

MAGIC CONSTRAINTS ON γ -RAY EMISSION FROM CYGNUS X-3

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ABSTRACT

Cygnus X-3 is a microquasar consisting of an accreting compact object orbiting around a Wolf-Rayet star. It has been detected at radio frequencies and up to high-energy γ rays (above 100 MeV). However, many models predict also a very-high-energy (VHE) emission (above hundreds of GeV) when the source displays relativistic persistent/transient ejections. Therefore, detecting such emission would improve the understanding of the jet physics. The imaging atmospheric Cherenkov telescope MAGIC observed Cygnus X-3 for about 70 hours between 2006 March and 2009 August in different X-ray/radio spectral states and also during a period of enhanced γ -ray emission. MAGIC found no evidence for a VHE signal from the direction of the microquasar. An

upper limit to the integral flux for energies higher than 250 GeV has been set to 2.2×10^{-12} photons $\text{cm}^{-2} \text{s}^{-1}$ (95% confidence level). This is the best limit so far to the VHE emission from this source. The non-detection of a VHE signal during the period of activity in the high-energy band sheds light on the location of the possible VHE radiation favoring the emission from the innermost region of the jets, where absorption is significant. The current and future generations of Cherenkov telescopes may detect a signal under precise spectral conditions.

Subject headings: acceleration of particles — binaries: general — gamma rays: observations — X-rays: binaries — X-rays: individual (Cygnus X-3)

1. INTRODUCTION

Cygnus X-3 is a bright and persistent X-ray binary, discovered in 1966 (Giacconi *et al.* 1967), but the high-energy processes occurring in the source are still poorly understood. It lies close to the Galactic plane at a distance between 3.4 and 9.8 kpc, probably at 7 kpc, depending on different distance estimates to the Cygnus OB2 association (Ling *et al.* 2009). The nature and the mass of the compact object are still subject of debate. Published results suggest either a neutron star of $1.4 M_{\odot}$ (Stark & Saia 2003) or a black hole of less than $10 M_{\odot}$ (Hanson *et al.* 2000). The identification of its donor star as a Wolf-Rayet star (van Kerkwijk *et al.* 1992) classifies it as a high-mass X-ray binary. Nevertheless Cygnus X-3 shows a short orbital period of 4.8 hours, typical of the low-mass binaries, which has been inferred from the modulation of both the X-ray (Parsignault *et al.* 1972) and infrared emissions (Becklin *et al.* 1973).

Despite the strong X-ray absorption in this system, which may be caused by the wind of the companion star, the X-ray spectrum has been intensively studied. The source shows two main spectral X-ray states resembling the canonical states of the black hole binaries: the hard state (HS) and the soft state (SS) (Zdziarski & Gierlinski 2004; Hjalmarsdotter *et al.* 2008). The HS is characterized by a weak soft thermal component and a strong non-thermal power-law emission peaking at hard X-ray energies. Whereas the SS, though showing a non-thermal tail (Szostek *et al.* 2008), is dominated by the optically thick thermal disk emission. In Cygnus X-3, however, the HS displays a high-energy cut-off at ≈ 20 keV, significantly lower than the ≈ 100 keV value found for black hole binaries (Hjalmarsdotter *et al.* 2004; Zdziarski & Gierlinski 2004).

Adding to its peculiarity, Cygnus X-3 is the brightest radio source among the X-ray binaries, quite frequently exhibiting huge radio flares (as intense as few thousand times the quiescent emission level of ~ 20 mJy at 1.5 GHz, Braes & Miley 1972) first seen by Gregory *et al.* (1972). During these outbursts, which occur mainly when the source is in the SS and last several days, Cygnus X-3 reveals the presence of collimated relativistic jets (e.g. Martí *et al.* 2001; Mioduszewski *et al.* 2001; Geldzahler *et al.* 1983; Miller-Jones *et al.* 2004). Thus, Cygnus X-3 has been classified as a microquasar. Based on arcsecond-scale radio observations and their relation with soft X-ray emission, six X-ray/radio states have been identified: quiescent (flux densities ~ 100 mJy), minor flaring (< 1 Jy), suppressed (< 100 mJy), quenched (< 30 mJy), major flaring (> 1 Jy) and post-flaring (Szostek *et al.* 2008; Tudose *et al.* 2010; Koljonen *et al.* 2010). In the transition from the X-ray hard/radio quiescent state to the SS, the radio emission is strongly suppressed and if it reaches the quenched level the source usually produces a major radio flare (Waltman *et al.* 1994).

