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VERY HIGH ENERGY GAMMA-RAY RADIATION FROM THE STELLAR MASS BLACK HOLE BINARY CYGNUS X-1

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ABSTRACT

We report on the results from the observations in the very high energy band (VHE; $E_\gamma \geq 100$ GeV) of the black hole X-ray binary (BHXB) Cygnus X-1. The observations were performed with the MAGIC telescope, for a total of 40 hr during 26 nights, spanning the period between 2006 June and November. Searches for steady γ-ray signals yielded no positive result, and upper limits to the integral flux ranging between 1% and 2% of the Crab Nebula flux, depending on the energy, have been established. We also analyzed each observation night independently, obtaining evidence of γ-ray signals at the 4.0 σ significance level (3.2 σ after trial correction) for 154 minutes of effective on-time (EOT) on September 24 between 20:58 and 23:41 UTC, coinciding with an X-ray flare seen by *RXTE*, *Swift*, and *INTEGRAL*. A search for faster-varying signals within a night resulted in an excess with a significance of 4.9 σ (4.1 σ after trial correction) for 79 minutes EOT between 22:17 and 23:41 UTC. The measured excess is compatible with a pointlike source at the position of Cygnus X-1 and excludes the nearby radio nebula powered by its relativistic jet. The differential energy spectrum is well fitted by an unbroken power law described as $dN/(dA\,dt\,dE) = (2.3 \pm 0.6) \times 10^{-12}(E/1\ \text{TeV})^{-3.2 \pm 0.6}$. This is the first experimental evidence of VHE emission from a stellar mass black hole and therefore from a confirmed accreting X-ray binary.

Subject headings: acceleration of particles — binaries: general — gamma rays: observations — X-rays: individual (Cygnus X-1)

Online material: color figure

1. INTRODUCTION

Cygnus X-1 is the best established candidate for a stellar mass black hole (BH) and one of the brightest X-ray sources in the sky (Bowyer et al. 1965). Located at a distance of 2.2 ± 0.2 kpc, it is composed of a $21 \pm 8\ M_\odot$ BH turning around an O9.7 Iab companion of $40 \pm 10\ M_\odot$ (Ziółkowski 2005) in a circular orbit of 5.6 days with an inclination between 25° and 65° (Gies & Bolton 1986). The X-ray source is thought to be powered mainly by accretion and displays the canonical high/soft and low/hard X-ray spectral states, depending on the accretion rate (Esin et al. 1998). The thermal soft component is produced by the accretion disk close to the BH, whereas hard X-rays are thought to be produced by inverse Compton scattering of soft

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TABLE 1
CYGNUS X-1 OBSERVATION LOG

