points: CTAO simulations (North 5h). Black points: CTAO flux ULs for a simulated observation of 5h.

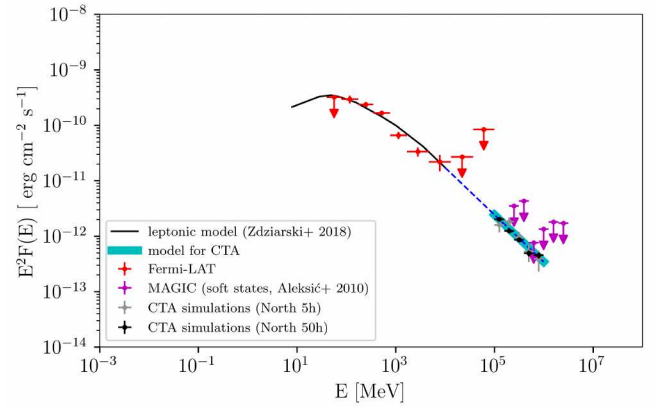


Figure 13. Gamma-ray spectral energy distribution of Cyg X-3. Black solid curve: leptonic model (Zdziarski et al. 2018). Power-law extension of the model up to TeV energies. Cyan solid curve: CTAO input model for the simulation. Red points: HE gamma-ray cumulative flaring spectrum (Zdziarski et al. 2018), Fermi-LAT (50 MeV – 100 GeV). Magenta points: VHE gamma-ray flux ULs (95% C.L.) from Aleksic et al. (2010), MAGIC (199 GeV – 3.16 TeV). Gray points: CTAO simulations (North 5h). Black points: CTAO spectrum for a simulated observation of 5h.

presented in Piano et al. (2012), but in Zdziarski et al. (2018), the electrons in the jet scatter blackbody soft photons from the companion star only. The orbital and geometrical parameters are similar. Also in this case, the model is focused on the HE emission from the microquasar ($E \leq 100$ GeV). Thus, we assumed a simple power-law extension of the model up to TeV energies (assuming: prefactor $P_f = 2.15 \times 10^{-19}$ ph cm $^{-2}$ s $^{-1}$ MeV $^{-1}$, index $\gamma = 2.85$ and pivot energy $E_0 = 1$ TeV). Similarly, we simulated 5 h and 50 h observations. The results of these simulations are shown in Fig. 13. In this case, by assuming a harder and brighter input spectrum, we found clear detections with CTAO-N: $\sim 10\sigma$ with 5-h observation, $\sim 30\sigma$ with 50 h observation.

Thus, by assuming two simple power-law input spectra adapted from theoretical leptonic models – both created ad hoc in order to account for the flaring activity observed by AGILE and *Fermi*-LAT

– a possible detection with CTAO North is plausible even with a few hours observations. It is important to note that these extrapolation do not take into account $\gamma\gamma$ absorption for pair production in the companion star’s photon field, which could be not negligible between 100 GeV and 1 TeV (Zdziarski et al. 2012). Nevertheless, we cannot rule out to detect the 4.8 h orbital modulation, in the case of a prolonged TeV flare. A CTAO detection of transient VHE gamma-ray activity would represent an unprecedented result for this elusive system, never observed at TeV energies. Nevertheless, a CTAO non-detection would give new strong constraints on theoretical models about microquasars. The lack of a transient VHE signal from Cyg X-3, correlated with non-thermal flaring activity, could indicate that: (i) the TeV signal, eventually produced in the jet, is absorbed for pair production by the companion star’s UV photons; (ii) the acceleration efficiency in the jet is intrinsically low, the maximum energies of the jet particles are not sufficient to generate TeV photons.

4.1.3 Cyg X-1

Cyg X-1 is a HMXB, composed of a black hole ($M_X = 21.2 \pm 2.2 M_\odot$) and a O9.7Iab supergiant companion star ($M_{\text{opt}} = 40.6^{+7.7}_{-7.1} M_\odot$, Miller-Jones et al. 2021). The system is located at a distance of $2.22^{+0.82}_{-0.17}$ kpc (Miller-Jones et al. 2021), and the orbital period is 5.6 days. The X-ray spectra can be accurately modeled by hybrid Comptonization models (Coppi 1999). The soft state of Cyg X-1 is characterized by a strong disk blackbody component peaking at $kT \sim 1$ keV and a power-law tail extending up to ~ 10 MeV, related to Comptonization processes in the corona. In the hard state, the accretion disk is truncated and the emission from the corona is dominant. In this state, the coronal plasma is composed by a hot quasi-thermal population of electrons ($kT \sim 100$ keV) with a sharp cutoff at ~ 200 keV. At sub-MeV energies, the microquasar exhibits a non-thermal power-law tail with a strong linear polarization (Laurent et al. 2011; Jourdain et al. 2012). This emission could be ascribed either to synchrotron processes in the jet, by assuming a very efficient particle acceleration and strong jet magnetic fields (Zdziarski et al. 2014), or to the corona itself (Romero et al. 2014). Recent studies investigate the physical origin of this power-law tail at sub-MeV energies, detected during both soft and hard spectral states (Cangemi et al. 2021). Above 100 MeV, deep observations with *Fermi*-LAT found evidences of persistent emission from Cyg X-1 only during hard X-ray spectral states (Zanin et al. 2016; Zdziarski et al. 2017). Transient HE emission was observed by AGILE (Bulgarelli et al. 2010; Sabatini et al. 2010, 2013) on 1-2 day timescales, in coincidence with both hard and soft X-ray spectral states. At TeV energies, a hint of detection ($\sim 4\sigma$) was observed by MAGIC on September 24, 2006 (Albert et al. 2007), during a hard X-ray flare of Cyg X-1. A $\sim 4\sigma$ persistent TeV signal was recently reported by LHAASO (LHAASO Collaboration 2024).

For Cyg X-1, we investigated the possibility that CTAO will detect both transient and persistent emission from the microquasar.

4.1.3.1 Cyg X-1: transient emission. In this case, we carried out a simulated short-term observation of Cyg X-1, during a possible VHE gamma-ray flare. We simulated a 30-minute observation with the same setup reported in Section 4.1.2: a multi-source simulation with photon energies between 100 GeV and 1 TeV. We assumed, as input spectrum for the simulation, the same power-law observed by MAGIC in September 24, 2006 (Albert et al. 2007); prefactor $P_f = 2.3 \times 10^{-18}$ ph cm $^{-2}$ s $^{-1}$ MeV $^{-1}$, index $\gamma = 3.2$, pivot energy $E_0 = 1$ TeV). We obtained an overall detection of the source at a significance level of $\sim 38\sigma$. The resulting spectrum is shown in Fig. 14, together with the observed flaring spectrum observed by MAGIC. Our results confirm that CTAO will be able to detect a flare similar to the one reported by MAGIC in 2006 in a few minute observation, with unprecedented spectral accuracy. A fainter TeV flare - weaker than the one reported by MAGIC - would require a longer CTAO observation (a few hours) to be significantly detected. This possibility will be properly assessed in a potential ToO observation, on the basis of the triggering flare flux in other wavelengths.

4.1.3.2 CygX-1: persistent emission. Cyg X-1 exhibits persistent HE emission during the hard state, as observed by *Fermi*-LAT (Zanin et al. 2016; Zdziarski et al. 2017). Thus, we investigated the possibility of a CTAO detection of VHE persistent emission above 100 GeV. Again, we assumed the same setup as reported in Section 4.1.2. We analyzed three different scenarios. In the first one, we assumed as input spectral model for CTAO, a simple extension of the power-law spectral shape reported in the *Fermi*-LAT 4FGL Catalog, without

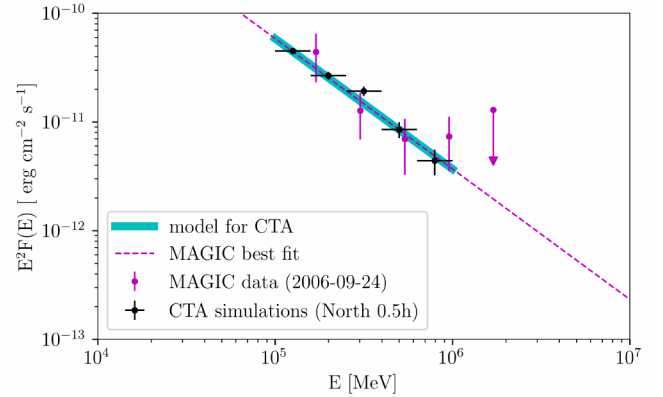


Figure 14. VHE gamma-ray spectral energy distribution of Cyg X-1, related to the 2006-September flaring activity. Magenta points: VHE gamma-ray spectrum from Albert et al. (2007), MAGIC (150 GeV – 1.9 TeV), accounting for 78.9 minutes of observation. Magenta dashed line: MAGIC best fit. Cyan solid curve: CTAO input model for the simulation. Black points: CTAO spectrum for a simulated observation of 30 minutes.

any cut off around 100 GeV (Abdollahi et al. 2020). In the second scenario, we assumed a spectral shape based on a purely leptonic theoretical model, in which gamma-ray emission is produced due to IC scatterings in the persistent jet during the hard state (Zdziarski et al. 2017). According to this model, a sharp cut off – due to the Klein-Nishina effects – is predicted at ~ 100 GeV. In the third scenario, we assumed a spectral shape based on the lepto-hadronic theoretical model presented in Kantzas et al. (2021). In that paper, the authors modeled the GeV persistent spectrum as detected by *Fermi*-LAT during the hard state, by assuming that both electrons and protons are accelerated in the jet. A comprehensive model, based on a superposition of leptonic (IC scatterings) and hadronic processes (gamma rays from the decay of neutral mesons, produced in $p\gamma$ interactions) can properly fit the multi-wavelength spectrum up to the high-energy emission from Cyg X-1.

For the first hypothesis (4FGL-like spectrum), we assumed a simple power-law (assuming: prefactor $P_f = 3.2 \times 10^{-14}$ ph cm $^{-2}$ s $^{-1}$ MeV $^{-1}$, index $\gamma = 2.15$ and pivot energy $E_0 = 4.15$ GeV). A multi-source simulation with photon energies between 100 GeV and 1 TeV has been carried out. With this spectrum, we obtained a detection with a significance of $\sim 17\sigma$ for a 50h simulated observation. The resulting simulated spectrum is shown in Fig. 15, together with the *Fermi*-LAT 4FGL spectrum (Abdollahi et al. 2020), and the MAGIC flux ULs during the hard state (Ahnen et al. 2017b).

For the second hypothesis (spectrum inferred from Zdziarski et al. 2017), we assumed a simple power-law (with prefactor $P_f = 9.5 \times 10^{-21}$ ph cm $^{-2}$ s $^{-1}$ MeV $^{-1}$, index $\gamma = 3.2$ and pivot energy $E_0 = 1$ TeV). A multi-source simulation with photon energies between 100 GeV and 1 TeV has been carried out. In this case, we did not detect any significant emission with CTAO with a simulated observation of 50 h (significance $\sim 2\sigma$). The resulting differential spectral ULs are shown in Fig. 16, together with the theoretical model from Zdziarski et al. (2017), the HE gamma-ray spectra as detected by *Fermi*-LAT (Zanin et al. 2016; Zdziarski et al. 2017), and the MAGIC ULs related to the hard state (Ahnen et al. 2017b).

For the third hypothesis (spectrum inferred from Kantzas et al. 2021), we used as input the theoretical model itself, by simulating photon energies between 100 GeV and 100 TeV. We carried out the usual multi-source binned analysis, and we found a clear detection

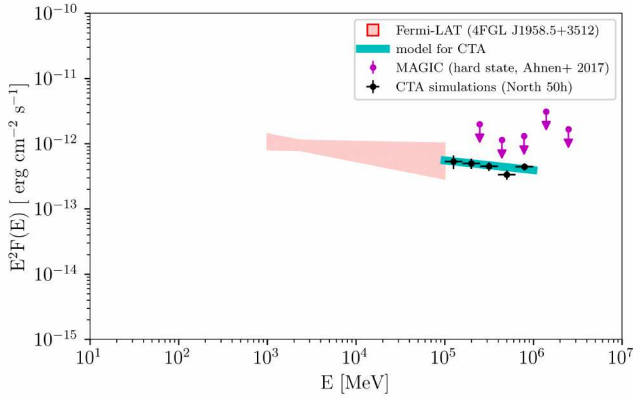


Figure 15. Gamma-ray SED of Cyg X-1, for a possible steady emission up to VHE. Red shaded region: The *Fermi*-LAT 4FGL Catalog HE steady spectrum, (Abdollahi et al. 2020), *Fermi*-LAT (1–100 GeV). Cyan solid curve: CTAO input model for the simulation. Magenta points: MAGIC (160 GeV – 3.5 TeV) VHE ULs (95% C.L.) from Ahnen et al. (2017b). Black points: CTAO spectrum for a simulated observation of 50 h.

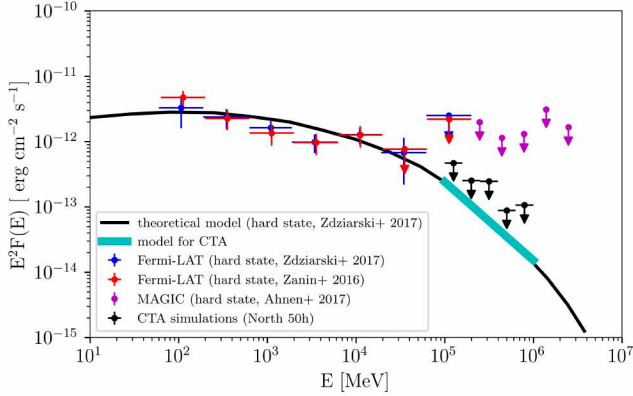


Figure 16. Gamma-ray SED of Cyg X-1, for a possible steady emission up to VHE. Black solid curve: theoretical model from Zdziarski et al. (2017), based on IC processes in the jet during the hard state. Blue points: HE steady spectrum during the hard state (Zdziarski et al. 2017), *Fermi*-LAT (60 MeV – 200 GeV). Red points: HE steady spectrum during the hard state (Zanin et al. 2016), *Fermi*-LAT (60 MeV – 200 GeV). Magenta points: MAGIC (160 GeV – 3.5 TeV) VHE flux ULs (95% C.L.) from Ahnen et al. (2017b). Cyan solid curve: input model used for the simulation. Black points: simulated spectrum for a CTAO observation of 50 h.

with a significance of $\sim 36\sigma$ for a 50h simulated observation. The resulting simulated spectrum is shown in Fig. 17, together with the theoretical model from Kantzas et al. (2021), the HE gamma-ray spectra as detected by *Fermi*-LAT (Zanin et al. 2016; Zdziarski et al. 2017), the MAGIC flux ULs during the hard state (Ahnen et al. 2017b) and the HAWC flux ULs between 0.1 and 100.0 TeV (Albert et al. 2021). In particular, we note that above 10 TeV the HAWC ULs for a prolonged stacked observation (1523 days) are below our theoretical model. This spectral behavior could weaken the chance of a CTAO sharp detection at the highest energies.