Cygnus X-3 has also historically drawn a great deal of attention due to numerous claims of detection at TeV and

PeV γ rays, using early-days detectors in these energy ranges (Vladimirsky *et al.* 1973; Danaher *et al.* 1981; Lamb *et al.* 1982; Dowthwaite 1983; Samorsky & Stamm 1983; Cawley *et al.* 1985; Chadwick *et al.* 1985; Bhat *et al.* 1986). However, a critical analysis of these observations raised doubts on their validity (Chardin & Gerbier 1989) and in recent years the more sensitive instruments have not confirmed those claims for energies above 500 GeV (Shilling *et al.* 2001; Albert *et al.* 2008a). Nevertheless, microquasars are believed to produce very high energy (VHE) emission inside the jets: high density and magnetic fields provided by the accretion disk and by the companion star create favorable conditions for effective production of γ rays (Levinson & Blandford 1996; Romero *et al.* 2003; Bosch-Ramon *et al.* 2006). This radiation could have either an episodic nature due to the ejection of strong radio-emitting blobs (Atoyan & Aharonian 1999), generally occurring in the SS in the case of Cygnus X-3 or a (quasi) stationary character being originated in the persistent compact jet present during the HS (Bosch-Ramon *et al.* 2006).

Using data from the Energetic Gamma-Ray Experiment Telescope (EGRET) detector aboard the Compton Gamma-Ray Observatory, Mori *et al.* (1997) reported an average flux of $(8.2 \pm 0.9) \times 10^{-7}$ photons $\text{cm}^{-2} \text{s}^{-1}$ at energies above 100 MeV coming from the direction of Cygnus X-3. However, no orbital modulation was detected in the signal, precluding a solid association. The experimental situation in the high-energy region has been drastically changed by the results recently published by *AGILE* (Tavani *et al.* 2009) and *Fermi/LAT* (Abdo *et al.* 2009). *AGILE* detected the source in five different moments, for a couple of days each, four of them corresponding to the peak emissions shown in the detailed *Fermi/LAT* light-curve (see below). The last detection, occurred in July 2009, has not been published yet by the *AGILE* collaboration (Bulgarelli *et al.*, in preparation). On the other hand, *Fermi/LAT* detected a clear signal from Cygnus X-3 above 100 MeV during two periods of enhanced activity lasting for several weeks and coinciding with the source being in the SS. The measured flux is variable and shows an orbital modulation, which confirms the origin of the signal from the microquasar. The *AGILE* flux level is comparable with the one of the *Fermi/LAT* flux peaks, as high as 2.0×10^{-6} photons $\text{cm}^{-2} \text{s}^{-1}$ above 100 MeV.

Observations of binary systems with imaging atmospheric Cherenkov telescopes (IACTs) in the VHE band have proven very fruitful in recent years, with the detection of the orbitally-modulated γ -ray emitters PSR B1259-63 (Aharonian *et al.* 2005a), LS 5039 (Aharonian *et al.* 2005b, 2006) and LS I +61 303 (Albert *et al.* 2006, 2008b, 2009; Acciari *et al.* 2008, 2009; Anderhub *et al.* 2009). However, these systems may be different from Cygnus X-3, since the radio and high-energy radiation could be produced in all three sources by the interaction of the winds of a star and an orbiting pulsar (Maraschi & Treves 1981; Tavani & Arons 1997; Dubus 2006). Nevertheless, Cygnus X-3 GeV γ -ray modulation presents some common features to those observed in