MJD (days)	T (minutes)	N_{excess} (events)	S (σ)	Post (σ)	U.L. [events (% CL)]
53,942.051	61.1	3.6 ± 4.8	0.8	<0.1	15.02(11.1)
53,964.887	105.6	4.8 ± 6.9	0.7	<0.1	21.49(9.2)
53,965.895	195.3	−13.2 ± 10.1	−1.3	<0.1	8.74(2.0)
53,966.934	124.8	9.4 ± 9.5	1.0	<0.1	33.07(11.9)
53,967.992	48.5	−9.0 ± 4.7	−1.7	<0.1	1.57(1.5)
53,968.883	237.5	−4.4 ± 11.6	−0.4	<0.1	22.76(4.3)
53,994.953	53.6	−4.0 ± 4.9	−0.8	<0.1	6.84(5.8)
53,995.961	58.1	−2.8 ± 4.6	−0.6	<0.1	7.76(6.0)
53,996.855	176.2	1.6 ± 9.1	0.2	<0.1	22.15(5.7)
53,997.883	132.7	5.2 ± 7.6	0.7	<0.1	22.95(7.8)
54,000.852	165.2	11.4 ± 9.7	1.2	<0.1	35.41(9.7)
54,002.875	154.4	36.8 ± 10.4	4.0	3.2	...
54,003.859	166.9	−7.0 ± 9.1	−0.8	<0.1	13.35(3.6)
54,004.891	123.3	−6.0 ± 7.9	−0.7	<0.1	11.33(4.1)
54,005.914	87.9	−2.2 ± 6.3	−0.3	<0.1	11.88(6.1)
54,006.938	28.0	5.4 ± 4.1	1.4	<0.1	15.26(24.6)
54,020.891	65.5	−8.6 ± 5.9	−1.4	<0.1	4.27(2.9)
54,021.887	68.6	−6.2 ± 5.7	−1.0	<0.1	6.30(4.1)
54,022.887	58.1	1.6 ± 5.9	0.3	<0.1	14.55(11.3)
54,028.863	68.6	3.4 ± 5.9	0.6	<0.1	18.28(12.0)
54,029.895	33.5	3.4 ± 5.1	0.7	<0.1	15.93(21.5)
54,030.863	19.6	−1.8 ± 3.0	−0.6	<0.1	5.41(12.5)
54,048.824	47.2	1.6 ± 5.7	0.3	<0.1	14.99(14.3)
54,049.824	47.9	−6.0 ± 5.4	−1.1	<0.1	6.09(5.7)
54,056.820	27.1	−5.2 ± 3.8	−1.3	<0.1	3.55(5.9)
54,057.820	21.5	1.2 ± 2.6	0.5	<0.1	7.96(16.7)

NOTE.—From left to right: Modified Julian Date of the beginning of the observation, total observation EOT, number of excess events, statistical significance of the excess, equivalent (*posttrial*) significance for 26 independent samples, and signal upper limit for the different observation nights. A cut SIZE > 200 photoelectrons (E_γ > 150 GeV) has been applied. Upper limits (Rolke et al. 2005) are at the 95% confidence level (CL) and are quoted in number of events and in units of the γ-ray flux measured for the Crab Nebula, assuming the Crab Nebula spectral slope ($\alpha = -2.6$).

photons by thermal electrons in a corona or at the base of a relativistic jet. The results from observations in the soft γ-ray range with COMPTEL (McConnell et al. 2002) and *INTEGRAL* (Cadolle Bel et al. 2006) strongly suggest the presence of a higher energy nonthermal component. In addition, fast episodes of flux variation by a factor between 3 and 30 have been detected at different timescales, ranging from milliseconds in the 3–30 keV band (Gierliński & Zdziarski 2003) to several hours in the 15–
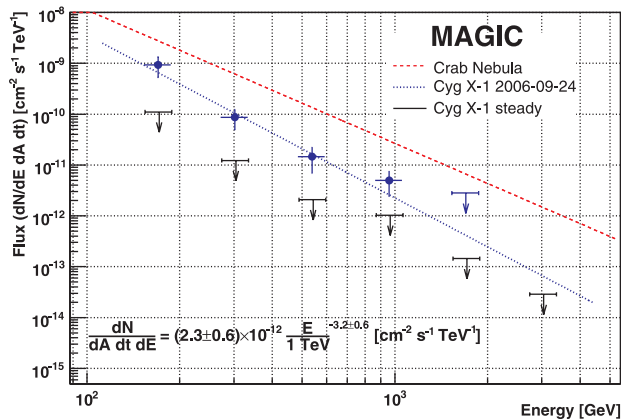

