Search for VHE signals from microquasars with MAGIC

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Abstract: Microquasars are accreting binary systems displaying relativistic radio jets where very high energy gamma rays might be produced via Inverse Compton scattering. The detection of the microquasar Cygnus X-3 above 100 MeV by both Fermi/LAT and AGILE satellites, together with the short flares from Cygnus X-1 reported by AGILE, confirmed that this class of astrophysical objects are interesting candidates for very high energy gamma-ray observations. The stand-alone imaging atmospheric Cherenkov MAGIC telescope, and later on the recently inaugurated stereoscopic system, made a significant effort to search for signals from microquasars. This paper reviews all MAGIC results of Cygnus X-3, Cygnus X-1, Scorpius X-1, and SS 433 observations. The stand-alone MAGIC telescope observed Cygnus X-3 for almost 60 hrs from March 2006 until August 2009 in many different X-ray spectral states where a very high energy emission is predicted and also simultaneously with a flux enhancement at high energies detected by Fermi/LAT. No significant signal was found in any of the observed conditions. The MAGIC stereoscopic system pointed at the Z-type low-mass X-ray binary Scorpius X-1 in May 2010 for 8 hrs. Simultaneous soft X-ray measurements allowed to define the X-ray spectral state of the source which could emit very-high-energy photons in the horizontal branch. MAGIC did not detect the source and put some constraints on the maximum TeV luminosity to jetpower ratio. Further observations of Cygnus X-1 were also carried out with the new and twice as sensitive stereoscopic system in Autumn 2009 for a total amount of 30 hrs. Finally, we also report on SS 433 observations obtained during two periods of minimum absorption processess from the accretion disk.

Keywords: microquasars, binary systems, MAGIC telescopes, very-high-energies

1 Introduction

Microquasars are X-ray binaries which display collimated relativistic jets at radio frequencies [1]. They consist of an accreting compact object, either a black hole or a neutron star, and a companion star. Depending on the mass of the companion, X-ray binaries are classified as high-mass (HMXBs) and low-mass (LMXBs) X-ray binaries.

It has been proposed that particles accelerated in the relativistic ejections might produce $\gamma$-ray emission via Inverse Compton (IC) scattering [2]. In the case of HMXBs, the massive and luminous stellar companion produces an intense target photon field for the IC scattering. However, this photon field could also absorb the produced $\gamma$-rays through pair production making the detection of the source at very high energies (VHEs) very difficult. This absorption effect is almost negligible for the LMXBs, but the IC scattering is less efficient. Nevertheless, the recent detection of the microquasar Cygnus X-3 above 100 MeV by both Fermi/LAT and AGILE satellites [3] [4], and the claim of short flares from Cygnus X-1 reported by AGILE [5] confirmed the microquasars as interesting target for Very-High-Energy (VHE) astrophysics.

The MAGIC telescopes, with their low energy thresholds below 100 GeV, are the best instrument among the current generation of imaging atmospheric Cherenkov telescopes (IACTs) to search for VHE signals from microquasars. MAGIC organized several observation campaigns of good microquasar candidates such as Cygnus X-3, Scorpius X-1, SS 433, and Cygnus X-1. These observations were carried out since 2006 and they will be described in detail in the next sections.

1.1 The MAGIC telescopes

MAGIC consists of two 17 m diameter imaging atmospheric Cherenkov telescopes (IACTs) located in the Canary island of La Palma, Spain (2200 m above sea level). It
became a stereoscopic system in Autumn 2009. The stereoscopic observation mode led to a significant improvement in the instrument performance [6]. The current sensitivity of the array yields $5 \sigma$ significance detections above 250 GeV of fluxes as low as 0.8% of the Crab Nebula flux in 50 hr. The energy threshold of the analysis lowered down to 50 GeV for low zenith angle observations.

The data analysis was performed by using the standard MAGIC analysis software, which is described in detail in [6].