LS 5039 and LS I +61 303. On the other hand, although observations of other well-established microquasars, such as GRS 1915+105 (Acero et al. 2009; Saito et al. 2009), did not reveal any signal, there is an interesting possibility of VHE emission from Cygnus X-1 (Albert et al. 2007a), still to be confirmed by an independent detection. The origin of this possible emission has been speculated to be linked to a maximum of the X-ray super-orbital modulation of the system (Rico 2008). Moreover, there is also a claim by *AGILE* about a Cygnus X-1 detection during a short flare (Sabatini et al. 2010, ATel #2512), which, however, has not been corroborated by *Fermi*/LAT yet¹. Such experimental results endorsed by the theoretical predictions, have encouraged deeper observations of the black hole binaries in the VHE band.

This paper reports observations of Cygnus X-3 performed with the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescope between 2006 and 2009. All these observations were carried out with the first stand-alone MAGIC telescope, MAGIC phase I. Cygnus X-3 observations were planned to cover different X-ray/radio states, including those that showed a strong high-energy γ -ray flux. This allowed us to search for VHE emission, above 250 GeV, from Cygnus X-3 in the different cases for which this radiation is predicted in theoretical scenarios. In addition, specific analyses were performed to look for predicted features, such as periodic and variable emission. Section 2 describes the performance of MAGIC, and the observational strategy. The analysis chain is explained in section 3. The results obtained by MAGIC in a multi-wavelength context are reported in section 4. A brief discussion follows in section 5.

2. OBSERVATIONS

MAGIC (phase I) is an IACT located at the Canary Island of La Palma (Spain), at 28.8°N, 17.8°W, 2200 m above sea level. It is a 17 m diameter IACT with an energy threshold of 60 GeV (with the standard trigger). The collected Cherenkov light is focused on a multi-pixel camera composed of 576 photomultiplier tubes (PMTs).

The performance of the MAGIC telescope changed over the years. The largest improvement followed the upgrade of the 300 MHz readout system in 2007 February. The new multiplexed 2GHz flash analog-digital converters improved the time resolution of the recorded shower images and reduced the contamination of the night sky background (Aliu et al. 2009). Accordingly, the telescope integral flux sensitivity improved from $\approx 2.5\%$ to $\approx 1.6\%$ of the Crab Nebula flux for energies greater than 270 GeV in 50 hours of observations. At these energies, the angular and energy resolutions are $\approx 0.1^\circ$, and $\approx 20\%$, respectively. MAGIC can provide γ -ray point-like source localization in the sky with a precision of $\approx 2'$ (Albert et al. 2008c). It is able to observe under moderate moonlight or twilight conditions (Albert et al. 2007b; Britzger et al. 2009), which, causing an increase of the night sky background, can be monitored through the PMT anode direct currents (DC).

MAGIC pointed towards Cygnus X-3 for a total of 69.2 hours between 2006 March and 2009 August. Since the source is expected to be variable, the observations were triggered by its state at other wavelengths. In 2006, observations were prompted by flares at radio frequencies. The MAGIC collaboration received two alerts from the RATAN-600 tele-

TABLE 1
CYGNUS X-3 OBSERVATION LOG^a.