FIG. 1.—Differential energy spectrum from Cygnus X-1 corresponding to 78.9 minutes of EOT between MJD 54,002.928 and 54,002.987 (2006 September 24). Also shown are the Crab Nebula spectrum, the best fit of a power law to the data, and the 95% confidence level upper limits to the steady γ-ray flux (Rolke et al. 2005).
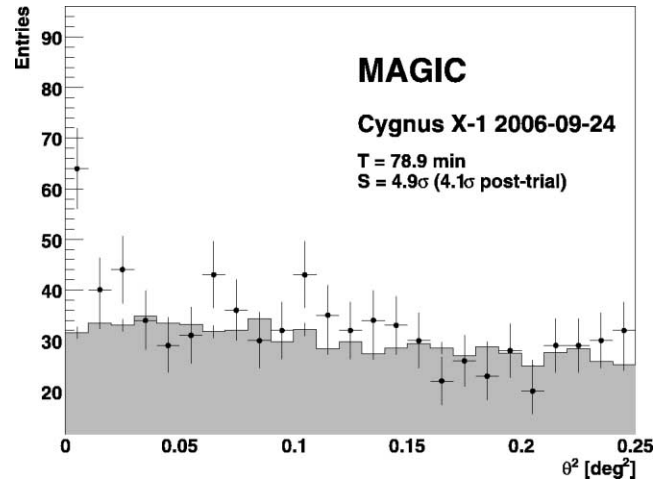

FIG. 2.—Distribution of θ^2-values for the source (*points*) and background (*histogram*) for an energy threshold of 150 GeV. [*See the electronic edition of the Journal for a color version of this figure.*]

300 keV band (Golenetskii et al. 2003). Radio emission stays at a rather stable level during the low/hard state, except for rarely observed flares (Fender et al. 2006), and appears to be quenched below a detectable level during the high/soft state (Brocksopp et al. 1999). On the other hand, VLBA images have shown the presence of a one-sided, elongated radio structure (15 mas length) during the hard state (Stirling et al. 2001), indicating the presence of a highly collimated (opening angle <2°) relativistic ($v \geq 0.6c$) jet. Romero et al. (2002) have suggested that Cygnus X-1 is a microblazar, where the jet axis is roughly aligned with the line of sight. The interaction of the outflow from the jet with the interstellar medium appears to produce a large-scale (~5 pc diameter), ringlike, radio-emitting structure (Gallo et al. 2005),