Thus, according to our simulations, CTAO will be able to detect a possible persistent VHE gamma-ray emission from the jet of Cyg X-1, if the spectrum is not characterized by a sharp cut off around 100 GeV. According to purely leptonic models, a sharp cut off is

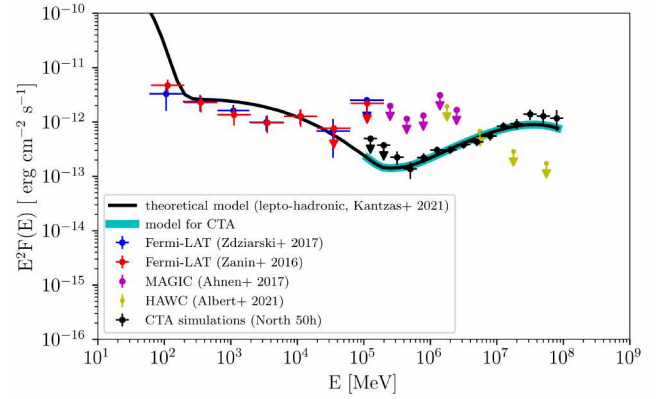


Figure 17. Gamma-ray SED of Cyg X-1, for a possible steady emission up to VHE. Blue, red and magenta points as reported in Fig. 16. Yellow ULs: HAWC observations (Albert et al. 2021). Black solid curve: theoretical model from Kantzas et al. (2021), based on lepto-hadronic processes in the jet during the hard state. Cyan solid curve: input model used for the simulation. Black points: simulated spectrum for a CTAO observation of 50 h.

expected below 1 TeV. On the contrary, hadronic processes could be responsible for a bright emission above 1 TeV, which could be detected by the CTAO Observatory.

4.2 Low-mass X-ray binaries

LMXBs harbor a low-mass companion star and a black hole (or an accreting neutron star), object tightly connected to jet launching that are responsible for the non-thermal multi-wavelength emission (see review in Chaty 2022). Up to now, no LMXB has been detected at HE (apart from tMSPs) and only strong hints of emission at HE have been reported in V404 Cyg. No LMXB has neither been detected at VHE by any IACT. (see e.g. Aleksić et al. 2011; Ahnen et al. 2017a; H. E. S. S. Collaboration et al. 2018). The most recent X-ray outburst of a black hole LMXB (BH-LMXB) which was followed up by the IACTs MAGIC, H.E.S.S. and VERITAS was that of MAXI J1820+070, without detecting any VHE emission (Abe et al. 2022). We examine here if CTAO will be able to detect such a similar exceptionally bright outburst but for a hypothetical source located within a maximal distance of 4 kpc from Earth. Based on the theoretical lepto-hadronic model of Kantzas et al. (2022), used since the modeled LMXB can be considered a canonical source, we perform a number of simulations where we rescale the predicted VHE emission for a number of different jet inclination angles between 5 and 65°. We perform each simulation for a number of different hypothetical sources at different distances within 2 and 4 kpc.

In Fig. 18, we show the predicted VHE flux for a BH-LMXB with inclination angle of 30° assuming that the emission persists in three different energy bins between 0.1 and 10 TeV, for at least 2 weeks, and compare it to the CTAO sensitivity curves (see Fig. 1).

We overall see that CTAO will be able to detect an outburst similar to MAXI J1820+070 in the sub-TeV regime within a few tens of minutes if the LMXB is located closer than ~ 4 kpc at energies < 1.6 TeV. The inclination angle of the LMXB we assume here is relatively small compared to the average value between 40 and 70° (see, e.g., Tetarenko et al. 2016), but LMXBs with an inclination angle greater than $\sim 30^\circ$ fail to be detected within the first hour of observations (Fig. 19). Sources with an inclination angle less than $\sim 20^\circ$ could be observed within a few minutes, such as the case

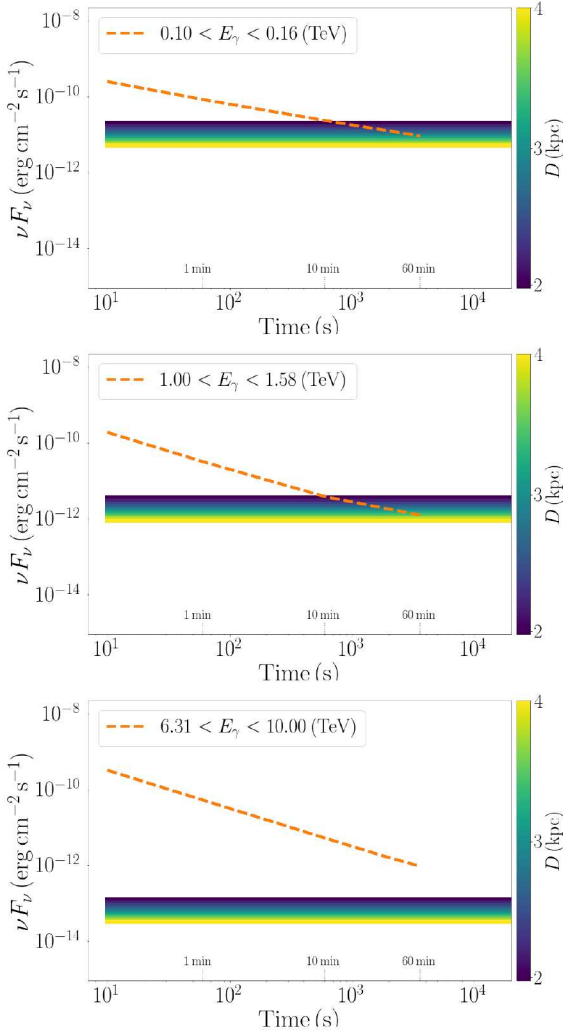


Figure 18. Predicted VHE emission of a hypothetical BH-LMXB for three different energy bins, as shown in the legends. The BH-LMXB follows the recent outburst of MAXI J1820+070, but with an inclination angle of 30° instead, and its distance given by the colormap (lighter colors correspond to more distant sources). We assume an emission lasting at least two weeks. The CTAO sensitivity for each energy bin is represented as a dashed orange line.

of MAXI J1836–194 or V4641 Sgr, both microblazar candidates (Russell et al. 2014; Gallo et al. 2014).

4.2.1 The case of V404 Cyg.

The system V404 Cyg is a LMXB located at a distance of 2.39 ± 0.14 kpc, inferred through parallax measurements (Miller-Jones et al. 2009). The system is composed of a $9^{+0.2}_{-0.6} M_\odot$ black hole and a $0.7^{+0.3}_{-0.2} M_\odot$ K3 III companion star with an orbital period of 6.4714 ± 0.0001 days (Casares et al. 1992). LMXBs are known to undergo long periods of quiescence (years) and rapid outburst states (weeks). After a ~ 26 year-long quiescent phase, V404 Cyg entered in a bright active phase in the second half of June 2015. The outburst, lasting ~ 2 weeks, was observed in all the bands of the electromagnetic spectrum, from radio to GeV energies. AGILE-GRID and *Fermi*-LAT observed a strong hint of emission in gamma rays ($\approx 4\sigma$), coincident with the

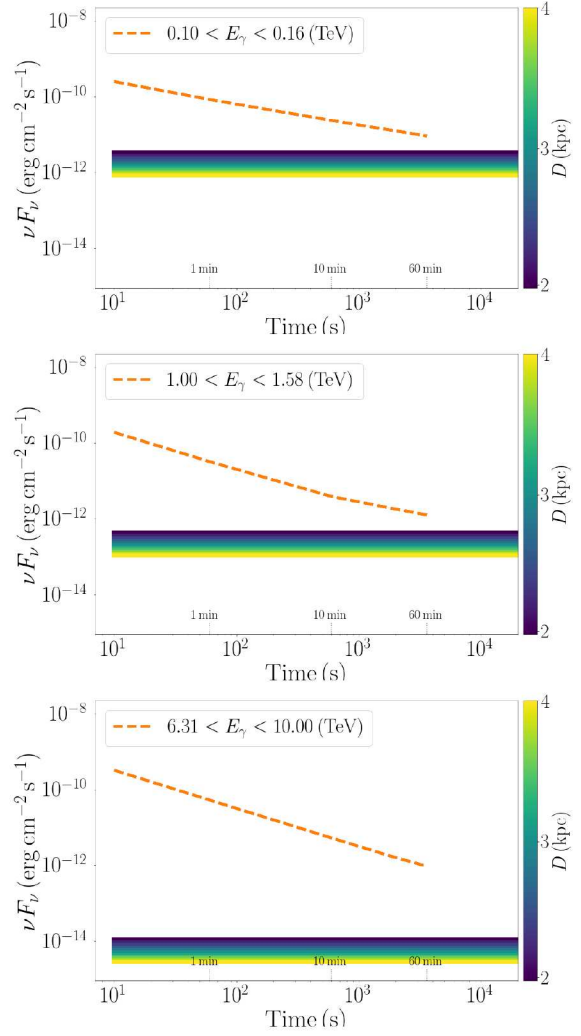


Figure 19. Same as Fig. 18 but for an inclination angle of 40° .

brightest peak of luminosity observed in radio, hard X-ray and soft gamma-ray bands (Loh et al. 2016; Piano et al. 2017). The gamma-ray event was observed between June 24 and 26 and it is simultaneous with rapid transitions between the optically thin and the optically thick phases of the radio emission in the jet, and coincident with a bright peak of the 511 keV emission line detected by INTEGRAL (Siegert et al. 2016). As for other microquasars, the HE emission could be related to either leptonic (IC scattering on soft photons) or hadronic processes (decay of π^0 mesons produced in proton-proton collisions) in the jet. Nevertheless, in this case the companion is an old spectral type, cold and small star, and it does not provide a sufficiently high density of seed photons and hadronic material in the stellar wind. Thus, the HE emission is possibly related to interactions between the particles accelerated in the jet and the radiation (and the magnetic field) of the jet itself. MAGIC repetitively pointed at V404 Cyg between June 18 and 27, for more than 10 hours, but the observations did not show any significant emission at TeV energies (Ahnen et al. 2017a).

V404 Cyg: transient emission We carried out a 50-h CTAO simulated observation for V404 Cyg with the same setup described in

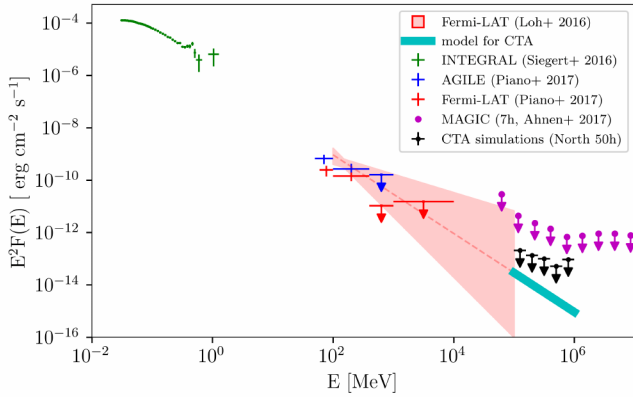


Figure 20. Multi-frequency SED of V404 Cyg, related to the 2015-June flaring activity. Green points: hard X-ray spectrum (Siebert et al. 2016), INTEGRAL data (30 keV – 2 MeV). Blue points: HE flaring spectrum (Piano et al. 2017), AGILE (50 MeV – 1 GeV). Red points: HE flaring spectrum (Piano et al. 2017), *Fermi*-LAT (60 MeV – 10 GeV). Red shaded region: HE flaring spectrum, (Loh et al. 2016), *Fermi*-LAT (100 MeV – 100 GeV). Magenta points: MAGIC (50 GeV – 10 TeV) VHE flux ULs (95% C.L.) from Ahnen et al. (2017a). Cyan solid curve: input model used for the simulation. Black points: simulated spectrum for a CTAO observation of 50 h.

Section 4.1.2: 100 GeV – 1 TeV simulated photons with a multi-source approach. The CTAO input spectral model for V404 Cyg is a simple extension of the power-law spectrum observed by *Fermi*-LAT during the 2015-June flaring activity and reported by Loh et al. (2016) (assuming: prefactor = 8×10^{-22} ph cm $^{-2}$ s $^{-1}$ MeV $^{-1}$, index $\gamma = 3.5$ and pivot energy $E_0 = 1$ TeV). The resulting spectrum from our simulation is shown in Fig. 20, together with the non-thermal HE spectra observed during the 2015-June flare. Thus, even if we assume the same spectral trend as observed by the HE gamma-ray detectors, we expect no detection with CTAO in a 50-h observation. This is in agreement with the simulations on LMXBs described in Subsection 4.2.

4.3 Transitional millisecond pulsars

Out of the three confirmed tMSPs, only PSR J1023+0038 is currently in the LMXB state, whereas XSS J1227–4853 and IGR J18245–2452 are currently in the RMSP state. As previously mentioned, other candidates were found through X-ray peculiar variability and association with *Fermi*-LAT sources (see review by Papitto & de Martino 2022). Particularly interesting are the two confirmed tMSPs PSR J1023+0038 and XSS J1227–485 that when in LMXB state they were found by *Fermi*-LAT with a luminosity of about 10^{34} erg s $^{-1}$ in the energy range 0.1–10 GeV, which is up to ten times brighter than the levels observed during the RMSP state (Papitto & Torres 2015; Torres et al. 2017). This fact makes them particularly interesting for a possible detection with CTAO. In this Section, we estimate the chances of detecting these two tMSPs with CTAO given also their relatively close distance of about 1.5 kpc.

4.3.1 PSR J1023+0038

This tMSP was initially detected as a variable source in the radio band (Bond et al. 2002) and showing clear characteristics of an accretion disc around the compact object in the optical band. Later, Thorstensen & Armstrong (2005) suggested PSR J1023+0038 as an

NS-LMXB. The observations did not reveal an accretion disc but the existence of a strong irradiation on the optical star from an unseen companion. The compact object was identified as a 1.69 millisecond radio pulsar in a 4.75 hr orbit around a 0.2 $M_{\odot}$ companion star (Archibald et al. 2009b). In June 2013 the source came back to a LMXB state, where it has remained until now, and the radio pulsar signal switched off. During the LMXB state, PSR J1023+0038 shows a peculiar behaviour in X-rays: it exhibits frequent modes switching between three different X-ray levels, dubbed high, low and flaring (Bogdanov et al. 2015). The HE gamma-ray emission detected by *Fermi*-LAT has been reported to brighten by a factor of 5 after the transition. The average *Fermi*-LAT spectrum is described by a power-law with index 1.8 and a cutoff at an energy of 2.3 GeV according to Takata et al. (2014) and by a power-law with index 2 and an energy cutoff at 3.7 GeV, the significance of the cutoff is 4.3σ level according to Torres et al. (2017). Neither pulsations nor steady emission were found in the VHE regime (Aliu et al. 2016). To test the capability of CTAO to detect emission from this source we first studied the HE gamma-ray emission from *Fermi*-LAT during the LMXB state (2013–2021), in order to obtain the spectral parameters of the source. For the *Fermi*-LAT analysis, all photons in the energy range 0.1–300 GeV included in a circular region of 10 degrees centered on the source were considered. The binned likelihood analysis was performed using 20 energy bins. The two spectral models that have been considered for the CTAO simulations are a logparabola and a broken power-law. We considered only these two models, because the simulation with the power law with an exponential cut-off model did not return any detectable spectral bin in the VHE range (the cut-off is at very low energies, a few GeV). On the other hand a simple power-law extending in the energy range from GeV up to 1 TeV appears physically difficult to achieve. This is compatible by the low significance of the results by Takata et al. (2014) and Torres et al. (2017).