2 Cygnus X-3

Cygnus X-3 is a microquasar [7] consisting of an accreting compact object of unknown nature and a Wolf-Rayet companion star [8]. This high-mass X-ray binary lies at a distance of 7 kpc, and has an orbital period of 4.8 hours [9]. Cygnus X-3 displays two main X-ray spectral states, which are similar to the canonical states of the black hole binaries [10]. The hard state (HS) is dominated by a non-thermal power-law emission peaking at 20 keV [11], whereas the soft state (SS) is characterized by a strong thermal component with a non-thermal tail. A finer classification of the spectral states was obtained by analyzing the correlation between X-ray and radio fluxes [12].

Cygnus X-3 was observed by the stand-alone MAGIC telescope for about 57 hours between March 2006 and August 2009. The results of these observations are described in more detail at [13], and will only be summarized here. These VHE observations where triggered by the source flux at other wavelengths. In 2006, MAGIC received two alerts of a flaring state at radio frequencies from the Russian RATAN-600 telescope, on March 10 and July 26, respectively. In 2007, a monitoring campaign of the hard state of Cygnus X-3 was planned. The X-ray spectral state of the source was defined by using public RXTE/ASM (1.5–12 keV) and Swift/BAT (15–50 keV) data, as follows: a) Swift/BAT daily count rate larger than 0.05 counts cm$^{-2}$ s$^{-1}$, and b) ratio between ASM and BAT count rates smaller than 200. During 2008 and 2009, MAGIC observed Cygnus X-3 following the two high-energy (HE) alerts issued by the AGILE team on April 18, 2008 and July 18, 2009, respectively.

The search for a time-integrated VHE emission from Cygnus X-3 was performed by combining all the available data. It yielded no significant excess events. The computed 95% confidence level (CL) upper limit (UL) to the integral flux is of $2.2 \times 10^{-12}$ photons cm$^{-2}$ s$^{-1}$ for energies above 250 GeV. It corresponds to 1.3% of the Crab Nebula flux at these energies.

Since the source is variable on time scales of days at other wavelengths, data from each day were analyzed separately. No signal was detected in of the observation nights. These daily integral flux ULs for energies above 250 GeV are shown in Figure 1 together with HE γ-ray (AGILE and Fermi/LAT [0.1–30 GeV]), hard X-ray (Swift/BAT [15–50 keV]), soft X-ray (RXTE/ASM [1.5–12 keV]) and radio measured fluxes from January 1, 2006 until December 15, 2009. This figure puts the MAGIC results in a multi-wavelength context allowing us to derive the X-ray spectral state of the source during MAGIC observations.

MAGIC pointed at Cygnus X-3 always when it was in its SS, except for the 2007 campaign when the HS was required by the observational trigger. The two 2006 observation campaigns, triggered by radio flares, started when the high-activity at radio frequencies had already ended, but still the source was in a SS. Also in April 2008, following an AGILE alert, MAGIC started its observations of Cygnus X-3 ten days after a huge radio flare and an enhanced HE activity period, when the source was still in the SS. The second AGILE alert was much more successful: MAGIC could take some data simultaneous with a HE peak emission, detected by both AGILE and Fermi/LAT [14, 15]. The HE flux enhancement seems to occur when the source is in its SS and is flaring at radio frequencies. The $\sim$4 hours of simultaneous data showed no significant VHE signal, yielding an integral flux at the level of 6% of the Crab Nebula flux.

Figure 2 shows the spectral energy distribution (SED) of Cygnus X-3 above 100 MeV for both the SS and the HE peak emission. The SED was computed by using the dif-
ferential flux MAGIC ULs, and the power-law spectra measured by both Fermi/LAT and AGILE with a photon index of 2.7 and 1.8, respectively (refer to [13] for further details). MAGIC ULs are compatible with the extrapolation of the Fermi/LAT power-law, but not with the AGILE extrapolation. The latter could suggest a spectrum cut-off between some tens of GeV and 250 GeV.