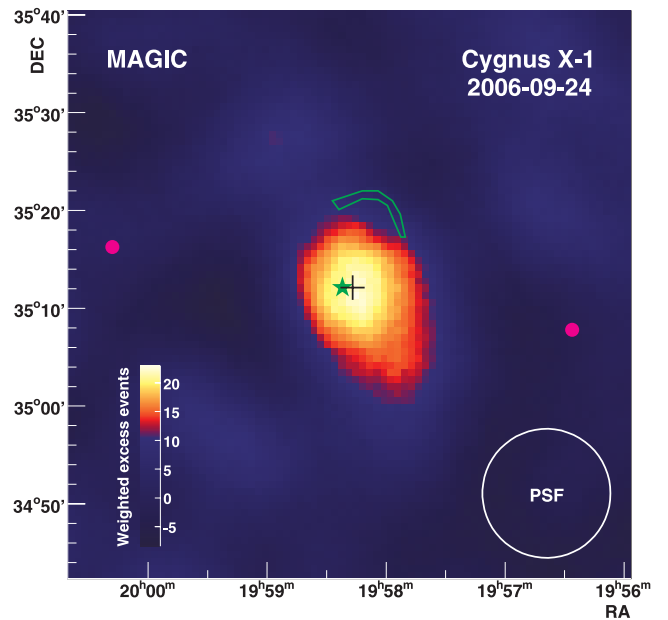
FIG. 3.—Gaussian-smoothed ($\sigma = 4'$) map of γ-ray excess events (background-subtracted) above 150 GeV around Cygnus X-1 corresponding to 78.9 minutes of EOT between MJD 54,002.928 and 54,002.987 (2006 September 24). The black cross shows the best-fit position of the γ-ray source. The position of the X-ray source and the radio-emitting ringlike structure are marked by the green star and contour, respectively. The purple circles mark the directions tracked during the observations. Note that the bin contents are correlated due to the smoothing.
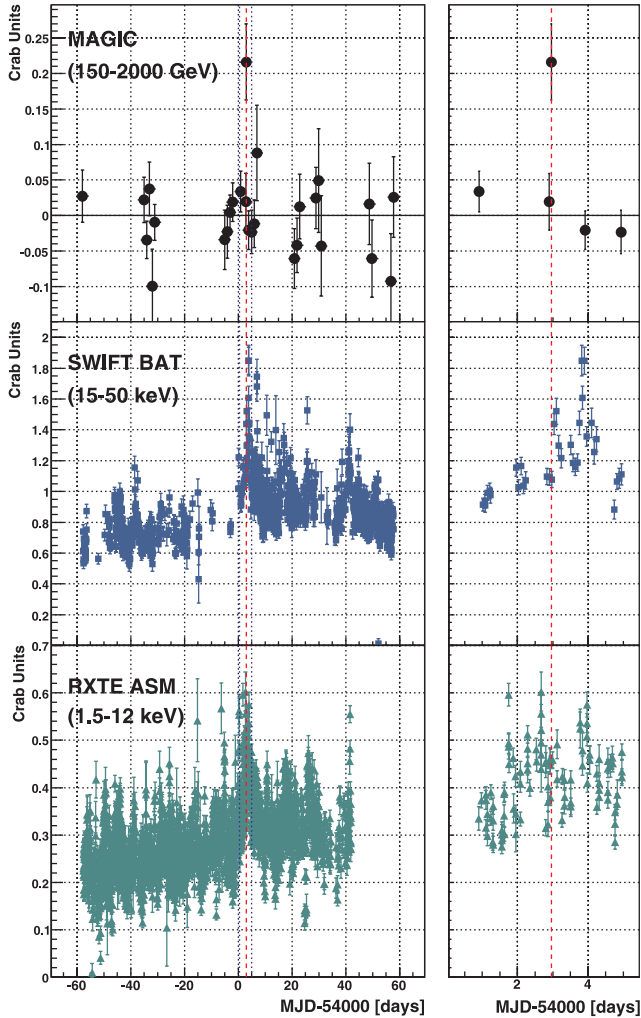
Fig. 4.—*From top to bottom*: MAGIC, *Swift*/BAT (from http://swift.gsfc.nasa .gov/docs/swift/results/transients/), and *RXTE*/ASM (from http://heasarc.gsfc.nasa .gov/xte_weather/) measured fluxes from Cygnus X-1 as a function of time. The left panels show the whole time spanned by MAGIC observations. The vertical, dotted blue lines delimit the range zoomed in the right panels. The vertical, dashed red line marks the time of the MAGIC signal.