The spectral input parameters inferred from the analysis of the *Fermi*-LAT data in the accretion phase are for the broken power-law: prefactor $P_f = (0.06 \pm 0.01) \times 10^{-10}$ photons cm $^{-2}$ s $^{-1}$ MeV $^{-1}$, $\alpha_1 = -2.12 \pm 0.03$, $\alpha_2 = -2.91 \pm 0.06$, Energy break = (1.15 ± 0.09) GeV; while for the logparabola: prefactor $P_f = (0.34 \pm 0.007) \times 10^{-10}$ photons cm $^{-2}$ s $^{-1}$ MeV $^{-1}$, $\alpha = 2.23 \pm 0.02$, $\beta = 0.16 \pm 0.02$, Energy break = 0.524 GeV.

Batches of 100 simulations were run using both CTAO-N and CTAO-S IRFs for 50, 100 and 200 hours of observations; we binned the simulated data into initial 20 logarithmic energy bins considering an energy range of 0.03–100 TeV. The resulting spectrum of PSR J1023+0038 is shown in Fig. 21 and, for simplicity, only the results with the highest statistic are reported (200 h observations). The full analysis results for the broken power-law model are reported in Table 5. The parameters obtained from the unbinned analysis are: $P_f = 7.31 \times 10^{-12}$ photons cm $^{-2}$ s $^{-1}$ MeV $^{-1}$, $\alpha_1 = -2.12$, $\alpha_2 = -2.91$, Energy break = 1.15 GeV. We find that long integration times are needed to detect this tMSP, with at least 100 h for CTAO-N and 50 h for CTAO-S. We tried to also fit the simulation obtained with a logparabola model but the fit did not converge, despite several attempts changing various parameters (prefactor, ROI, etc.). This is likely caused by the very low statistics of the simulated spectrum.

4.3.2 XSS J1227–48538

XSS J1227–48538 was initially detected as a hard X-ray source and was tentatively identified as a cataclysmic variable, similarly to PSR J1023+0038, based on the double-peaked emission lines (typical

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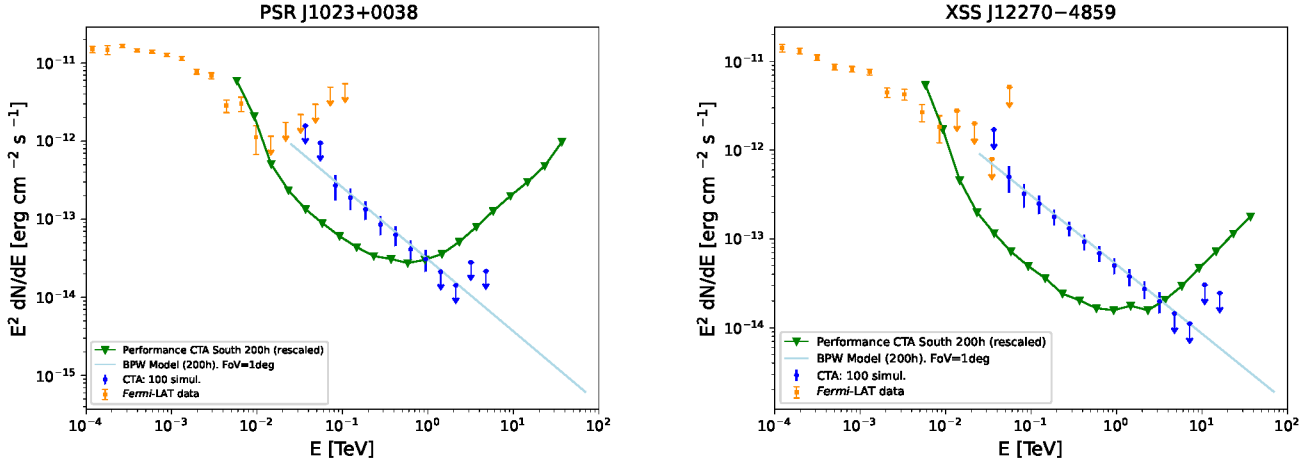


Figure 21. CTAO-S simulations for the tMSP PSR J1023+0038 (on the left) and XSS J1227-48538 (on the right) considering the broken power-law model. We consider 200 h of observations. The CTAO performance curve (green) is rescaled for 200 h. The *Fermi*-LAT spectrum during the accretion phase is reported in orange.

Table 5. Broken power-law model significance's results for North and South IRFs, considering 50, 100 and 200 h of observations of the tMSP PSR J1023+0038.

	Hours	TS	σ
North	50	18.50	4.30
	100	39.86	6.31
	200	77.15	8.78
South	50	29.36	5.42
	100	55.47	7.45
	200	114.77	10.71

of an accretion disc) in the optical spectrum (Masetti et al. 2006). While the low X-ray luminosity was not in contrast with a cataclysmic variable interpretation, the peculiar X-ray variability with mode switching and the unexpected association with a *Fermi*-LAT source prone to identify XSS J1227-48538 as an unusual LMXB (de Martino et al. 2010). The system transitioned to a radio pulsar state between November 14 and December 21, 2012, characterized by the disappearance of the emission lines in the optical spectrum and the softening observed in the radio, optical, X-ray and gamma-ray bands (Bassa et al. 2014; Torres et al. 2017). Just after the transition, observations with the Giant Metrewave Radio Telescope allowed to detect a radio pulsar with a 1.69 ms spin period in a binary system with an orbital period of 6.9 hr (Roy et al. 2015). Before the transition to the radio state, the gamma-ray emission was a factor of 2 larger (Torres et al. 2017). The *Fermi*-LAT analysis performed for the period in which the source was in the sub-luminous disk state (2008-2012) provides results consistent with those reported by Xing & Wang (2015) and Torres et al. (2017): XSS J1227-48538 is best described by a power-law with a cutoff at $E_{\text{cut}} = 5.3$ GeV (at 3.4σ) and a spectral index of $\gamma = 2$. The *Fermi*-LAT analysis procedure performed on this source is similar to that described before for the other tMSP.

Similarly to PSR J1023+0038, the two spectral models considered for the CTAO simulations are the logparabola and the broken power-law. As input models for the CTAO simulations we considered the

output from the *Fermi*-LAT study. For the broken power-law: $P_f = (2.71 \pm 0.71) \times 10^{-12}$ photons $\text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}$, $\text{Index1} = -2.23 \pm 0.04$, $\text{Index2} = -2.77 \pm 0.10$, Energy break = (1.32 ± 1.44) GeV. For the logparabola: $P_f = (3.26 \pm 0.91) \times 10^{-11}$ photons $\text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}$, $\alpha = 2.28 \pm 0.05$, $\beta = 0.09 \pm 0.02$, Energy break = (4.45 ± 5.42) GeV. We performed batches of 100 simulations using only the CTAO-S site IRFs and 50, 100 and 200 h of observations. The simulated data were binned into 20 logarithmic energy bins in an energy range of 0.03-100 TeV.

The resulting spectrum of XSS J1227-48538 is shown in Figure 21 and, for simplicity, we reported only the results with the highest statistics. The complete results of the analysis for the broken power law are reported in Table 6 and the parameters of the unbinned analysis are: $P_f = 3.15 \times 10^{-12}$ photons $\text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}$, $\alpha_1 = -2.23$, $\alpha_2 = -2.78$, Energy break = 1.33 GeV. The source could be detected with CTAO-S at 8.14σ with 50 h of observation.

As for PSR J1023+0038, we interpret the non convergence of the logparabola model as caused by the fact that the flux inferred from the fit falls marginally below the CTAO sensitivity curve for 200 hours.

Our simulations prove that the detection of the spectral component seen by *Fermi*-LAT from of close-by tMSPs when in a disc state could be possible with long exposures, provided that the emission has no cutoff at few GeVs. While this will likely not allow to catch fully a transition if lasting less than several days, here we demonstrate that once a transition has occurred CTAO could be able to detect such type of sources, identifying tMSPs as VHE emitters for the first time. While during the rotation-powered state MSP binaries will not be at the reach of CTAO, the known tMSPs have demonstrated an increase of their HE flux by a factor of 3-10 when transitioning from the radio to the disc states (see Torres et al. (2017)). The possibility to look-back in the CTAO Galactic Plane and other higher latitude pointings, where many MSP binaries are located, will be crucial for assessing any possibly related VHE flux increase or for complementing the X-rays and lower-energy coverage in case only upper limits are obtained. Also, if there are additional components (not considered here, such as magnetic reconnection of pulsar wind) it could be possible to detect changes in the VHE flux along transitions.

Table 6. Broken power-law model significance's results for South IRFs, considering 50, 100 and 200 h of observations of the tMSP XSS J1227-48538.

	Hours	TS	σ
South	50	66.26	8.14
	100	128.04	11.31
	200	253.99	15.94

4.4 Flares in PWNe: the Crab Nebula

The Crab Nebula is the best-studied PWN in the VHE regime. It is located at a distance of ≈ 2.2 kpc with ≈ 3.8 pc of size (Trimble 1973; Davidson & Fesen 1985). Since 2009, several rapid and bright flares have been detected from the nebula at HE with space-borne gamma-ray instruments (Tavani et al. 2011; Abdo et al. 2011; Buehler et al. 2012; Mayer et al. 2013; Striani et al. 2013; Arakawa et al. 2020). The observed flares presented variability timescales of hours. During these flaring periods, the nebula showed rapid variations of flux and large releases of energy (Tavani et al. 2011; Abdo et al. 2011). Several multi-wavelength campaigns involving *Chandra* X-Ray Observatory, Keck Observatory and Very Large Array (VLA) (Weisskopf et al. 2013) and TeV searches by IACTs (Mariotti 2010; Ong 2010; H. E. S. S. Collaboration et al. 2014; Aliu et al. 2014a; van Scherpenberg et al. 2019) were carried out to follow these flares. However, none of them reported a correlation of the flares with morphological and/or spectral variations in the nebula.

CTAO will cover a fundamental energy range to understand the origin of these flares: on the one hand, the low energy threshold will allow the sampling of the *Fermi*-LAT spectral shape at few tens of GeV of synchrotron nature, providing important clues on the acceleration and emission processes; on the other hand, the excellent sensitivity in the TeV regime will serve to explore the IC component that might arise at a detectable level from the electron population behind the MeV flares, off-scattering soft photon fields.

To evaluate the capability of CTAO to detect Crab flares, we performed simulations of the SEDs both in flaring and steady (non-flaring) states of the nebula. We simulated flares of different spectral characteristics starting from a parent particle population, varying the physical properties of the environment. In particular, we simulated three types of flares: a very bright flare with a similar flux (at hundreds of MeV) to the one observed by *Fermi*-LAT in April 2011 (Buehler et al. 2012; Striani et al. 2013), which is the flare with the largest flux to date, and two dimmer flares corresponding to the first one re-scaled by a factor of 0.5 and 0.1. Thus, the corresponding flux enhancement at the simulated flares' peaks (above 100 MeV of energy) ranges from 3 to 30 times the average flux of the nebula, as observed in tens of flares detected since 2007 (Huang et al. 2021). Since no spectral variability has been reported at HE, we assume the same spectral model for these dimmer flares.

The simulations of the nebula in flaring and steady states are performed for the CTAO-N with the methods and tools presented in previous works (Mestre et al. 2020, 2021). Mestre et al. (2021) pointed to the crucial role of the LSTs, best sensitive at the sub-TeV energy regime, in the prospects for the Crab flares' detection (even in the early stages of CTAO-N operations). The latter, however, cast doubts on CTAO-S prospects due to the lack of LSTs in the Alpha configuration. The electron population was simulated with a fixed index (Γ_e) of 2.5, to guarantee the detection in the TeV regime (e.g., from 1.25 TeV to 50 TeV) of the brightest model of flare in less than 10 h at 95% confidence level (see Fig. 6 of Mestre et al. 2021). The different flare models are computed for a magnetic field

Table 7. In the second, third, and fourth columns, the observation time (in hours) necessary to detect different models of flares from 1.25 TeV to 50 TeV with CTAO-N at 3σ (5σ) significance. The first column indicates the magnetic field chosen for the acceleration region. The observation times in the second column are computed for flare models fitted to the *Fermi*-LAT SED (at the moment of maximum flux level) of the April 2011 flare. For the third and fourth columns, the LAT SED (dubbed F_{2011}) was re-scaled prior to the fit by a factor of 0.5 and 0.1, respectively. The models with an asterisk imply an energy in electrons above 1 TeV larger than 5×10^{43} erg. We assume Crab is in flaring state during the entire observation time.

Model B [μ G]	Model SED		
	F_{2011}	$0.5 \times F_{2011}$	$0.1 \times F_{2011}$
1000	22 (46)	351* (> 500)	$> 500^*$
500	0.8 (1.6)	14* (31)	$> 500^*$
100	0.03 (0.05)	0.13 (0.24)	68* (133)

(B) in the acceleration region ranging from 100μ G to 1 mG and compared (see section 2 of Mestre et al. 2021) to the steady nebula SED in both tens of GeV (e.g., from 20 GeV to 200 GeV) and TeV regimes. We obtained the simulations of the Crab nebula SED in steady state from Mestre et al. 2020. To compare the flaring and steady nebula simulations, we computed the mean total expected excess (e.g., counts from the source after background subtraction), both in flaring and steady state, in 21 bins of energy from 12 GeV to 200 TeV with observation times ranging from a few minutes to 500 h. We compared the excess distributions using the Pearson's chi-squared test, corresponding the null hypothesis (H_0) to the steady state. Then, we consider the flare implies a detectable flux level if H_0 is rejected at 3σ significance (see Table 7; values in parentheses correspond to 5σ confidence).