Obs. Cycle	Date (yyyy mm dd)	MJD	Eff. Time (h)	Zd ($^\circ$)	DC ^b (μ A)	Spectral ^c State
I	2006 03 23	53817	0.45	45–50	3.5	
	2006 03 24	53818	0.25	47–50	2.5	
	2006 03 26	53820	0.53	44–50	1.5	
	2006 03 28	53822	0.70	42–50	1.4	
	2006 03 30	53824	0.80	41–50	1.3	SS
	2006 03 31	53825	0.90	40–50	1.4	
	2006 04 01	53826	1.00	38–50	1.8	
	2006 04 02	53827	0.92	40–50	1.2	
	2006 04 03	53828	1.05	38–50	1.2	
II	2006 07 27	53943	3.10	12–34	1.2	
	2006 07 28	53944	2.53	12–31	1.1	
	2006 07 29	53945	1.73	12–20	1.2	SS
	2006 07 30	53946	1.36	12–20	1.1	
	2006 08 01	53948	0.92	12–20	1.4	
	2006 08 02	53949	1.88	12–19	1.2	
III	2007 07 06	54286	2.16	19–45	2.3	
	2007 07 07	54287	4.53	12–45	2.3	
	2007 07 08	54288	1.07	26–45	1.5	
	2007 07 09	54289	0.38	34–40	1.5	
	2007 07 14	54295	1.82	12–21	1.5	
	2007 07 15	54296	1.93	12–21	1.5	
	2007 07 16	54297	1.93	12–21	1.4	
	2007 07 24	54305	1.75	12–23	1.4	
	2007 07 26	54307	0.98	19–30	1.4	HS
	2007 07 27	54308	0.5	19–30	1.4	
	2007 08 04	54316	0.73	27–35	1.5	
	2007 08 06	54318	2.72	12–30	1.6	
	2007 08 07	54319	1.93	13–31	1.3	
2007 08 08	54320	1.58	14–31	1.4		
2007 09 03	54346	1.86	13–37	2.5		
IV	2008 04 28	54584	0.31	32–40	2.9	
	2008 04 29	54585	1.07	24–41	3.2	SS
	2008 04 30	54586	1.33	23–40	2.6	
V	2009 07 19	55031	3.48	12–36	1.2	
	2009 07 21	55033	2.21	14–42	1.2	
	2009 07 22	55034	1.63	12–27	1.1	SS
	2009 08 01	55044	1.81	17–39	1.5	
	2009 08 02	55045	0.88	27–41	1.6	

^aFrom left to right: observational cycle, date of the beginning of the observations, also in MJD, effective time after quality cuts, zenith angle range, the anode PMT DCs and the spectral state.

^bThe anode PMT DCs show the level of the moonlight conditions.

^cSpectral state was derived by using *Swift*/BAT and *RXTE*/ASM data.

scope on 2006 March 10 and on 2006 July 26 (Trushkin, private communication). Both radio flares had a X-ray counterpart: the source was in the SS according to *RXTE*/ASM and *Swift*/BAT measurements. In 2007, the observations were triggered using public *RXTE*/ASM (1.5–12 keV) and *Swift*/BAT (15–50 keV) data, as follows: a) *Swift*/BAT daily flux larger than 0.05 counts $\text{cm}^{-2} \text{s}^{-1}$ and b) ratio between *RXTE*/ASM and *Swift*/BAT count rates lower than 200. These criteria guaranteed the source to be in the HS. During 2008 and 2009, MAGIC observed Cygnus X-3 following high-energy γ -ray alerts issued by the *AGILE* satellite. The first of these alerts arrived in 2008 April 18, the second one in 2009 July 18 (Tavani, private communication). These last two campaigns occurred when the source was in the SS.

At La Palma, Cygnus X-3 culminates at a zenith angle of 12° . The observations were carried out at zenith angles between 12° and 50° . They were performed partially in on-off mode and in false-source tracking mode (wobble) (Fomin et al. 1994), the latter pointing to two directions at $24'$ distance and opposite sides of the source. The entire Cygnus X-3 data

¹ Preliminary results can be found at <http://fermisky.vlogspot.com/2010/03/lat-limit-on-cyg-x-1-during-reported.html>

set recorded by MAGIC amounts to 69.2 hours, out of which 12.5 hours² were rejected from further analysis because of their anomalous event rates, leading to a total of 56.7 hours of useful data distributed in 39 nights of observation. The details of the observations are quoted in Table 1.

