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# Results of the historical observations of the microquasar Cygnus X-3 with the MAGIC telescopes

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Cygnus X-3 is a microquasar consisting of a compact object of unknown nature and a Wolf-Rayet star, which orbit each other with a very short period of 4.8 hours. The compact object launches powerful jets that are an excellent site for particle acceleration up to relativistic energies. The presence of these relativistic particles, combined with the proximity to the star and its high luminosity, make the conditions in the source very favorable for inverse Compton scattering of stellar photons by the jet electrons, resulting in gamma-ray emission. Cygnus X-3 has been detected in a broad frequency range, from radio to gamma rays above 100 MeV, although it has never been confirmed as a very-high-energy (VHE, above 100 GeV) gamma-ray emitter. Studies of microquasars in gamma rays have recently become a hot topic in the community after the LHAASO detection of four microquasars above 100 TeV, establishing these sources as potential contributors to the Galactic cosmic-ray spectrum at energies above the PeV. Due to the scientific interest of the source, the MAGIC telescopes have observed Cygnus X-3 in the VHE band since they became operational. In this contribution, we will present a long-term analysis of 130 h collected by MAGIC between 2013 and 2024. This represents the largest available dataset (in both exposure and time coverage) at VHE to date, resulting in the strongest VHE upper limits of the source between 100 GeV and a few TeV. Both the temporal and spectral constraints of Cygnus X-3 during this 11-year period will be interpreted within the multi-wavelength context, providing meaningful constraints on the source properties based on its (lack of) emission in gamma rays at different energies.

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## 1. Introduction

Microquasars (MQs) are binary systems composed of a compact object that accretes matter from a stellar companion and generates relativistic jets [1]. The recent observation of ultra-high-energy (UHE, E > 100 TeV) gamma-ray emission from MQs [2–4] indicates that accreting black holes and their surrounding environments are capable of accelerating particles with remarkable efficiency, reaching energies up to and exceeding 1 PeV.

Cygnus X-3 is a microquasar located at a distance of 9.7 ± 0.5 kpc [5], with an orbital period of 4.8 hours [6]. The exact nature of its compact object remains uncertain, as the estimated mass is consistent with both a black hole and a neutron star (see e.g., [7]). The donor star in the system is a Wolf-Rayet (WR) star with a mass in the range of 8–14 $M_\odot$ [8, 9], making Cygnus X-3 the only known MQ with a companion of this type [10]. The system occasionally experiences intense radio flares, with fluxes reaching several tens of Jy e.g., [11], making it the brightest MQ in the radio band. Unlike most MQs, Cygnus X-3 exhibits powerful jet activity even during the soft X-ray spectral state, typically around 50 days after transitioning from the hard state [12]. Additionally, the radio/X-ray correlation deviates from the behavior observed in other MQs, suggesting that a more refined classification of accretion states is necessary for this source [13].

*Fermi*–LAT has consistently detected Cygnus X-3 in high-energy (HE; $E > 100$ MeV) gamma rays, with emission extending up to tens of GeV [14]. This radiation is understood to result from inverse Compton scattering, where photons from the Wolf-Rayet companion interact with high-energy electrons in the jet [15]. Observations at very-high-energy (VHE; $E > 100$ GeV) gamma rays have been conducted with MAGIC [16] and VERITAS [17], but no significant emission has been detected to date. The small orbital separation and high luminosity of the companion star provide favorable conditions for VHE gamma-ray production via Inverse Compton processes, making the lack of detection particularly intriguing. One plausible explanation is that these same environmental conditions also lead to significant gamma-ray absorption through pair production with stellar photons e.g., [18]. Notably, LHAASO has reported an excess of VHE and UHE gamma rays originating from a $\sim 6°$ region known as the Cygnus Bubble, which includes Cygnus X-3 as well as other established gamma-ray sources [19]. This excess includes two photons with energies exceeding 1PeV consistent with the position of Cygnus X-3; if this association is confirmed, it would establish the system as an extreme particle accelerator.

In this work, we present the results of 12 years of observations of Cygnus X-3 with the MAGIC telescopes. In Sec. 2, the observations and data analysis methods are described. The results obtained for the analysis of Cygnus X-3 are presented in Sec. 3. A summary of the work and future analysis steps are collected in Sec. 4.