The simulations performed show that the different models of flare are best detected in the GeV regime and in particular in less than an hour at energies below 200 GeV, see Fig. 22. In the TeV regime, flares dimmer than April 2011 flare by a factor 0.5 (at hundreds of MeV) would be detected in less than 10 h for $B < 500 \mu$ G (see Table 7). As a reference, the gamma-ray flares from the Crab detected with *Fermi*-LAT showed varied duration scales from a few days to weeks and complex substructures, with sub-flares of a few hours or day-long duration (Huang et al. 2021). Some of the models considered imply an energy in TeV electrons larger than $\tau_{\text{syn}} \times L_\gamma \approx 5 \times 10^{43}$ erg, being τ_{syn} the synchrotron cooling time, and $L_\gamma \sim 2 \times 10^{35}$ erg s $^{-1}$, the luminosity of the nebula in gamma rays (Rudak & Dyks 1998). However, note that the energy in electrons available in the nebula is not limited to the one computed above if particle re-acceleration takes place, which would introduce additional boosts in the electron population energy reservoir. The simulations performed, together with previous results reported (see Mestre et al. 2021), provide excellent prospects for detecting flares from the Crab Nebula with CTAO, especially for the LST subarray, featuring the best sensitivity at energies of a few tens of GeV.

4.5 Novae

The only nova that has been detected at TeV energies so far is the symbiotic system RS Oph (Acciari et al. 2022; H. E. S. S. Collaboration et al. 2022; Abe et al. 2025) which shows recurrent outburst every 15-20 years and harbours a white dwarf accreting from a late-type giant companion star. However, it could be argued that the detection is due to selection-effects based on the fact that RS Oph is relatively

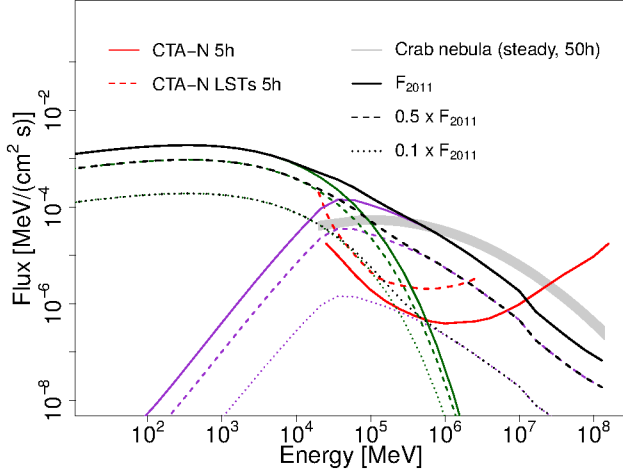


Figure 22. The synchrotron (green lines), IC (purple lines), and total (black lines) emission from the Crab Nebula for different flare models. The solid lines correspond to the model fitted to the *Fermi*-LAT April 2011 flare data at energies above 80 MeV for a particle index of 2.5. The dashed and dotted lines correspond to the same model re-scaled by a factor of 0.5 and 0.1, respectively. All the models are computed for a magnetic field of $500 \mu\text{G}$. The red solid and dashed lines correspond to the sensitivities of the CTAO-N and, if considering only its four LSTs for 5 h of integration time, respectively. The Crab Nebula steady spectrum simulations for 50 h of observation time with CTAO-N are noted with the grey shaded area (3σ region).

nearby (see below). By number, novae that involve a small, low-mass donor such as a main sequence star (these are usually the *classical novae*, see Chomiuk et al. 2021) are by far the most common type of system. The majority of novae have been observed in outburst only once in a human life timescale, and so far only a handful of novae are known to erupt with a recurrence time of $\sim$ tens of years. It has been predicted from binary population synthesis studies (Kemp et al. 2021, 2022) that most commonly, novae with evolved donors are more likely to contribute to the total current Galactic nova rate, even though by number these systems make up a smaller fraction of nova binaries.

As pointed out recently by De et al. (2021), a large number of novae in optical bands might be being missed due to a number of sources residing behind and in the Galactic bulge. Taking obscuration by dust into account, De et al. (2021) estimated a current Galactic nova rate of $43.7 \pm_{8.7}^{19.5}$ per year. This is notably much larger than the actual Galactic nova detection rate of $\lesssim 10$ per year.

Kemp et al. (2022) estimated the Galactic nova rate to be 33 per year. That study showed that the most common type of nova in our Galaxy today is expected to originate from a binary system involving a giant-like donor (see Fig. 11 in the aforementioned paper as a guide). As mentioned previously, currently the only system to have clearly been detected at VHE (and detected also at HE) is the symbiotic recurrent nova RS Oph. Though some groups have investigated detailed modelling of shock generation in nova systems (Hachisu & Kato 2022; Metzger et al. 2016), which is believed to be mainly hadronic in nature, it is still not clear how many Galactic novae would be detectable by CTAO at and beyond the $\sim$ TeV energy range. The majority of novae thus far detected at GeV energies with no clear evidence for a TeV component have been classical novae (not symbiotic systems like RS Oph, see e.g. Zheng et al. 2022). Nonetheless, we anticipate several more novae could be observed

with CTAO (see Chomiuk et al. 2021), particularly if these novae are detected at other wavelengths early on enabling rapid triggering and follow-up. However, assuming we can expect of the order of ~ 30 Galactic novae per year, even with adequate triggering, it is unlikely that all of these outbursts will be detectable by CTAO. If CTAO-N would have been operational since August 2008 to April 2023, it would have been able to perform observations of 7 novae detected in HE gamma-ray by *Fermi*-LAT, in the 5 nights after their detection in optical. Assuming a similar rate of novae detected at HE gamma-ray in the future, it means that CTAO-N would observe ~ 0.5 novae per year triggered by their HE gamma-ray emission.

CTAO observations will be important to put constraints on the maximum energies attainable in nova explosions and the physical mechanisms involved in the production of VHE gamma rays. We estimated the capability of CTAO to detect nova outbursts based on both theoretical modelling and empirical results. First, simple theoretical considerations based on the RS Oph detection are adopted to assess the gamma-ray emission at different outburst stages, following the approach in Acciari et al. (2022); H. E. S. S. Collaboration et al. (2022). Second, a parametric study based on phenomenological parameters involved in the emission of gamma rays in nova outbursts is performed to estimate the parameter space we could constrain with CTAO observations. Finally, we considered dedicated numerical simulations of RS Oph to assess the expected detectability with CTAO.

4.5.1 Modelling approach

We explored the capability of CTAO to constrain the physical parameters of nova phenomena of different types, building up from basic arguments. The expected gamma-ray emission is obtained for different properties of a shock expanding with velocity $v_{\text{sh}}(t)$, generated by ejected material of total mass $M_{\text{ej}}(t)$ slamming into the companion star's wind and producing gamma rays through hadronic interactions. To accelerate protons to high energies via diffusive shock acceleration (DSA), the magnetic field has to be amplified in the shock. The maximum energy particles attain at a shock is limited ultimately by the Hillas condition (Hillas 1984). However a more constraining limit is determined by either the time taken before radiative cooling dominates over acceleration, or by the necessary escape of the particles up-stream of the shock, in order to excite magnetic field fluctuations to a sufficient level ahead of the shock (Bell 2004). The maximum energy E_{max} in the particle spectrum, defined as a power-law function with an exponential cutoff, can be then described as:

$$E_{\text{max}} = 10 \left(\frac{v_{\text{sh}}}{5000 \text{ km/s}} \right) \left(\frac{R_{\text{sh}}}{1 \text{ AU}} \right)^{-1} \left(\frac{B_*}{1 \text{ G}} \right) \text{ TeV}, \quad (2)$$

with R_{sh} the position of the shock with respect to the white dwarf, and B_* the companion surface magnetic field (typically $\sim 1 \text{ G}$ for a red giant). R_{sh} can be expressed in terms of shock velocity, for which we assumed free expansion during the first few days, followed by radiative expansion when entering the Sedov-Taylor phase (Bode & Kahn 1985). The particle flux per unit of time and energy is computed using the condition that a fixed fraction (50%) of the kinetic energy of the protons ($E_{\text{kin}} = \frac{1}{2} M_{\text{ej}} v_{\text{sh}}^2$) is transferred to non-thermal particles (Acciari et al. 2022; H. E. S. S. Collaboration et al. 2022). Once the particle spectrum is defined as function of these three parameters (v_{sh} , B_* , M_{ej}) at different evolutionary stages of the shock expansion, we derive the gamma-ray emission originated by proton-proton interaction assuming a density of the ejecta which can be approximated following equation 4 in Acciari et al. (2022).

The particle spectrum and density was used to compute the non-thermal emission, using the Naïma spectral model class (Zabalza 2015) included in Gammapy.

In Fig. 23 we show the expected gamma-ray flux at different times from the nova explosion, considering several physical parameters in the shock. The upper panels show the expected emission for a explosion similar to RS Oph, with B_* , M_{ej} equal to 1 G and $10^{-6} M_{\odot}$, respectively, located at a distance of 2 kpc (left) and of 4 kpc (right). The effect of increasing the star surface magnetic field (10 G) and decreasing the ejecta mass ($10^{-7} M_{\odot}$) is shown in the bottom panels, for a fixed distance of 2 kpc. For reference, the isoflux line at $10^{-13} \text{ TeV cm}^{-2} \text{ s}^{-1}$ is marked when possible with a white line. The region below such line should be easily accessible to CTAO.

4.5.2 Parametric space study

We utilised a phenomenological approach to study the parameter space of gamma-ray emission from novae. The emission was assumed to be produced by hadronic processes from π^0 decay (Kafexhiu et al. 2014), as indicated by the gamma-ray emission of RS Oph (see Section 4.5.3). The π^0 decay radiative model was parameterised using the target proton density (n_h) and the relativistic proton energy distribution. For the latter, we considered a particle distribution function parameterised as a power-law model with an exponential cutoff. We described the parameter space under study as a 3D space, where we set the parameter space domain in the range of plausible values based on observed novae at gamma rays. A 2D grid was defined with different values for the prefactor (A) and the cutoff energy (E_{cp}) of the proton energy distribution. The former in the range between $A = [10^{28}, 10^{32}] \text{ protons eV}^{-1}$ at a pivot energy of 100 GeV and the latter between $E_{\text{cp}} = [10, 1000] \text{ GeV}$. Two slices for the target proton density were used for the third axis, $n_h = 10^8 \text{ cm}^{-3}$ and $n_h = 10^{11} \text{ cm}^{-3}$, which correspond to typical shock density values in novae (Metzger et al. 2016). The distance to the gamma-ray emitter was fixed to $d = 2 \text{ kpc}$. The spectral energy distribution for each model was obtained using the software package Naïma (Zabalza 2015).

The emission detectability was assessed for both arrays of CTAO using the official IRFs from `prod5-v0.1` in the Alpha configuration (20deg-AverageAz for 5 h observation time). The results of the simulations for CTAO-N and CTAO-S are shown in panels *a* and *b* of Fig. 24, respectively. The total proton energy above 100 GeV (W_p) multiplied by $\frac{n_h}{d^2}$, hereafter “effective proton energy reservoir”, was used as a function of E_{cp} to display the ratio between the integral source flux and the CTAO sensitivity. This ratio was computed to obtain a qualitative estimation of the detectability of CTAO for each model in the parameter space. The higher the integral flux-to-CTAO-sensitivity ratio, the more feasible the detection. Moreover, the region where we would detect each model with CTAO in at least one energy bin is lower-delimited in Fig. 24 by a dashed orange line to have a more precise boundary of the detection region. Therefore, the region between the dashed orange line and the white region (integral flux-to-CTAO-sensitivity close to 0) delimits the border of the parameter space where CTAO will likely begin to detect the gamma-ray emission of the models. Qualitatively, RS Oph would be located approximately in the top right corner of Fig. 24, while V959 Mon (the first classical nova discovered by *Fermi*-LAT; Ackermann et al. 2014) would be in the lower left region of the plots.

The integral gamma-ray emission and the integral flux-to-CTAO-sensitivity ratio in Fig. 24 increases as the effective proton energy reservoir and E_{cp} increase. Both top regions of plots *a* and *b* in Fig. 24

have positive values of integral flux-to-CTAO-sensitivity ratio (about 30% of the total combinations), while the bottom region do not (about 70% of the total combinations). When comparing the results between CTAO-N and CTAO-S, the former extends the parameter space region with positive integral flux-to-CTAO-sensitivity towards models with $E_{\text{cp}} < 250 \text{ GeV}$. On the other hand, the latter presents a wider detection region towards $E_{\text{cp}} > 250 \text{ GeV}$ than CTAO-N. CTAO-N overperforms CTAO-S with about 10% more detections. The better performance of CTAO-N at low energies is expected because the parameter space under study was restricted to produce most of the gamma-ray emission below 1 TeV and it is also connected with the presence of four LSTs in the CTAO-N Alpha configuration, as it is observed from current novae detected at gamma rays. Therefore, the lack of LSTs, which dominates the CTAO sensitivity at these energies (Cherenkov Telescope Array Consortium et al. 2019), in the Southern array (Alpha configuration) will reduce the parameter space of detectability with CTAO-S.

Thus, CTAO is expected to give strong constraints only to a sub-space of the whole parameter space under study. For about 30% of the area of the parameter space covered in Fig. 24 could be likely detected with CTAO, in particular, where the relativistic protons have a high value of prefactor and cutoff energy. Assuming that the target proton number density is the number density of the main ejection of matter in the outburst, the results suggest that for denser ejecta, the detection region with CTAO will cover a wide range of parameter values of the relativistic proton energy distribution. CTAO-N should outperform CTAO-S for novae with $E_{\text{cp}} < 250 \text{ GeV}$, while for $E_{\text{cp}} > 250 \text{ GeV}$, CTAO-S should perform better than CTAO-N at high energies.

4.5.3 RS Oph

RS Oph is a symbiotic nova formed by a high-mass white dwarf ($1.2 - 1.4 M_{\odot}$) and a red giant star (M0 III, Anupama & Mikolajewska 1999), which transfers material to the compact object. In the literature, its distance has been estimated ranging from 1 kpc to 5 kpc (Barry et al. 2008, see also the discussion about the distance estimation in Section C.1 of the supplementary material of Acciari et al. 2022), being the most recent value of about $2.68 \pm 0.16 \text{ kpc}$ from *Gaia* DR3 catalog (Gaia Collaboration 2020). RS Oph undergoes recurrent nova outbursts with a periodicity of about 15 years. Its last eruption occurred in August 2021. Covered widely at different wavelengths, the 2021 outburst was detected at VHE gamma rays, adding a new object class to the list of VHE emitters. The HE and VHE gamma-ray emission was consistent mainly with a hadronic origin (dominated by π^0 decay), likely originated by the interaction of the ejected material with the dense wind of the red giant (Acciari et al. 2022; H. E. S. S. Collaboration et al. 2022). The gamma-ray spectrum showed hints of hardening with time produced by the migration of gamma rays to higher energies (Acciari et al. 2022). The HE light curve presented a power-law decay after reaching the maximum emission phase. The index of the temporal decay at HE with *Fermi*-LAT and the one obtained at VHE by the H.E.S.S. Collaboration were compatible within errors with values 1.35 ± 0.07 and 1.43 ± 0.18 , respectively (Cheung et al. 2022; H. E. S. S. Collaboration et al. 2022). It is expected that RS Oph will undergo another outburst when CTAO will be in operation. Hence, we carried out numerical simulations of RS Oph to estimate its detectability with CTAO along the temporal evolution of the outburst.