3. DATA ANALYSIS

Data analysis was carried out using the standard MAGIC calibration and analysis software: once the PMT signal pulses are calibrated (Albert *et al.* 2008d), pixels containing no useful information for the shower image reconstruction are discarded. This is done by an image cleaning procedure which takes into account the amplitude and the timing information of the calibrated signals (Aliu *et al.* 2009). The constraints on the signal amplitude are increased in case of moonlight conditions, when the pixel DCs become larger than $2.5 \mu\text{A}$ (see Table 1). This higher image cleaning allows to use the standard Monte Carlo (MC) during the analysis of these data, without the need of any correction, as long as the average pixel DCs are below $4 \mu\text{A}$ (Britzger *et al.* 2009).

Afterwards, the surviving pixels are used to compute the Hillas event image parameters (Hillas 1985). In addition, Hillas and timing variables are combined into a single γ /hadron discriminator (*hadronness*) and an energy estimator by means of the Random Forest classification and regression algorithm, which takes into account the correlation between the different Hillas and timing variables (Breiman 2001; Albert *et al.* 2008e). These algorithms are trained with a sample of MC simulated γ -ray events and a sample of background events extracted from real data. The used timing variables allow an improvement of the analysis sensitivity of a factor 1.4 (1.2) in data recorded with the new ultra-fast (old 300 MHz) readout system (Aliu *et al.* 2009).

Images with a total charge below 200 photo-electrons were discarded from further analysis in order to homogenize the different data and MC samples and achieve a common stable energy threshold of all the analyses. The number of γ -ray candidates in the direction of the source is estimated by using the distribution of *alpha* angle (Hillas 1985), which is related to the shower orientation. The evaluation of the background depends on the data taking mode. For data taken in the on-off mode in which the signal data sample is called “on” data, the background is estimated using a different sample, called “off” data. The latter has a similar amount of data recorded during the same epoch as the “on” sample at similar zenith angles and atmospheric conditions with no known γ -ray source in the field of view. For the observations carried out in wobble mode the background is extracted from 3 circular control regions, located symmetrically to the source position with respect to the camera center.

The Cygnus X-3 data set extends over five different, one-year long cycles of observation, which are characterized by varying performances of the telescope. In addition, cycle I data were recorded in on-off mode, all the others in wobble mode, cycle IV data were taken under moderate moonlight conditions.

Each cycle of data was analyzed separately using the appropriate image cleaning procedure, and a matching sample of MC simulated γ -ray events. The analysis selection cuts, on

² 9.6 hours were rejected due to high-altitude Saharan dust (calima), which affects the atmosphere above Canary islands and is more intense during summer.

hadronness and *alpha*, for each cycle of data were obtained optimizing the sensitivity in a Crab Nebula sample and requiring at least 70% γ -ray selection efficiency. The selected Crab Nebula sample was recorded during the same cycle at similar zenith angles and in the same data taking mode.

All the analyses were then combined in order to calculate the integral flux upper limits (UL) for energies greater than 250 GeV, which is the energy threshold of each cycle of data. The obtained ULs at 95% confidence level (CL) were computed after Rolke *et al.* (2005) method assuming a Gaussian background and a 30% of systematic uncertainties in the flux level (Albert *et al.* 2008c). The spectrum was assumed to be Crab-like (Aharonian *et al.* 2004), with a photon index 2.6. However, a 30% change in the photon index yields a variation of less than 1% in the ULs.

4. RESULTS

A search for VHE γ -ray emission from Cygnus X-3 was performed separately for each cycle of observations. None of them yielded a significant excess. The combination of all the data samples yields a 95% CL upper limit to an integral flux of 2.2×10^{-12} photons $\text{cm}^{-2} \text{s}^{-1}$ for energies greater than 250 GeV. It corresponds to 1.3% of the Crab Nebula flux at these energies. The differential flux upper limits are shown in Table 2 and in Figure 1.