Simultaneous X-ray and VHE observations were carried out by MAGIC and RXTE/PCA in May 2010 for ~8 hours. Results have been published in detail in [17]. The X-ray data were used to study the source X-ray spectral state during MAGIC observations. The X-ray results are illustrated in Figure 3 [17]. During this campaign, the source practically covered the full double-banana-shaped track. The gray box in the figure indicates the data selected as HB. The analysis of the MAGIC data showed no significant signal either in the entire data sample, or in the HB state. Table 1 shows the obtained ULs above 300 GeV. The ULs to the integral flux in the HB state set an UL on the maximum TeV luminosity to jet power ratio of $10^{-3}$. This is a value similar to that obtained for Cygnus X-3. [13].

Table 1: Integral flux ULs for the different X-ray spectral states of Sco X-1.

| X-ray state | Effective time (hr) | UL (>30 GeV) (cm$^{-2}$ s$^{-1}$) | C.U. |
|-------------|---------------------|----------------------------------|------|
| All         | 7.75                | $2.4 \times 10^{-12}$            | 1.9% |
| HB          | 3.58                | $3.4 \times 10^{-12}$            | 2.7% |
| NB/FB       | 4.17                | $2.8 \times 10^{-12}$            | 2.3% |

3 Scorpius X-1

Sco X-1, located at $2.8 \pm 0.3$ kpc, is a prototype Z-type low-mass X-ray binary. It contains a neutron star orbiting around a M star every 0.787 d. Z sources show a strong variability in the X-ray intensity and colors in time scales of hours, and display a Z-shaped track in the a hard color versus soft color diagram (CD). Sometimes, the Z-track is better described by a double banana shape, such as for Sco X-1. Along this track different X-ray spectral states can be identified. They are known as Horizontal Branch (HB), Normal Branch (NB) and Flaring Branch (FB) [15]. Sco X-1 covers the whole track in a few tens of hours, spending roughly half of the time in the HB. Radio emission and a non-thermal power-law hard X-ray emission have been only detected when the source is in the HB [16]. These results indicate the presence of particle accretion up to VHEs, and suggest a possible production of VHE $\gamma$-rays via IC scattering in this spectral state.

4 Cygnus X-1

Cygnus X-1 is the prime example of a black hole microquasar. It shows the canonical X-ray HS and SS and a fast variability in different wavelengths at distinct timescales. Radio emission stays stable during the HS, and appears quenched during the SS [18]. Highly collimated jets were detected in VLBA radio images suggesting that the source
is a microblazar [19, 20].

MAGIC monitored Cygnus X-1 for ∼ 50 hrs in 2006, and found an evidence of signal at the level of 4.1σ (post-trial) on September 24th, 2006 [21]. The source was in the HS and in coincidence with a hard X-ray flare. Following this promising result, MAGIC observed the source for an additional 90 hrs between July 2007 and November 2009. The last campaign was performed with the stereoscopic system. However, no significant VHE signal was found in this sample.

5 SS433

SS433 is an eclipsing binary system containing a black hole orbiting every 13.1 days around a supergiant star. The system displays relativistic jets precessing with a period of 162.4 days in a cone of half opening angle of 21° [22]. The radio shell of W50 which surrounds the compact object is distorted by the jet precession. The latter extends in the east-west direction along the axis of the jet precession and shows X-ray diffuse lobes symmetrically displaced east and west of SS433 [23]. These lobs, also known as “ears”, present a knotty structure. The large jet and the diffuse non-thermal emission along the jet make the microquasar into a good candidate for VHE γ-ray emission. However, it is known that severe absorption effects produced by the strong accretion disk wind could be at work for about 80% of the precessing period [24].

MAGIC pointed towards SS 433 for 6 hrs in August 2008 and ∼10 hrs with the stereoscopic system in May and June 2010. These observations were carried out during precessional phases where the absorption of γ-rays should be at its lowest. In addition, the eclipsing companion which covers the jet inner region every ∼13 days was also avoided. MAGIC searched for VHE emission coming from both the central source and the “ears”, but no significant emission was found. The ULs to the integral flux at energies above 150 GeV are at the level of 1% (3.6 × 10^{-12} photons cm^{-2} s^{-1}) and 5% (2.1 × 10^{-11} photons cm^{-2} s^{-1}) of the Crab flux for the central source and the “ears” respectively.

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