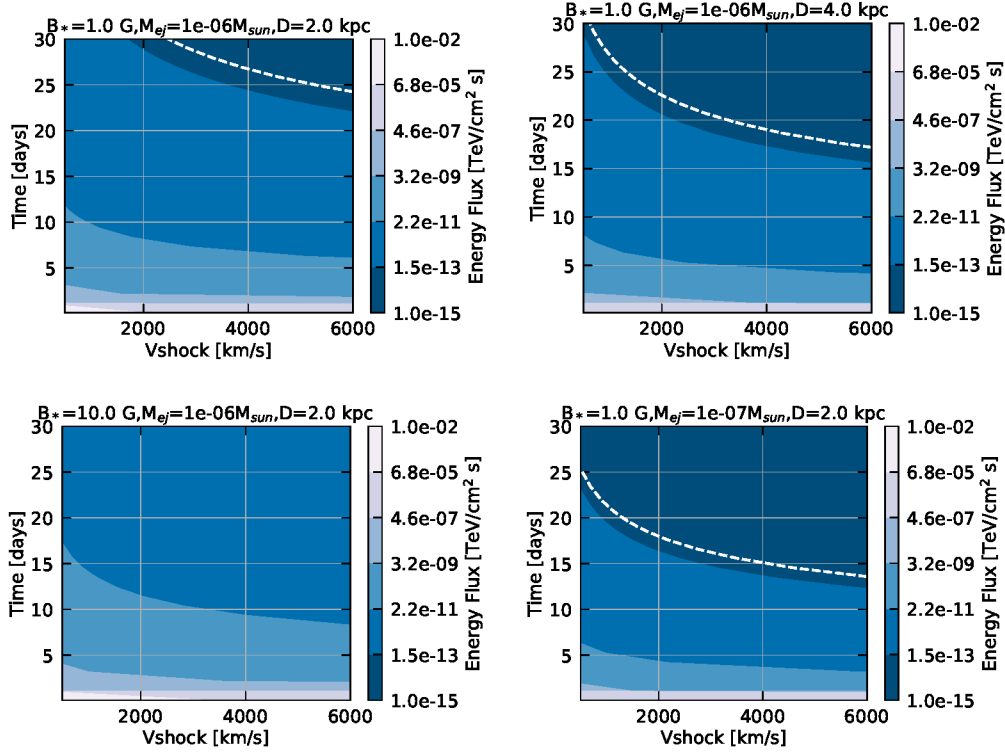


Figure 23. Expected energy flux in gamma rays with time after nova explosion as a function of shock velocity, integrated above 10 GeV. Top left: for an RS Oph-like system at 2 kpc. Top right: for the same physical properties yet at a larger distance of 4 kpc. Bottom left: with increased magnetic field strength. Bottom right: with decreased mass-loss rate. In all plots the white dashed line indicates the CTAO isoflux line at $10^{-13} \text{ TeV cm}^{-2} \text{ s}^{-1}$. Below this line the region should be easily accessible to CTAO.

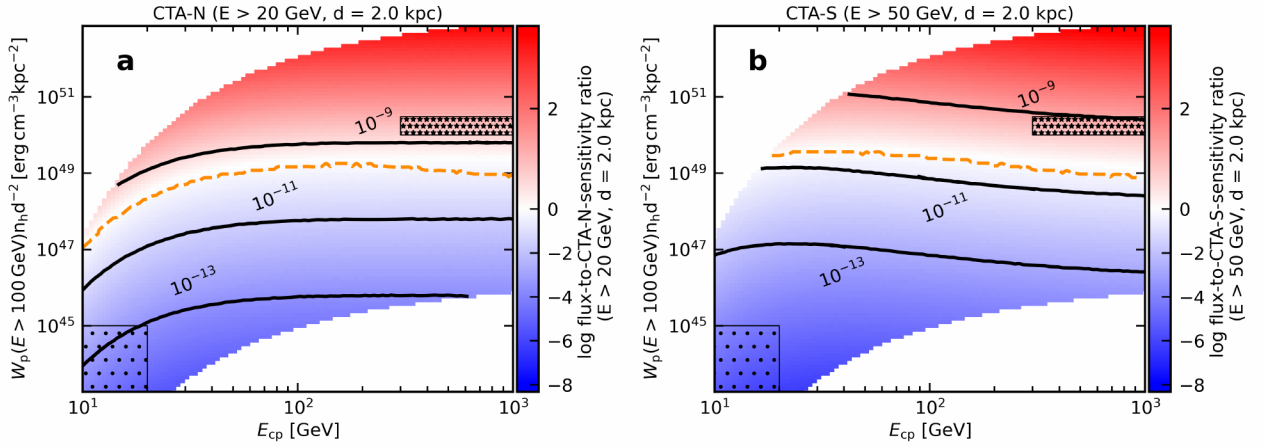


Figure 24. Logarithmic integral flux-to-CTAO-sensitivity ratio for CTAO-N (panel a), integrated above 20 GeV and CTAO-S (panel b), integrated above 50 GeV for different values in the defined parameter space (see text) of n_h , cutoff energy (E_{cp}) and prefactor (A) of the proton energy distribution function at a fixed distance of $d = 2.0 \text{ kpc}$. The sensitivity was computed for a total observation time of 5 hours. The orange dashed line indicates the domain in the parameter space with detection in at least one energy bin for different values of n_h , E_{cp} and A . Solid black lines are curves at constant integrated flux (10^{-13} , 10^{-11} and $10^{-9} \text{ cm}^{-2} \text{ s}^{-1}$) above 20 GeV and 50 GeV for CTAO-N and CTAO-S panels, respectively. The regions where V959 Mon and RS Oph would be approximately located in the parameter space are marked with black dots and stars, respectively.

Table 8. Daily parameter values of the log-parabola spectral models used to simulate RS Oph. Adapted from Acciari et al. (2022).

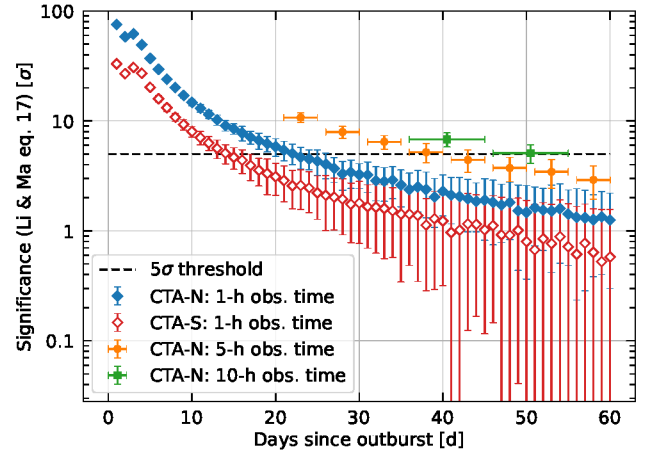
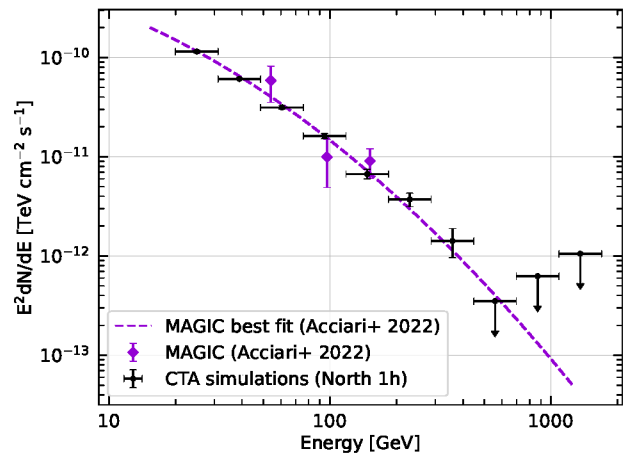
Model day	Prefactor at 130 GeV [$10^{-10} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$]	α	β
Day 1	5.40	3.86	0.194
Day 2	4.54	3.73	0.175
Day 3	5.37	3.64	0.173
Day 4 – 59	5.00	3.44	0.147

4.5.4 RS Oph: CTAO simulations

We performed the numerical simulations of RS Oph with CTAO using the official IRFs from prod5-v0.1 for the CTAO northern and southern arrays. In particular, the closest IRFs set to the culmination of RS Oph in the CTAO-N and CTAO-S site were used (North-40deg-SouthAz, South-20deg-NorthAz) for 0.5 h observation time. A total of 59 daily observations of 1 hour each were simulated starting one day after the beginning of the nova outburst (batches of 100 simulations per day). We simulated this source based on the gamma-ray spectral and temporal profile reported by the MAGIC and H.E.S.S. Collaborations, respectively. The best daily-fit spectral log-parabola models from Acciari et al. (2022) were considered to model the gamma-ray emission. Spectral variations were only contemplated for the simulations of the first four days, when spectral information in Acciari et al. (2022) was available during the outburst. The spectral parameter values utilised in the different log-parabola models are shown in Table 8. After the fourth day, the spectral profile was fixed to the one from the last day with spectral information (fourth day), and the simulated gamma-ray emission was scaled to follow the power-law temporal decay reported by H.E.S.S. We set the index value of the power-law decay to $\gamma = 1.4$.

The statistical detection significance as a function of time is shown in Fig. 25. The results confirm that RS Oph would be clearly detected with CTAO-N and CTAO-S for the first days, reaching a detection significance of about 60σ and 30σ in an hour with CTAO-N and CTAO-S, respectively. RS Oph is not only detectable with CTAO during the first days after the outburst, but CTAO would also daily detect RS Oph up to 20 and 15 days after the outburst with the northern and southern arrays, respectively. If we consider the combined data of 5 and 10 adjacent days with CTAO-N, the detection would be possible even up to 36 – 40 and 46 – 55 days, respectively. The 5σ detection would be limited down to 23 – 27 and 38 – 47 days with CTAO-S. The resulting SED for the first simulated observation (day 1 after the outburst) is shown in Fig. 26 together with the observed spectrum obtained with MAGIC for the same observation time. The results suggest that CTAO will be able to probe the gamma-ray emission for several weeks after the outburst with a precise spectral coverage at least during the first days. Using 1-h observation, CTAO would be able to characterize the curvature of the VHE gamma-ray emission of RS Oph. For example, for the simulated observation of day 1, a log-parabola spectral model is preferred over a power-law model at 3.7σ .

Consequently, if one assumes that the next RS Oph outburst follows the same behaviour as the 2021 eruption, a plausible assumption based on the similarities observed at radio, optical and X-ray for the first weeks between 2006 and 2021 outbursts (Munari et al. 2022; Acciari et al. 2022; Page et al. 2022), CTAO observations can provide detailed coverage of the gamma-ray emission during the future RS Oph outburst. Also, we could probe the maximum energy

**Figure 25.** Daily statistical detection significance (equation 17 of Li & Ma 1983) from 1-hour simulated observation with CTAO-N and CTAO-S (blue filled diamonds and red empty diamonds, respectively) as a function of the number of days since the outburst of RS Oph. The 5-day (i.e. 5-h observation time, filled orange circles) and 10-day (i.e. 10-h observation time, filled green squares) combined significance for CTAO-N are computed when the daily and 5-day statistical detection significance reach a 5σ detection (dashed black line), respectively. Error bars correspond to the standard deviation of the statistical detection significance distribution for the 100 simulations per day.**Figure 26.** VHE γ -ray SED of RS Oph after 1 day since the outburst. The best-fit model from Acciari et al. (2022) using MAGIC and Fermi-LAT for the first night of observation is used (magenta dashed line) to simulate the source with CTAO. The CTAO-N flux points for a 1-hour observation time are shown as black points. Also, the MAGIC flux points (computed using 1-h observation time of data after cuts) from Acciari et al. (2022) are displayed (magenta points).

of the accelerated particles and the nova physical conditions across different outburst stages.

4.5.5 Other novae

To date, RS Oph is the only recurrent nova system from which gamma-ray emission at TeV energies has been detected during outburst. Nevertheless, several other recurrent novae, in particular symbiotic binary systems with high mass-transfer rates and dense winds, are also promising potential gamma-ray emitters. T Coronae Borealis (T CrB) in particular is a nearby symbiotic binary system, located closer to Earth than RS Oph, from which two prior outbursts have been observed in optical wavelengths (Schaefer 2023). Models predict that the next outburst will occur in 2024.4 ± 0.3 years (Schaefer et al. 2023) and, if a shock evolution comparable to RS Oph can be assumed, particle acceleration and detectable VHE gamma-ray emission is highly expected. Other novae that are expected to plausibly occur over the lifetime of CTAO are the recurrent novae V394 Coronae Australis, CI Aquilae or V3890 Sgr and possible superflares arising from V2487 Oph (Schaefer 2019; Schaefer et al. 2022).

Recurrent novae - those from which more than a single outburst has been observed - tend to be associated with symbiotic binary systems due to their high mass transfer rate. This also renders them good candidates for particle acceleration to very high energies. Although MeV to GeV emission has been detected from classical novae by *Fermi*-LAT, the extension of their spectral energy distributions into the energy range detectable by IACTs is not expected a priori. Only continued observations of a range of novae during outburst with different physical properties will provide further insights into particle acceleration occurring in these systems.

4.6 Magnetars: discussion

On April 15, 2020, the *Fermi*-GBM and the *Fermi*-LAT instruments detected MeV and GeV gamma-ray emission from a giant flare event of a magnetar located in the NGC 253 galaxy (Roberts et al. 2021; *Fermi*-LAT Collaboration et al. 2021). The first time detection of GeV emission from a giant magnetar flare is particularly interesting, with the detection of two photons with energies 1.3 GeV and 1.7 GeV. According to *Fermi*-LAT Collaboration et al. (2021), these two GeV photons are produced via synchrotron emission considering the presence of a strong magnetic field which is generated in the shocks. It is proposed that these GeV photons are produced in the dissipation associated with the collision of the giant flare outflow and the external shell generated from swept-up material. This indicates that non-thermal processes accelerating particles at high-energies are at work. IC scattering can also occur in these events, and giant magnetar flares have been proposed as potential GeV-TeV emitters. TeV emission on millisecond timescales could be produced during giant flare events, which might be luminous enough to be detectable by IACTs (Lyubarsky 2014; Murase et al. 2016), including CTAO. This TeV emission could be produced via synchrotron maser mechanism, triggered by strong magnetic disturbances from the magnetosphere and propagating outwards, until they dissipate by interacting with the ambient nebula. In the case of dissipation of disturbances within the magnetar wind, a non-thermal tail can plausibly arise, potentially leading to the production of VHE gamma-ray emission (Metzger et al. 2020).