## 2. Observations

The Major Atmospheric Gamma-ray Imaging Cherenkov (MAGIC) telescopes [20] consist of two imaging atmospheric Cherenkov telescopes located at the Roque de los Muchachos Observatory on the Canary Island of La Palma (28°45′22″ N, 17°53′30″ W), at an altitude of 2200 m above sea level. Each telescope has a diameter of 17 meters and is equipped with a photomultiplier camera providing a field of view of approximately 3.5°. In their standard operational mode, the MAGIC



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**Table 1:** Monthly distribution of the MAGIC observations of Cygnus X-3 analysed for this work. The depicted observation times are after data-quality selection.

| Year | Obs. time (h) | Zenith angles (°) |
|---|---|---|
| 2013 | 1.3 | 31 – 49 |
| 2014 | 9.9 | 11 – 58 |
| 2015 | 2.1 | 12 – 47 |
| 2016 | 53.4 | 11 – 52 |
| 2018 | 8.3 | 11 – 37 |
| 2019 | 12.3 | 11 – 51 |
| 2020 | 22.5 | 12 – 44 |
| 2021 | 3.1 | 29 – 50 |
| 2024 | 16.8 | 12 – 58 |
| Total | 129.7 | 11 – 58 |

telescopes are designed to detect Cherenkov light produced by electromagnetic air showers initiated by gamma rays, covering an energy range from roughly 50 GeV to beyond 50 TeV.

MAGIC has been observing Cygnus X-3 since 2006. Observations were carried out in single-telescope (mono) mode until 2010; since then, the system has operated in stereo mode. In this work, we analyze the data collected in stereo mode between November 26, 2013 (MJD 56622), and August 8, 2024 (MJD 60530), accounting to a total of 190 hours of observations. After applying quality cuts to remove suboptimal data, 129.7 hours of effective exposure remained, covering zenith angles up to 58°. A summary of the annual observation times is provided in Table 1.

The data analysis was carried out using the MAGIC Reconstruction Software (`MARS`) [21], following the standard procedure for point-like sources described in [22]. Observations were conducted in the so-called wobble mode [23], in which the camera center is alternated every 20 minutes among four different positions, each offset by 0.4° from the position of Cygnus X-3. This observation strategy enables background estimation from regions in the camera that are symmetric with respect to the source location.

The significance of the source detection was calculated following the method described by [24]. To estimate the background, an exclusion mask was applied around the position of the known VHE emitter TeV J2032+4130 [25], located 0.5° from Cygnus X-3.

## 3. Results

Figure 1 shows the $\theta^2$ plots for the observed time after quality cuts with MAGIC for each of the three energy cuts allowed by the analysis. The resulting significances of the source are 0.90 $\sigma$ for lower energies, 0.25 $\sigma$ for medium energies and 1.76 $\sigma$ for higher energies [1]. Therefore, no detection of the source can be confirmed in any energy range. Nevertheless, there seems to be a

[1]These energy cuts are dependent on several parameters of the analysis. As an approximation, lower energies refer to energies greater than 100 GeV, medium energies to E $\gtrsim$ 250 GeV and higher energies to E $\gtrsim$ 1 TeV

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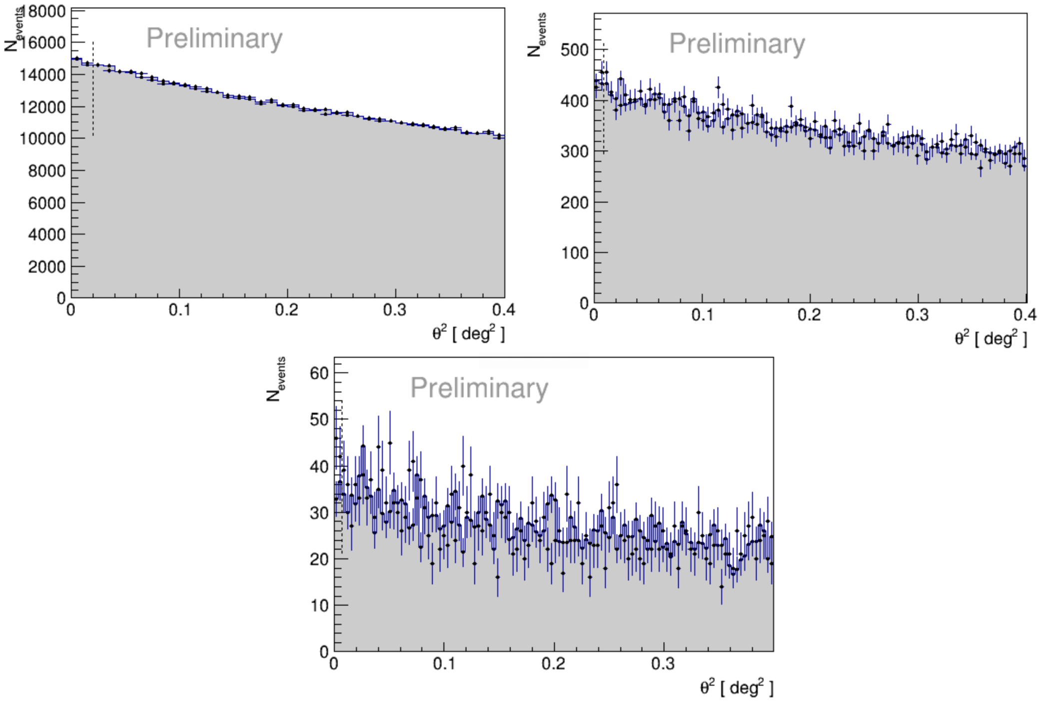