Given that Cygnus X-3 flux is variable at other energy bands on time scales of days, γ -ray signals were searched for also on a daily basis. No significant excess events were found in any observation night. The integral flux ULs for energies above 250 GeV are shown in Table 3 and in the top panel of Figure 2.

In Figure 2, MAGIC results are presented on a multi-wavelength context where the above-mentioned flux variability at different energy bands is rather clear. In particular, it displays daily MAGIC VHE integral ULs, and high-energy γ -ray (*AGILE* and *Fermi*/LAT [0.1–30 GeV]), hard X-ray (*Swift*/BAT [15–50 keV]), soft X-ray (*RXTE*/ASM [3–5 keV]), and radio measured fluxes from 2006 January 1 (MJD 53736) until 2009 December 15 (MJD 55180). The soft X-ray energy band of *RXTE*/ASM is between 1.5 and 12 keV, out of which only the 3–5 keV band was used, as it yields to

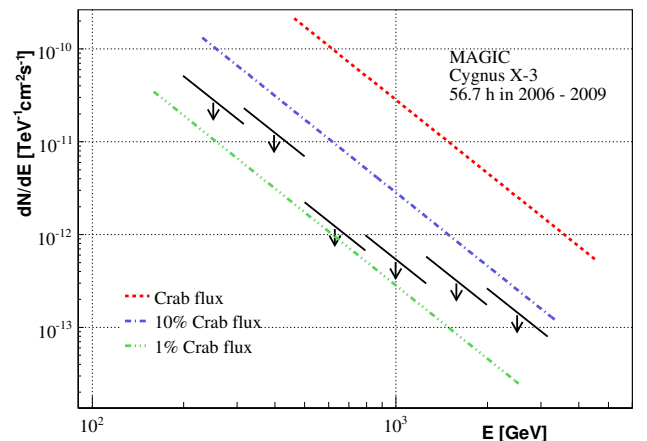


FIG. 1.— Differential flux upper limits at 95% CL for the VHE time-integrated emission. The slope of the arrows indicates the assumed power-law spectrum with a photon index 2.6.