Magnetars are also relevant for their possible connection with other transient sources, such as, e.g., GRBs, super luminous supernovae, and fast radio bursts (FRB).

The association of a burst from the Galactic magnetar SGR 1935+2153 with an extremely bright FRB-like radio pulse on April 28, 2020 led to the first unequivocal association between FRBs and magnetars (CHIME/FRB Collaboration et al. 2020; Bochenek et al.

2020; Mereghetti et al. 2020; Tavani et al. 2021). The radio flare showed a double-peak structure, pattern also detected at X rays. The X-ray burst was of intermediate energetics, significantly too faint to be classified as a giant flare. However, even if the X-ray emission was not particularly energetic, this burst showed a harder spectra with respect to the typical bursts from SGR 1935+2154 and other magnetars.

Comparing the peak emission of the April 28, 2020 burst (Mereghetti et al. 2020), which reached a value of $50 \text{ ph cm}^{-2} \text{ s}^{-1}$ (in the 15-50 keV band) to other energetic transient events, such as GRB 190114C (MAGIC Collaboration et al. 2019), we see that the X-ray energetics are compatible with those of the second X-ray peak. Current IACTs such as H.E.S.S. (Abdalla et al. 2021) and MAGIC (López-Oramas et al. 2021) have led campaigns to search for a VHE component in SGR 1935+2154. Abdalla et al. (2021) observed the source 2 hours prior the CHIME and STARE2 flare and then simultaneously to different X-ray flares. No VHE emission was detected and an UL at $E > 600 \text{ GeV}$ of $2.4 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ was established. Similarly, the MAGIC multi-wavelength monitoring campaign (López-Oramas et al. 2021) did not find any significant signal, even though some X-ray flares were present during the monitoring campaign. On October 8, CHIME detected three more millisecond events (Good & CHIME/FRB Collaboration 2020) from SGR 1935+2154 (with no X-ray counterpart reported), which were confirmed by FAST on October 9 (Zhu et al. 2020). The radio fluence of these event was lower than that of April 2020. During simultaneous observations by Swift and MAGIC on October 9, a forest of bursts was detected in the hard X-ray range, but no TeV emission was revealed (López-Oramas et al. 2021). The H.E.S.S. and MAGIC observations set constraints to the persistent emission in SGR1935+2154 and to the bursting emission. However, depending on the emission region in the magnetar and the interaction with the surrounding nebula (existing in the case of SGR 1935+2154), future detection of VHE bursts is still plausible.

The new radio facilities that will operate at the time of CTAO will provide the detection of up to hundreds of FRB per day. Many of these will have good localizations and will be inside the CTAO field of view, making it possible to search for prompt and/or delayed very high-energy emission. Although no magnetar outburst has been yet detected at TeV, the existence of MeV and GeV emission maintains the expectations of a possible TeV component, making magnetars good source candidates for CTAO. The CTAO Observatory should aim at observing magnetar flares as soon as possible, triggering on external alerts. Automatic re-pointing of the telescopes can take place whenever certain observational criteria (such as i.e. flare type, brightness, multi-wavelength counterparts or distance) are fulfilled. The high sensitivity of CTAO at short timescales while provide new insights onto the physics of magnetars at VHE.

5 SYNERGIES WITH LARGE ASTRONOMICAL FACILITIES

Simultaneous coordinated observations with telescopes and facilities at different wavelengths are crucial for understanding the processes and mechanisms at work in the sources of our interest (see Cherenkov Telescope Array Consortium et al. 2019 for a detailed review). Co-ordination, response to real-time alerts and target-of-opportunity (ToOs) are key in time domain astrophysics when observing transient events. In the case of Galactic transients, external alerts can trigger ToO observations by CTAO of new Galactic events or renewed activity of known sources. The trigger criteria is dependent on the type

of source observed, with different time urgency and duration varying in terms of the evolution of the specific phenomena. Regarding the observational strategy, a first description on the triggering criteria, expected trigger rate and target priority is already provided in [Cherenkov Telescope Array Consortium et al. \(2019\)](#). Updated strategies for multi-wavelength follow-up and needs are already being collected and discussed in a dedicated operations requirement document⁹, where different studies for the planning and optimization of the CTAO follow-up programme are being conducted.

For a prompt reaction and fast reposition, CTAO will need to manage external and internal scientific alerts, for which a *transient handler* subsystem is under development ([Egberts et al. 2022](#)). The LST-1 transient handler is already operational and has allowed the follow-up of different transient alerts ([Carosi et al. 2021](#)). Furthermore, a real-time analysis will be performed by CTAO via the *Science Alert Generation* system with the goal of issuing science alerts of transient phenomena to the community with a latency of about 20 seconds ([Bulgarelli et al. 2024](#)), increasing the synergies of CTAO with the astronomical community.

The radio band is of general interest for providing information of the non-thermal processes, and radio facilities are key for locating acceleration sites and shocks and to provide feedback on fast events such as magnetar flares or stellar flares. For that purpose, CTAO will need an external trigger from a radio observatory sensitive to (millisecond) bursts and capable of issuing prompt alerts. Current generation of telescopes such as CHIME, with a large field of view and collecting area, have proven their efficiency for detecting these alerts ([CHIME/FRB Collaboration et al. 2020](#)). An example of clear synergies are those with the MeerTRAP project to follow-up fast radio signals ([Rajwade et al. 2020](#); [Bezuidenhout et al. 2022](#)).

In the optical and infrared domain prompt reaction would be facilitated by coordinating with external observatories within time zones close to those of CTAO sites. In the case of CTAO North, it should be pursuing synergies mainly with La Palma, Tenerife (and CAHA) telescopes in Spain, while in the CTAO South the most appropriate choice would be the different ESO telescopes and other large facilities in Chile, such as the Rubin Observatory Legacy Survey of Space and Time (LSST), which will be key for time-domain astronomy (see [Hambleton et al. 2022](#)). The availability of imaging and spectroscopic instrumentation in both hemispheres does largely fulfill the observational needs required for coordinated campaigns. Specific target of opportunity proposals could be eventually placed by the CTAO community. In parallel, small optical telescopes either on-site or operated by nearby CTAO institutions could also play a key role in this effort if the targets are bright enough as in the case of novae or gamma-ray binaries. This could serve to mitigate the often high-time pressure on large telescopes. Additionally, support optical telescopes would ensure a fast follow-up on transients and would provide sufficient coverage in the case of bright sources.

Space missions will allow to study the X-ray domain with improved capabilities. The Space Variable Objects Monitor (SVOM) [4 - 150 keV range] has been recently launched and although its core science is focused in GRB detection, it has the capabilities for detecting i.e. thermonuclear explosions and outbursts of Galactic origin due to the sensitivity of the ECLAIRs (50mCrab per orbit) telescope ([Wei et al. 2016](#)). Synergies with future instruments such as the Advanced Telescope for High-ENergy Astrophysics (Athena) [0.2–12 keV] ([Barcons et al. 2017](#)), scheduled for launch in mid 2030s contemporaneous to the CTAO era, are also expected.

The high-energy band ($E > 100$ MeV) is currently explored by the *Fermi*-LAT satellite ([Atwood et al. 2009](#)). Triggers from *Fermi*-LAT have been important for the detection of Galactic transients such as novae in the VHE domain. Simultaneous MeV-GeV information is also important to disentangle between hadronic and leptonic processes. If *Fermi* lifetime extends through (at least partially) CTAO lifetime, it will provide the needed coverage and alerts to certain observations/triggers. Just recently, the AGILE satellite, that also operated in this energy range, ceased its operations and re-entered the atmosphere ([Tavani et al. 2024](#)). For the moment, there is no obvious successor to *Fermi* or AGILE in the same energy domain, although some missions could take over. A successor will be crucial to fully exploit the full potential of gamma-ray astronomy. The High Energy cosmic-Radiation Detection facility (HERD) is expected to be operational from 2026 on board of the Chinese Space Station, detecting gamma rays above 0.5 GeV and with potential for transient detection ([Cagnoli et al. 2024](#)).

Finally, in a multi-messenger context, CTAO will be able to search for the electromagnetic counterpart of gravitational waves (GWs) and neutrinos in the Milky Way. The Laser Interferometer Space Antenna (LISA) mission will be the first GW observatory on space (scheduled launch on 2030) and will key to study white dwarf mergers ([Lamberts et al. 2019](#); [Georgousi et al. 2023](#)). Neutrino alerts from the next generation of detectors such as IceCube-Gen2 will also be crucial in the case of a Galactic core-collapse supernova ([Aartsen et al. 2021](#)).

6 SUMMARY AND CONCLUSIONS

We have studied the capabilities of the forthcoming CTAO to detect transient and variable emission from Galactic sources of different nature. We additionally tested longer exposure times in specific cases of high interest for the observatory. CTAO will be able to discover new transients with not significant degradation in the sensitivity, with a maximum of 15% in the crowded inner regions of the Galaxy when overlapping with strong emitters. Similarly, in order to detect variability from dim systems, our simulations have shown that sources with a photon flux $< 1 \times 10^{-13}$ ph cm⁻² s⁻¹ will require > 10 h of observations to detect this variability. For sources with fluxes above this threshold, only 5–10 h are required. In the case of strong sources ($\geq 3 \times 10^{-12}$ ph cm⁻² s⁻¹), short exposures 0.5–1.0 h are required, implying that low variations in the flux can be detectable from bright sources. For the case of generic transient sources with the fluxes $< 10^{-13}$ ph cm⁻² s⁻¹ TeV⁻¹ CTAO will not detect any source in about one hour observation time, while for those with fluxes $< 10^{-9}$ ph cm⁻² s⁻¹ TeV⁻¹ in an uncrowded region, CTAO would be able to detect $\geq 65\%$ of sources within just 1 hour of observation for both arrays for the different zenith angles and configurations of the geomagnetic field used in this study if all sources are visible. Any visibility constraints will significantly lower this number.

The unique sensitivity at short timescales together with the fast slewing capabilities of the LSTs and the aforementioned capacities of CTAO will allow the detection and discovery of a variety of sources of different nature, according to our simulations:

- (i) CTAO will detect VHE from microquasars and from the interaction between their jets and the surrounding environment. Our simulations show that CTAO will likely detect both transient and persistent emission from the massive microquasars Cyg X-1 and Cyg X-3. CTAO will also significantly detect SS 433 including possible flux variability. In the case of LMXBs, CTAO will detect outbursts within few tens of minutes from a nearby source (< 4 kpc) with relatively

⁹ In preparation

small inclination angle ($<30^\circ$). Longer exposure times are required for LMXBs with larger angles.

- (ii) We tested the case of tMSPs, concluding that CTAO will need long integration times (>50 h) to be able to detect the possible emission of tMSPs when they are in the LMXB state. These systems could be detected during a transition from RSMP to LMXB if an additional VHE component is present, which could provide crucial information on particle interaction.
- (iii) Flaring emission from the Crab Nebula will be best detected by CTAO (or LST sub-array) at low energies ($E < 200$ GeV) in less than 1 h. In the TeV regime, integration times of <10 h will be needed, specially for the detection of dimmer flares.
- (iv) In the case of novae, CTAO will be able to detect close-by novae. As an example of the only VHE novae known to date, our simulations reveal that CTAO will detect the symbiotic recurrent nova RS Oph with high significance in only 30 min, allowing for a detailed measurement, and therefore detailed modeling, of its SED from energies as low as 20 GeV. Combined with multi-wavelength observations, the temporal and spectral analyses of CTAO observation would improve our understanding of the acceleration processes in novae.

Regarding sources of different nature from the aforementioned, we could expect CTAO to detect emission from magnetars during a giant flare and even likely during intermediate flares associated with an FRB. Other possible transient events are flares from SFXTs, for which a detection would definitely identify SFXTs as VHE emitters. Other variable VHE candidates are runaway stars and young stellar objects. Serendipitous discoveries are also possible while performing, e.g., surveys. Simultaneous multi-wavelength and multi-messenger observations will be crucial to maximize the scientific output of the CTAO observatory.

ACKNOWLEDGEMENTS

We gratefully acknowledge financial support from the following agencies and organizations:

State Committee of Science of Armenia, Armenia; The Australian Research Council, Astronomy Australia Ltd, The University of Adelaide, Australian National University, Monash University, The University of New South Wales, The University of Sydney, Western Sydney University, Australia; Federal Ministry of Education, Science and Research, and Innsbruck University, Austria; Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Fundação de Amparo à Pesquisa do Estado do Rio de Janeiro (FAPERJ), Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP), Fundação de Apoio à Ciência, Tecnologia e Inovação do Paraná - Fundação Araucária, Ministry of Science, Technology, Innovations and Communications (MCTIC), Brasil; Ministry of Education and Science, National RI Roadmap Project DO1-153/28.08.2018, Bulgaria; The Natural Sciences and Engineering Research Council of Canada and the Canadian Space Agency, Canada; ANID PIA/APOYO AFB230003, ANID-Chile Basal grant FB 210003, Núcleo Milenio TITANs (NCN19-058), FONDECYT-Chile grants 1201582, 1210131, 1230345, and 1240904; Croatian Science Foundation, Rudjer Boskovic Institute, University of Osijek, University of Rijeka, University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Zagreb, Faculty of Electrical Engineering and Computing, Croatia; Ministry of Education, Youth and Sports, MEYS LM2018105, LM2023047, EU/MEYS CZ.02.1.01/0.0/0.0/16_013/0001403, CZ.02.1.01/0.0/0.0/18_046/0016007,