which implies that most of the energy from the system is released by a radiatively inefficient relativistic jet.

Three other binary systems have been detected so far in the VHE domain, namely, PSR B1259−63 (Aharonian et al. 2005a), LS I +61 303 (Albert et al. 2006a), and LS 5039 (Aharonian et al. 2005b). In PSR B1259−63, the TeV emission is thought to be produced by the interaction of the relativistic wind from a young nonaccreting pulsar with the relativistic wind from a companion star. Recent results suggest that LS I +61 303 also contains a nonaccreting neutron star (Dhawan et al. 2006), while the situation is not yet clear in the case of LS 5039. As of now, there is no experimental evidence of VHE emission from any Galactic BHXB system.

In this Letter we report on the—to our knowledge—first results of observations of Cygnus X-1 in the VHE regime, performed with the Major Atmospheric Gamma Imaging Cerenkov (MAGIC) telescope. Our results pose a stringent upper limit to the steady VHE flux and include evidence of an intense, fast flaring episode occurring in coincidence with an X-ray flare. We briefly describe the observations and data analysis,

derive the spatial and spectral features of the observed excess, and discuss the obtained results.

2. OBSERVATIONS AND RESULTS

The BHXB Cygnus X-1 was observed with MAGIC for a total of 46.2 hr between 2006 June and November. MAGIC is an imaging atmospheric Cerenkov telescope (IACT) located at La Palma (Canary Islands, Spain), at 28.8°N, 17.8°W, 2200 m above seal level. The telescope's sensitivity is ∼2% of the Crab Nebula flux in 50 hr of observations. The angular resolution is ∼0.1°, and the energy resolution above 150 GeV is about 20%. MAGIC can provide γ-ray source localization in the sky with a precision of ∼2′ and is able to observe under moderate moonlight or twilight conditions (Albert et al. 2007). At La Palma, Cygnus X-1 culminates at a zenith angle of 5°, and the observations were carried out at zenith angles between 5° and 35°. The brightest object in the Cygnus X-1 field of view is the 3.89 mag, K0 spectral-type star η Cygni, located 26′ away from Cygnus X-1. The observations were carried out in the false-source track (wobble) mode (Fomin et al. 1994), with two directions at 24′ distance and at opposite sides of the source direction. This technique allows for a reliable estimation of the background, with no need of extra observation time. One of the tracked directions corresponds roughly to that of η Cygni, which reduces the effect of the star in the data analysis.

Data corresponding to 46.2 hr from 26 nights of observation were analyzed using the standard MAGIC calibration and analysis software (Albert et al. 2006b; Gaug et al. 2005). Data runs with anomalous event rates (6.2 hr) were discarded for further analysis, leading to a total of 40.0 hr of useful data (see Table 1 for details). Hillas variables (Hillas 1985) were combined into an adimensional γ/hadron discriminator (*hadronness*) and an energy estimator by means of the Random Forest classification algorithm, which takes into account the correlation between the different Hillas variables (Breiman 2001; Bock et al. 2004). The incoming direction of the primary γ-ray events was estimated using the DISP method, suited for observations with a single IACT (Fomin et al. 1994; Domingo-Santamaría et al. 2005). These algorithms were trained with a sample of Monte Carlo–simulated γ-ray events (Majumdar et al. 2005) and optimized on 3.7 hr of observations of the Crab Nebula performed during the same epoch at similar zenith angles (12°– 32°), yielding the following signal selection cuts: hadronness < 0.1 and $\theta < 0.1°$ (where θ is the angular distance to the source position). The residual background was evaluated from five circular control regions, located symmetrically to the source position with respect to the camera center. For daily searches, we increase the sample for background estimation by adding control regions corresponding to close days, obtaining, on average, 22 times higher statistics than is found in the on-source region.

A search for steady γ-ray signals was performed for the entire recorded data sample, yielding no significant excess. This allows us to establish the first upper limits to the VHE γ-ray steady flux of Cygnus X-1 in the range between 150 GeV and 3 TeV (see Fig. 1), of the order of 1%–5% of the Crab Nebula flux. Given the timescale of the variability of Cygnus X-1 at other energy bands, γ-ray signals are also searched for on a daily basis. The results are shown in Table 1. We obtain results compatible with background fluctuations at a 99% CL for all the searched samples, except for MJD = 54,002.875 (2006 September 24). We derive upper limits to the integral flux above 150 GeV between 2% and 25% of the Crab Nebula flux (depending basically on the observation time) for all samples compatible with background fluctuations. The data from 2006 Sep-

tember 24 were further subdivided into two halves to search for fast-varying signals, obtaining 0.5 σ and 4.9 σ effects for the first (75.5 minutes EOT starting at MJD 54,002.875) and second (78.9 minutes EOT starting at MJD 54,002.928) samples, respectively. The posttrial probability is conservatively estimated by assuming 52 trials (two per observation night) and corresponds to a significance of 4.1 σ. The sample corresponding to MJD 54,002.928 was further subdivided into halves, obtaining 3.2 σ and 3.5 σ excesses in each. At this point, we stopped the data split process.