**Figure 1:** Cygnus X-3 $\theta^2$ plots for the total observed time obtained with MAGIC. Top left at lower energies, top right at midium energies and bottom at higher energies. Per each of the $\theta^2$ bins, the gray bars represent the average number of off counts in each of the off wobble regions and the blue dots the counts on region counts. The source region (for a point-like source in this case) is represented by the vertical black dashed line.

higher signal excess for higher energies. However, the excess in the number of photons is compatible with fluctuations of the background and/or the signal region.

Fig. 2 shows the 95% confidence level upper limits (ULs) for the differential flux of Cygnus X-3 in the energy range of the analysis. We can see that the ULs obtained decrease towards higher energies. For comparison, the values obtained by [16] for Cygnus X-3 in 2010 are also represented in brown in Fig. 2. Comparing both results, it is appreciable that the results obtained in this work have a lower energy threshold than the ones from the previous observations. This is due to the fact that the observations analyzed in this work were performed in stereo mode, i.e. with two operating telescopes, which allowed us to have a 96.4 GeV threshold versus the 199 GeV limit from 2010 obtained with one single telescope (mono observations). In addition, it is also noticeable that the ULs are lower, and therefore more constraining than the ones in the bibliography. This is given by the difference in observed time for both analysis, 129.7 h studied in this work versus 56.7 h in the other study and by the fact that the observations prior to 2010 were performed with one single telescope (mono observations) while from 2010 they were carried out with two telescopes (stereo mode).

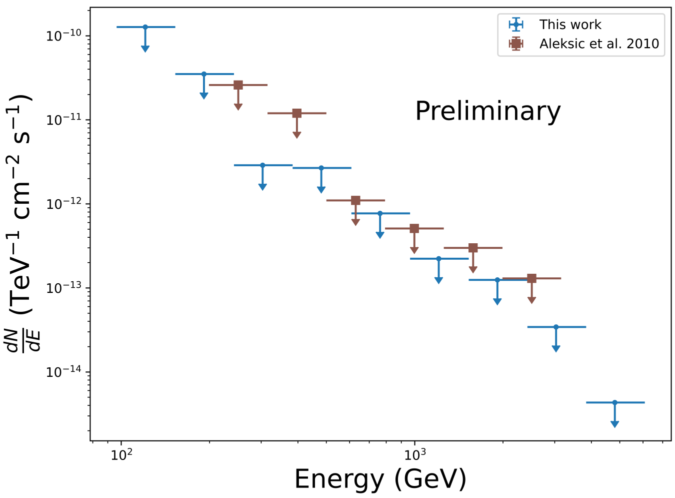


**Figure 2:** Cygnus X-3 differential flux upper limits obtained with MAGIC. The results obtained in this work are represented in blue, while the ones obtained by [16] are represented in brown.

## 4. Summary

We have studied 129.7 hours of Cygnus X-3 observations under good conditions with the MAGIC telescopes. Results show no detection of the source (0.90, 0.25 and 1.76 sigma for lower, medium and higher energies, respectively) after analyzing the data following the standard procedure for a point-like source. A modest excess (1.76 $\sigma$) is observed at higher energies. Differential flux ULs are also derived for these data. Even though there is no source detection, the ULs computed in this work are the most constraining ones up to date for Cygnus X-3 at VHE, as seen by the comparison with previous observations. Further studies of Cygnus X-3 properties based on orbital phase are under development.

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