CZ.02.1.01/0.0/0.0/16_019/0000754 and CZ.02.01.01/00/22_008/0004632, Czech Republic; Academy of Finland (grant nr.317636 and 320045), Finland; Ministry of Higher Education and Research, CNRS-INSU and CNRS-IN2P3, CEA-Irfu, ANR, Regional Council Ile de France, Labex ENIGMASS, OCEVU, OSUG2020 and P2IO, France; The German Ministry for Education and Research (BMBF), the Max Planck Society, the German Research Foundation (DFG, with Collaborative Research Centres 876 & 1491), and the Helmholtz Association, Germany; Department of Atomic Energy, Department of Science and Technology, India; Istituto Nazionale di Astrofisica (INAF), Istituto Nazionale di Fisica Nucleare (INFN), MIUR, Istituto Nazionale di Astrofisica (INAF-OABRERA) Grant Fondazione Cariplo/Regione Lombardia ID 2014-1980/RST_ERC, Italy; ICRR, University of Tokyo, JSPS, MEXT, Japan; Netherlands Research School for Astronomy (NOVA), Netherlands Organization for Scientific Research (NWO), Netherlands; University of Oslo, Norway; Ministry of Science and Higher Education, DIR/WK/2017/12, the National Centre for Research and Development and the National Science Centre, UMO-2016/22/M/ST9/00583, Poland; Slovenian Research Agency, grants P1-0031, P1-0385, I0-0033, J1-9146, J1-1700, N1-0111, and the Young Researcher program, Slovenia; South African Department of Science and Technology and National Research Foundation through the South African Gamma-Ray Astronomy Programme, South Africa; The Spanish groups acknowledge funds from "ERDF A way of making Europe" and the Spanish Ministry of Science and Innovation and the Spanish Research State Agency (AEI) via MCIN/AEI/10.13039/501100011033 through government budget lines PGE2021/28.06.000X.411.01, PGE2022/28.06.000X.411.01, PGE2022/28.06.000X.711.04, and grants PID2022-137810NB-C22, PID2022-136828NB-C42, PID2022-139117NB-C42, PID2022-139117NB-C41, PID2022-136828NB-C41, PID2022-138172NB-C43, PID2022-138172NB-C42, PID2022-139117NB-C44, PID2021-124581OB-I00, PID2021-125331NB-I00, PID2019-104114RB-C31, PID2019-107847RB-C44, PID2019-104114RB-C32, PID2019-105510GB-C31, PID2019-104114RB-C33, PID2019-107847RB-C41, PID2019-107847RB-C43, PID2019-107847RB-C42; the "Centro de Excelencia Severo Ochoa" program through grants no. CEX2019-000920-S, CEX2020-001007-S, CEX2021-001131-S; the "Unidad de Excelencia María de Maeztu" program through grants no. CEX2019-000918-M, CEX2020-001058-M; the "Ramón y Cajal" program through grants RYC2021-032552-I, RYC2021-032991-I, RYC2020-028639-I and RYC-2017-22665; and the "Juan de la Cierva" program through grants no. IJC2019-040315-I and JDC2022-049705-I. La Caixa Banking Foundation is also acknowledged, grant no. LCF/BQ/PI21/11830030. They also acknowledge the project "Tecnologías avanzadas para la exploración del universo y sus componentes" (PR47/21 TAU), funded by Comunidad de Madrid regional government. Funds were also granted by the Junta de Andalucía regional government under the "Plan Complementario de I+D+I" (Ref. AST22_00001) and "Plan Andaluz de Investigación, Desarrollo e Innovación" (Ref. FQM-322); by the "Programa Operativo de Crecimiento Inteligente" FEDER 2014-2020 (Ref. ESFRI-2017-IAC-12) and Spanish Ministry of Science and Innovation, 15% co-financed by "Consejería de Economía, Industria, Comercio y Conocimiento" of the Gobierno de Canarias regional government. The Generalitat de Catalunya regional government is also gratefully acknowledged via its "CERCA" program and grants 2021SGR00426 and 2021SGR00679. Spanish groups were also kindly supported by European Union funds via the "Horizon 2020" program, grant no. GA:824064, and NextGenerationEU, grants

no. PRTR-C17.II, CT19/23-INVM-109, and "María Zambrano" program, BDNS: 572725. This research used computing and storage resources provided by the Port d'Informació Científica (PIC) data center; Swedish Research Council, Royal Physiographic Society of Lund, Royal Swedish Academy of Sciences, The Swedish National Infrastructure for Computing (SNIC) at Lunarc (Lund), Sweden; State Secretariat for Education, Research and Innovation (SERI) and Swiss National Science Foundation (SNSF), Switzerland; Durham University, Leverhulme Trust, Liverpool University, University of Leicester, University of Oxford, Royal Society, Science and Technology Facilities Council, UK; U.S. National Science Foundation, U.S. Department of Energy, Argonne National Laboratory, Barnard College, University of California, University of Chicago, Columbia University, Georgia Institute of Technology, Institute for Nuclear and Particle Astrophysics (INPAC-MRPI program), Iowa State University, the Smithsonian Institution, V.V.D. is funded by NSF grant AST-1911061, Washington University McDonnell Center for the Space Sciences, The University of Wisconsin and the Wisconsin Alumni Research Foundation, USA.

The research leading to these results has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) under grant agreements No 262053 and No 317446. This project is receiving funding from the European Union's Horizon 2020 research and innovation programs under agreement No 676134.

ALO acknowledges the programa Ramón y Cajal for which this publication is part through the Project RYC2021-032991-I, funded by MICIU/AEI/10.13039/501100011033, and the European Union "NextGenerationEU"/PRTR. ALO also acknowledges past support from the JSPS Fellowship for Overseas Researchers of the Japan Society for the Promotion of Science. AJR acknowledges support from an ARC fellowship through award number FT170100243. Part of this research was undertaken with the assistance of resources and services from the National Computational Infrastructure (NCI), which is supported by the Australian Government, through the UNSW HPC Resource Allocation Scheme. DdM acknowledges financial support from INAF AstroFund2022 FANS project. AP acknowledges financial support from the National Institute for Astrophysics (INAF) Research Grant "Uncovering the optical beat of the fastest magnetised neutron stars (FANS)" and from the Italian Ministry of University and Research (MUR), PRIN 2020 (prot. 2020BRP57Z) "Gravitational and Electromagnetic-wave Sources in the Universe with current and next-generation detectors (GEMS)".

This research made use of *ctools*, a community-developed gamma-ray astronomy science analysis software. *ctools* is based on *GammaLib*, a community-developed toolbox for the scientific analysis of astronomical gamma-ray data. This research made use of *gammapy*,¹⁰ a community-developed core Python package for TeV gamma-ray astronomy.

DATA AVAILABILITY

The official CTAO observatory IRFs (Maier et al. 2023) used in this manuscript are available in: *prod3b-v2* <https://zenodo.org/record/5163273> and *prod5-v0.1* <https://zenodo.org/record/5499840>. The *ctools* (ascl:1601.005) DOI is: [10.5281/zenodo.4727876](https://zenodo.org/record/4727876). The

gammapy DOI is 10.5281/zenodo.4701488. The simulations of the Galactic Plane Survey used in Section 2 were retrieved from <https://zenodo.org/doi/10.5281/zenodo.8402519>.

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The main individual authors that contributed to this manuscript are, in alphabetical order:

A. Aguasca-Cabot, simulations and drafting of the novae subsection; M. Chernyakova, C. Dignam, simulations and drafting of the SS 433 and microquasars subsections; D. Kantzas, simulations and drafting of the LMXBs subsection and modeling of Cygnus X-1 microquasar; A. López-Oramas, coordinator and editor of the manuscript, general drafting; P. L. Luque-Escamilla, drafting of optical and infrared synergies; S. Markoff, simulations and drafting of the LMXBs subsection and modeling of Cygnus X-1 microquasar; J. Martí, drafting of optical and infrared synergies; D. de Martino, internal review of the manuscript; S. McKeague, simulations and drafting of the SS 433 and microquasars subsections; S. Mereghetti, drafting of the magnetar subsection; E. Mestre, simulations and drafting of the Crab Nebula flares subsection; A. Mitchell, simulations and drafting of the novae subsection; E. de Oña-Wilhelmi, simulations and drafting of the Crab Nebula flares and the novae subsections; G. Piano, simulations and drafting of the Cygnus X-3, Cygnus X-1, V404 Cyg and microquasars subsections; P. Romano, early perspectives with CTAO, SFXT discussion and internal review of the manuscript; A. J. Ruiter, simulations and drafting of the nova subsection; I. Sadeh, simulations and drafting of the capabilities of CTAO for transient detection section; O. Sergijenko, simulations and drafting of the detectability of transients of unknown origin section; L. Sidoli, SFXTs and other sources; A. Spolon, simulations and drafting of the tMSPs subsection; L. Zampieri, simulations of the tMSPs subsection.

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- Abeyssekara A. U., et al., 2018a, *Nature*, **562**, 82
- Abeyssekara A. U., et al., 2018b, *ApJ*, **861**, 134
- Abeyssekara A. U., et al., 2018c, *ApJ*, **867**, L19
- Acciari V. A., et al., 2022, *Nature Astronomy*, **6**, 689
- Ackermann M., et al., 2014, *Science*, **345**, 554
- Ackermann M., et al., 2017, *ApJ*, **843**, 139
- Aguasca-Cabot A., et al., 2023, Gammapy: Python toolbox for gamma-ray astronomy, <https://zenodo.org/records/8033275>
- Ahnen M. L., et al., 2015, *A&A*, **582**, A67
- Ahnen M. L., et al., 2017a, *MNRAS*, **471**, 1688
- Ahnen M. L., et al., 2017b, *MNRAS*, **472**, 3474
- Albert J., et al., 2007, *ApJ*, **665**, L51
- Albert A., et al., 2021, *ApJ*, **912**, L4
- Aleksić J., et al., 2010, *ApJ*, **721**, 843
- Aleksić J., et al., 2011, *ApJ*, **735**, L5
- Aleksić J., et al., 2013, *A&A*, **549**, A23
- Alfaro R., et al., 2024, *Nature*, **634**, 557
- Aliu E., et al., 2012, *ApJ*, **754**, 77
- Aliu E., et al., 2014a, *ApJ*, **781**, L11
- Aliu E., et al., 2014b, *ApJ*, **788**, 78
- Aliu E., et al., 2016, *ApJ*, **831**, 193
- Ansoldi S., et al., 2016, *A&A*, **585**, A133
- Antokhin I. I., Cherepashchuk A. M., Antokhina E. A., Tatarnikov A. M., 2022, *ApJ*, **926**, 123
- Anupama G. C., Mikołajewska J., 1999, *A&A*, **344**, 177
- Arakawa M., Hayashida M., Khangulyan D., Uchiyama Y., 2020, *ApJ*, **897**, 33
- Araya M., HAWC Collaboration 2019, in 36th International Cosmic Ray Conference (ICRC2019). p. 619 ([arXiv:1907.10197](https://arxiv.org/abs/1907.10197))
- Archibald A. M., et al., 2009a, *Science*, **324**, 1411
- Archibald A. M., et al., 2009b, *Science*, **324**, 1411
- Atwood W. B., et al., 2009, *ApJ*, **697**, 1071
- Barcons X., et al., 2017, *Astronomische Nachrichten*, **338**, 153
- Barry R., Mukai K., Sokoloski J., Danchi W., Hachisu I., Evans A., Gehrz R., Mikołajewska J., 2008, in RS Ophiuchi (2006) and the Recurrent Nova Phenomenon. p. 52
- Bassa C. G., et al., 2014, *MNRAS*, **441**, 1825
- Bell A. R., 2004, *MNRAS*, **353**, 550
- Bezuidenhout M. C., et al., 2022, *MNRAS*, **512**, 1483
- Bochenek C. D., Ravi V., Belov K. V., Hallinan G., Kocz J., Kulkarni S. R., McKenna D. L., 2020, *Nature*, **587**, 59
- Bode M. F., Evans A., 2008, *Classical Novae*. Vol. 43, doi:10.1017/CBO9780511536168,
- Bode M. F., Kahn F. D., 1985, *MNRAS*, **217**, 205
- Bogdanov S., et al., 2015, *ApJ*, **806**, 148
- Bond H. E., White R. L., Becker R. H., O'Brien M. S., 2002, *PASP*, **114**, 1359
- Bordas P., Yang R., Kafexhiu E., Aharonian F., 2015, *ApJ*, **807**, L8
- Brinkmann W., Pratt G. W., Rohr S., Kawai N., Burwitz V., 2007, *A&A*, **463**, 611
- Buehler R., et al., 2012, *ApJ*, **749**, 26
- Bulgarelli A., et al., 2010, *The Astronomer's Telegram*, **2512**, 1
- Bulgarelli A., et al., 2024, in Ibsen J., Chiozzi G., eds, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series Vol. 13101*, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series. p. 1310129, doi:10.1117/12.3017825
- CHIME/FRB Collaboration et al., 2020, *Nature*, **587**, 54
- CTA Consortium 2023, *arXiv e-prints*, p. [arXiv:2310.02828](https://arxiv.org/abs/2310.02828)
- CTA-LST Project et al., 2023, *arXiv e-prints*, p. [arXiv:2306.12960](https://arxiv.org/abs/2306.12960)
- Cagnoli I., Kyrtatzis D., Serini D., 2024, *Nuclear Instruments and Methods in Physics Research A*, **1068**, 169788
- Cangemi F., et al., 2021, *A&A*, **650**, A93
- Cao Z., et al., 2021, *Nature*, **594**, 33
- Cao Z., et al., 2023, *arXiv e-prints*, p. [arXiv:2305.17030](https://arxiv.org/abs/2305.17030)
- Carosi A., López-Oramas A., 2024, *Universe*, **10**, 163
- Carosi A., et al., 2021, *arXiv e-prints*, p. [arXiv:2108.04309](https://arxiv.org/abs/2108.04309)
- Casares J., Charles P. A., Naylor T., 1992, *Nature*, **355**, 614

REFERENCES

Aartsen M. G., et al., 2021, *Journal of Physics G Nuclear Physics*, **48**, 060501