The distribution of θ^2 for signal and background events corresponding to the 78.9 minutes EOT sample starting at MJD 54,002.928 is shown in Figure 2. The excess is consistent with a pointlike source located at the position of Cygnus X-1. The map of excess events around the source is shown in Figure 3. A Gaussian fit yields the location $\alpha = 19^h58^m17^s$, $\delta = 35°12'8''$ with statistical and systematic uncertainties 1.5′ and 2′, respectively, compatible within errors with the position of Cygnus X-1 and excluding the jet-powered radio nebula at a distance of ~8′. The energy spectrum is shown in Figure 1. It is well fitted (χ^2/dof = 0.5) by the following power law: $dN/(dA\,dt\,dE) = (2.3 \pm 0.6) \times 10^{-12}(E/1 \ \text{TeV})^{-3.2 \pm 0.6} \ \text{cm}^{-2} \ \text{s}^{-1} \ \text{TeV}^{-1}$, where the quoted errors are statistical only. We estimate the systematic uncertainty to be 35% on the overall flux normalization and 0.2 in the determination of the spectral index.

3. DISCUSSION

The excess from the direction of Cygnus X-1 occurred simultaneously with a hard X-ray flare detected by *INTEGRAL* (~1.5 crab between 20 and 40 keV and ~1.8 crab between 40 and 80 keV; Türler et al. 2006), *Swift*/BAT (~1.8 crab between 15 and 50 keV), and *RXTE*/ASM (~0.6 crab between 1.5 and 12 keV). Figure 4 shows the correlation between MAGIC, *Swift*/BAT, and *RXTE*/ASM light curves. The TeV excess was observed at the rising edge of the first hard X-ray peak, 1–2 hr before its maximum, while there is no clear change in soft X-rays. In addition, the MAGIC nondetection during the following night (yielding a 95% CL upper limit corresponding to a flux ~5 times lower than the one observed in the second half of 2006 September 24) occurred during the decay of the second hard X-ray peak. This phenomenology leads us to think that, during the 2006 September 24 night, soft and hard X-rays were produced in different regions. Furthermore, hard X-rays and VHE γ-rays could be produced in regions linked by the collimated jet, e.g., the X-rays at the jet base and the γ-rays at an interaction region between the jet and the stellar wind. These pro-cesses would have different physical timescales, thus producing a shift in time between the TeV and X-ray peaks. Note that the distance from the compact object to the TeV production region is constrained below 2′ by MAGIC observations, and therefore it is unrelated to the nearby radio-emitting ringlike structure (Gallo et al. 2005). A jet scenario, however, is not devoid of constraints either. The observed TeV excess took place at phase 0.91, with phase 1 being the moment when the BH is behind the massive star. At this phase, MAGIC observations are available only for the night of 2006 September 24, which precludes any possible analysis of a putative periodicity feature of the TeV emission. If the TeV emission were produced in the jet well within the binary system, the photon-photon absorption in the stellar photon field would be dramatic, making a TeV detection very unlikely. For instance, Bednarek & Giovannelli (2007) computed the opacity to pair production for different injection distances from the center of the massive star and from the angles of propagation, finding that photons propagating through the intense stellar field toward the observer would find in their way opacities of about 10 at 1 TeV. Admittedly, the inclination of the orbit and the angle of propagation to the observer can change these numbers, but not the fact that MAGIC observes the excess at the position where the expected opacity is highest. Therefore, even without an explanation for a TeV flare, we must consider that the emission could have originated far from the compact object. Interactions of the jet with the stellar wind may lead to such a situation.

In summary, for the first time we have found experimental evidence of VHE emission produced by a Galactic stellar mass BH. We have also found the first evidence of VHE gamma rays produced at an accreting binary system. Our results show that a possible steady VHE flux is below the present IACT's sensitivity and that tight upper limits have been derived. On the other hand, we have found evidence of an intense flaring episode during the inferior conjunction of the optical star, at a timescale shorter than 1 day and a rising time of about 1 hr, correlated with a hard X-ray flare observed by *Swift* and *INTEGRAL*. These results point to the existence of a whole new phenomenology in the young field of VHE astrophysics of binary systems to be explored by present and future IACTs.

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