Abdalla H., et al., 2019, *Nature*, **575**, 464

Abdalla H., et al., 2021, *ApJ*, **919**, 106

Abdo A. A., et al., 2010a, *Science*, **329**, 817

Abdo A. A., et al., 2010b, *ApJ*, **725**, L73

Abdo A. A., et al., 2011, *Science*, **331**, 739

Abdollahi S., et al., 2020, *ApJS*, **247**, 33

Abe H., et al., 2022, *MNRAS*, **517**, 4736

Abe K., et al., 2025, *A&A*, **695**, A152

- Chaty S., 2022, Accreting Binaries; Nature, formation, and evolution, doi:10.1088/2514-3433/ac595f.
- Cherenkov Telescope Array Consortium et al., 2019, Science with the Cherenkov Telescope Array, doi:10.1142/10986.
- Chernyakova M., et al., 2019, *A&A*, **631**, A177
- Cheung C. C., et al., 2022, *ApJ*, **935**, 44
- Chomiuk L., Metzger B. D., Shen K. J., 2021, *ARA&A*, **59**, 391
- Coppi P. S., 1999, The Physics of Hybrid Thermal/Non-Thermal Plasmas. p. 375
- Corral-Santana J. M., Casares J., Muñoz-Darias T., Bauer F. E., Martínez-Pais I. G., Russell D. M., 2016, *A&A*, **587**, A61
- Davidson K., Fesen R. A., 1985, *ARA&A*, **23**, 119
- De K., et al., 2021, *ApJ*, **912**, 19
- Donath A., et al., 2023, *A&A*, **678**, A157
- Dubus G., Cerutti B., Henri G., 2010, *MNRAS*, **404**, L55
- Duncan R. C., Thompson C., 1992, *ApJ*, **392**, L9
- Egberts K., Hoischen C., Steppa C., Füssling M., Neise D., de Ona Wilhelmi E., Oya I., 2022, in Adler D. S., Seaman R. L., Benn C. R., eds, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series Vol. 12186, Observatory Operations: Strategies, Processes, and Systems IX. p. 121860L (arXiv:2209.05888), doi:10.1117/12.2629372
- Fabrika S., 2004, Astrophysics and Space Physics Reviews, **12**, 1
- Falcke H., Kording E., Markoff S., 2004, *A&A*, **414**, 895
- Fermi LAT Collaboration et al., 2009, *Science*, **326**, 1512
- Fermi-LAT Collaboration et al., 2021, *Nature Astronomy*.
- Fioletti V., Ribeiro D., Humensky T. B., Bulgarelli A., Maier G., Moralejo A., Nigro C., 2019, in 36th International Cosmic Ray Conference (ICRC2019), p. 673 (arXiv:1907.08018), doi:10.22323/1.358.0673
- Franckowiak A., Jean P., Wood M., Cheung C. C., Buson S., 2018, *A&A*, **609**, A120
- Frederiks D. D., Palshin V. D., Aptekar R. L., Golenetskii S. V., Cline T. L., Mazets E. P., 2007, *Astronomy Letters*, **33**, 19
- Funk S., Hinton J. A., CTA Consortium 2013, *Astroparticle Physics*, **43**, 348
- Gaia Collaboration 2020, VizieR Online Data Catalog, p. I/350
- Gallagher J. S., Starrfield S., 1978, *ARA&A*, **16**, 171
- Gallo E., Plotkin R. M., Jonker P. G., 2014, *MNRAS*, **438**, L41
- Gavriil F. P., Gonzalez M. E., Gotthelf E. V., Kaspi V. M., Livingstone M. A., Woods P. M., 2008, *Science*, **319**, 1802
- Geldzahler B. J., Pauls T., Salter C. J., 1980, *A&A*, **84**, 237
- Georgousi M., Karnesis N., Korol V., Pieroni M., Stergioulas N., 2023, *MNRAS*, **519**, 2552
- Gomez-Gomar J., Hernanz M., Jose J., Isern J., 1998, *MNRAS*, **296**, 913
- Good D., CHIME/FRB Collaboration 2020, The Astronomer's Telegram, **14074**, 1
- Göğüş E., et al., 2016, *ApJ*, **829**, L25
- H. E. S. S. Collaboration et al., 2014, *A&A*, **562**, L4
- H. E. S. S. Collaboration et al., 2018, *A&A*, **612**, A10
- H. E. S. S. Collaboration et al., 2022, *Science*, **376**, 77
- H. E. S. S. Collaboration Olivera-Nieto L., Reville B., Hinton J., Tsiros M., 2024, *Science*, **383**, 402
- Hachisu I., Kato M., 2022, *ApJ*, **939**, 1
- Hambleton K. M., et al., 2022, arXiv e-prints, p. arXiv:2208.04499
- Harding A. K., Contopoulos I., Kazanas D., 1999, *ApJ*, **525**, L125
- Hernanz M., Tatischeff V., 2012, *Baltic Astronomy*, **21**, 62
- Hillas A. M., 1984, *ARA&A*, **22**, 425
- Huang X., Yuan Q., Fan Y.-Z., 2021, *ApJ*, **908**, 65
- Iben I. J., 1982, *ApJ*, **259**, 244
- IceCube Collaboration et al., 2018, *Science*, **361**, eaat1378
- Jourdain E., Roques J. P., Chauvin M., Clark D. J., 2012, *ApJ*, **761**, 27
- Kafexhiu E., Aharonian F., Taylor A. M., Vila G. S., 2014, *Phys. Rev. D*, **90**, 123014
- Kantzas D., et al., 2021, *MNRAS*, **500**, 2112
- Kantzas D., Markoff S., Lucchini M., Ceccobello C., Grinberg V., Connors R. M. T., Uttley P., 2022, *MNRAS*, **510**, 5187
- Kaspi V. M., Beloborodov A. M., 2017, *ARA&A*, **55**, 261
- Kato M., Saio H., Hachisu I., Nomoto K., 2014, *ApJ*, **793**, 136
- Kemp A. J., Karakas A. I., Casey A. R., Izzard R. G., Ruiter A. J., Agrawal P., Broekgaarden F. S., Temmink K. D., 2021, *MNRAS*, **504**, 6117
- Kemp A. J., Karakas A. I., Casey A. R., Kobayashi C., Izzard R. G., 2022, *MNRAS*, **509**, 1175
- Knödseder J., et al., 2016, *A&A*, **593**, A1
- Koljonen K. I. I., Hannikainen D. C., McCollough M. L., Pooley G. G., Trushkin S. A., 2010, *MNRAS*, **406**, 307
- LHAASO Collaboration 2024, arXiv e-prints, p. arXiv:2410.08988
- Lamberts A., Blunt S., Littenberg T. B., Garrison-Kimmel S., Kupfer T., Sanderson R. E., 2019, *MNRAS*, **490**, 5888
- Laurent P., Rodriguez J., Wilms J., Cadolle Bel M., Pottschmidt K., Grinberg V., 2011, *Science*, **332**, 438
- Lhaaso Collaboration et al., 2021, *Science*, **373**, 425
- Li T. P., Ma Y. Q., 1983, *The Astrophysical Journal*, **272**, 317
- Li J., Rea N., Torres D. F., de Oña-Wilhelmi E., 2017, *ApJ*, **835**, 30
- Li J., Torres D. F., Liu R.-Y., Kerr M., de Oña Wilhelmi E., Su Y., 2020, *Nature Astronomy*, **4**, 1177
- Loh A., et al., 2016, *MNRAS*, **462**, L111
- López-Oramas A., et al., 2021, *PoS, ICRC2021*, 783
- Lyubarsky Y., 2014, *MNRAS*, **442**, L9
- MAGIC Collaboration et al., 2019, *Nature*, **575**, 455
- MAGIC Collaboration et al., 2020, *A&A*, **635**, A158
- Maier G., Gueta O., Zanin R., 2023, CTAO Instrument Response Functions: Comparison of prod5 and prod3b releases, doi:10.5281/zenodo.8050921, https://doi.org/10.5281/zenodo.8050921
- Malyshev D., Zdziarski A. A., Chernyakova M., 2013, *MNRAS*, **434**, 2380
- Margon B., 1984, *ARA&A*, **22**, 507
- Mariotti M., 2010, The Astronomer's Telegram, **2967**, 1
- Martin P., Dubus G., Jean P., Tatischeff V., Dosne C., 2018, *A&A*, **612**, A38
- Masetti N., et al., 2006, *A&A*, **459**, 21
- Mayer M., Buehler R., Hays E., Cheung C. C., Dutka M. S., Grove J. E., Kerr M., Ojha R., 2013, *ApJ*, **775**, L37
- Mazets E. P., et al., 2008, *ApJ*, **680**, 545
- Mereghetti S., 2008, *A&ARv*, **15**, 225
- Mereghetti S., Pons J. A., Melatos A., 2015, *Space Sci. Rev.*, **191**, 315
- Mereghetti S., et al., 2020, *ApJ*, **898**, L29
- Mestre E., de Oña Wilhelmi E., Zanin R., Torres D. F., Tibaldo L., 2020, *MNRAS*, **492**, 708
- Mestre E., de Oña Wilhelmi E., Khangulyan D., Zanin R., Acero F., Torres D. F., 2021, *MNRAS*, **501**, 337
- Metzger B. D., Caprioli D., Vurm I., Beloborodov A. M., Bartos I., Vlasov A., 2016, *MNRAS*, **457**, 1786
- Metzger B. D., Fang K., Margalit B., 2020, *ApJ*, **902**, L22
- Miller-Jones J. C. A., Jonker P. G., Dhawan V., Briskin W., Rupen M. P., Nelemans G., Gallo E., 2009, *ApJ*, **706**, L230
- Miller-Jones J. C. A., et al., 2021, *Science*, **371**, 1046
- Mirabel I. F., Rodríguez L. F., 1998, *Nature*, **392**, 673
- Munari U., Giroletti M., Marcote B., O'Brien T. J., Veres P., Yang J., Williams D. R. A., Woudt P., 2022, *A&A*, **666**, L6
- Murase K., Kashiyama K., Mészáros P., 2016, *MNRAS*, **461**, 1498
- Observatory C. T. A., Consortium C. T. A., 2021, CTAO Instrument Response Functions - prod5 version v0.1, doi:10.5281/zenodo.5499840, https://doi.org/10.5281/zenodo.5499840
- Ong R. A., 2010, The Astronomer's Telegram, **2968**, 1
- Paczynski B., 1992, *Acta Astron.*, **42**, 145
- Page K. L., et al., 2022, *MNRAS*, **514**, 1557
- Papitto A., Torres D. F., 2015, *ApJ*, **807**, 33
- Papitto A., de Martino D., 2022, in Bhattacharyya S., Papitto A., Bhattacharya D., eds, Astrophysics and Space Science Library Vol. 465, Astrophysics and Space Science Library. pp 157–200 (arXiv:2010.09060), doi:10.1007/978-3-030-85198-9_6
- Papitto A., et al., 2013, The Astronomer's Telegram, **5069**, 1
- Paredes J. M., et al., 2013, *Astroparticle Physics*, **43**, 301
- Patruno A., et al., 2014a, *ApJ*, **781**, L3
- Patruno A., et al., 2014b, *ApJ*, **781**, L3
- Piano G., et al., 2012, *A&A*, **545**, A110
- Piano G., Munar-Adrover P., Verrecchia F., Tavani M., Trushkin S. A., 2017, *ApJ*, **839**, 84
- Prokhorov D. A., Moraghan A., 2023, *MNRAS*, **519**, 2680
- Rajwade K., et al., 2020, in Evans C. J., Bryant J. J., Motohara K., eds, Society

- of Photo-Optical Instrumentation Engineers (SPIE) Conference Series Vol. 11447, Ground-based and Airborne Instrumentation for Astronomy VIII. p. 114470J ([arXiv:2103.08410](#)), doi:10.1117/12.2559937
- Rasul K., Chadwick P. M., Graham J. A., Brown A. M., 2019, *MNRAS*, **485**, 2970
- Reid M. J., Miller-Jones J. C. A., 2023, *ApJ*, **959**, 85
- Roberts O. J., et al., 2021, *Nature*, **589**, 207
- Romero G. E., Vieyro F. L., Chaty S., 2014, *A&A*, **562**, L7
- Roy J., et al., 2015, *ApJ*, **800**, L12
- Rudak B., Dyks J., 1998, *MNRAS*, **295**, 337
- Russell T. D., Soria R., Motch C., Pakull M. W., Torres M. A. P., Curran P. A., Jonker P. G., Miller-Jones J. C. A., 2014, *MNRAS*, **439**, 1381
- Sabatini S., et al., 2010, *ApJ*, **712**, L10
- Sabatini S., et al., 2013, *ApJ*, **766**, 83
- Schaefer B. E., 2019, in American Astronomical Society Meeting Abstracts #234. p. 122.07
- Schaefer B. E., 2023, *MNRAS*, **524**, 3146
- Schaefer B. E., Pagnotta A., Zoppelt S., 2022, *MNRAS*, **512**, 1924
- Schaefer B. E., Kloppenborg B., Waagen E. O., Observers T. A., 2023, The Astronomer's Telegram, **16107**, 1
- Siebert T., et al., 2016, *Nature*, **531**, 341
- Stappers B. W., et al., 2014, *ApJ*, **790**, 39
- Striani E., et al., 2013, *ApJ*, **765**, 52
- Sun X.-N., Yang R.-Z., Liu B., Xi S.-Q., Wang X.-Y., 2019, *A&A*, **626**, A113
- Svinkin D., et al., 2021, *Nature*, **589**, 211
- Takata J., et al., 2014, *ApJ*, **785**, 131
- Tatischeff V., Hernanz M., 2007, *ApJ*, **663**, L101
- Tavani M., et al., 2009, *Nature*, **462**, 620
- Tavani M., et al., 2011, *Science*, **331**, 736
- Tavani M., et al., 2021, *Nature Astronomy*, **5**, 401
- Tavani M., F. Addis A., Argan A., 2024, The Astronomer's Telegram, 16450
- Tetarenko B. E., Sivakoff G. R., Heinke C. O., Gladstone J. C., 2016, *ApJ Supplement Series*, **222**, 15
- Thorstensen J. R., Armstrong E., 2005, *AJ*, **130**, 759
- Torres D. F., Rea N., Esposito P., Li J., Chen Y., Zhang S., 2012, *ApJ*, **744**, 106
- Torres D. F., Ji L., Li J., Papitto A., Rea N., de Oña Wilhelmi E., Zhang S., 2017, *ApJ*, **836**, 68
- Trimble V., 1973, *PASP*, **85**, 579
- Veledina A., et al., 2024a, *Nature Astronomy*, **8**, 1031
- Veledina A., et al., 2024b, *A&A*, **688**, L27
- Wei J., et al., 2016, *arXiv e-prints*, p. arXiv:1610.06892
- Weisskopf M. C., et al., 2013, *ApJ*, **765**, 56
- Weng S.-S., et al., 2022, *Nature Astronomy*, **6**, 698
- Xing Y., Wang Z., 2015, *The Astrophysical Journal*, **808**, 17
- Xing Y., Wang Z., Zhang X., Chen Y., Jithesh V., 2019, *ApJ*, **872**, 25
- Yaron O., Prialnik D., Shara M. M., Kovetz A., 2005, *ApJ*, **623**, 398
- Yusifov I., Küçük I., 2004, *A&A*, **422**, 545
- Zabalza V., 2015, in 34th International Cosmic Ray Conference (ICRC2015). p. 922 ([arXiv:1509.03319](#)), doi:10.22323/1.236.0922
- Zanin R., Fernández-Barral A., de Oña Wilhelmi E., Aharonian F., Blanch O., Bosch-Ramon V., Galindo D., 2016, *A&A*, **596**, A55
- Zdziarski A. A., Sikora M., Dubus G., Yuan F., Cerutti B., Ogorzałek A., 2012, *MNRAS*, **421**, 2956
- Zdziarski A. A., Mikolajewska J., Belczynski K., 2013, *MNRAS*, **429**, L104
- Zdziarski A. A., Pjanka P., Sikora M., Stawarz L., 2014, *MNRAS*, **442**, 3243
- Zdziarski A. A., Malyshev D., Chernyakova M., Pooley G. G., 2017, *MNRAS*, **471**, 3657
- Zdziarski A. A., et al., 2018, *MNRAS*, **479**, 4399
- Zheng J.-H., Huang Y.-Y., Zhang Z.-L., Zhang H.-M., Liu R.-Y., Wang X.-Y., 2022, *Phys. Rev. D*, **106**, 103011
- Zhu W., Wang B., Zhou D., et al., 2020, The Astronomer's Telegram, **14084**, 1
- de Martino D., et al., 2010, *A&A*, **515**, A25
- van Scherpenberg J., Mirzoyan R., Vovk I., Peresano M., Zaric D., Temnikov P., Godinović N., Besenrieder J., 2019, in 36th International Cosmic Ray Conference (ICRC2019). p. 812 ([arXiv:1909.04356](#))

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