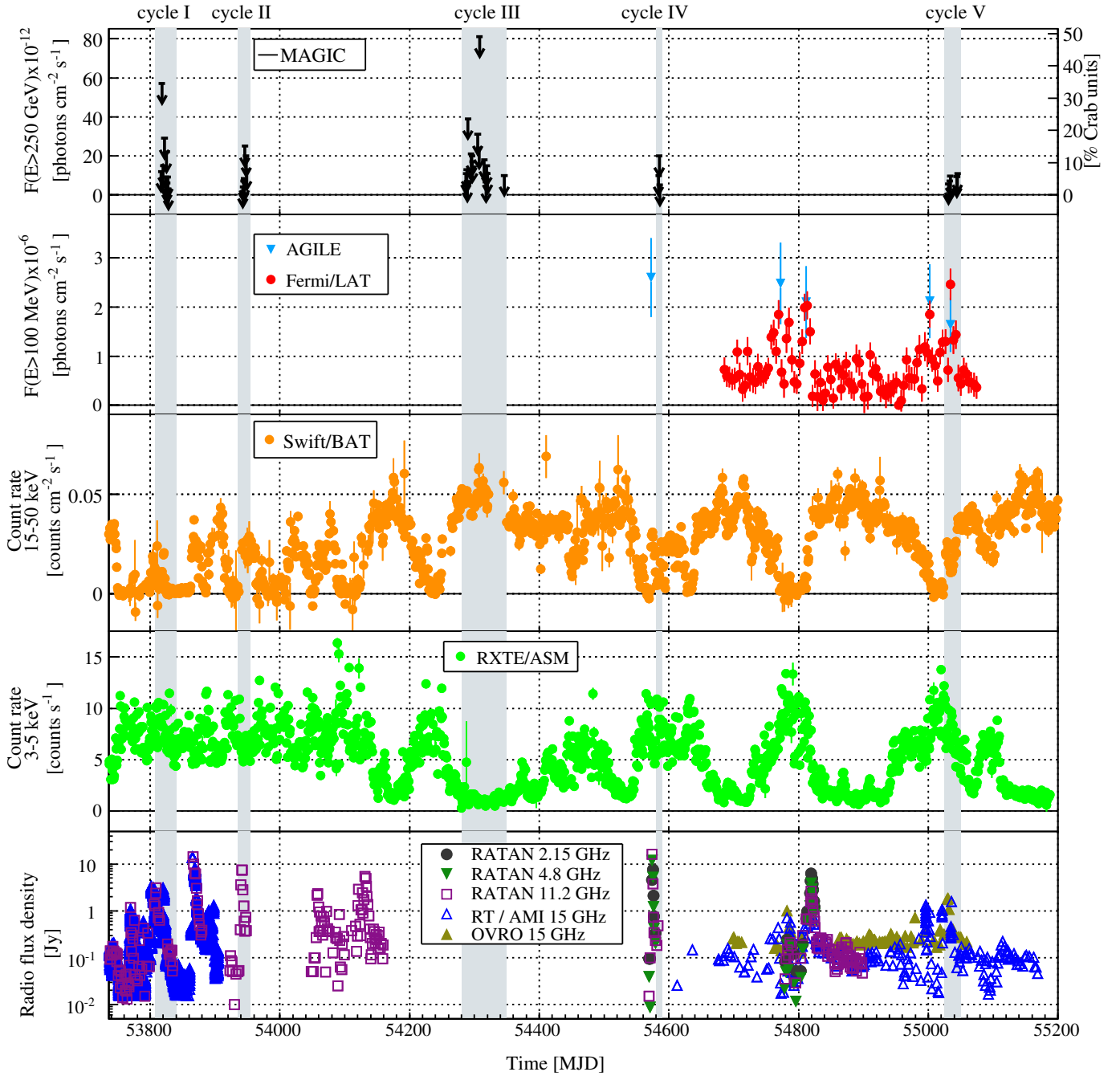


FIG. 2.— From top to bottom: daily MAGIC VHE integral flux upper limits for $E > 250$ GeV, and high-energy γ -ray (*AGILE* and *Fermi/LAT*), hard X-ray (*Swift/BAT*), soft X-ray (*RXTE/ASM*) and radio fluxes measured for Cygnus X-3 as function of time (from 2006 January 1 until 2009 December 15). The grey bands show the periods corresponding to the MAGIC observations. The OVRO and AMI 15 GHz data generally agree well, except for the offset apparent during steady periods which is due to unrelated extended emission resolved out by AMI.

the cleanest radio/X-ray correlation (Szostek et al. 2008). The radio measurements, displayed in logarithmic scale, were provided by the RATAN-600 telescope at 2.15, 4.8 and 11.2 GHz, and by the Ryle telescope (RT), the Arcminute Microkelvin Imager (AMI) telescope and the Owens Valley Radio Observatory (OVRO) 40-meter telescope at 15 GHz.

The soft and hard X-ray fluxes shown in Figure 2 allow us to derive the X-ray spectral state of Cygnus X-3 during MAGIC observations. Cycle III data are the only ones taken when the source was in the HS, as requested by the observational trigger. All the other observations were carried out

when the source was in the SS. The first two MAGIC observational campaigns (cycles I and II) were triggered by flares at radio frequencies, which are expected when the source is in SS. Unfortunately, the conditions on the trigger, together with MAGIC constraints on observation time did not allow a simultaneous coverage of the flaring states: MAGIC started pointing towards Cygnus X-3 twelve and two days after the strong radio emission, respectively. On the other hand, in the last observational cycles (IV and V), MAGIC observed the source during the SS, following two *AGILE* alerts on a high-flux activity in the high-energy band: the GeV emission oc-

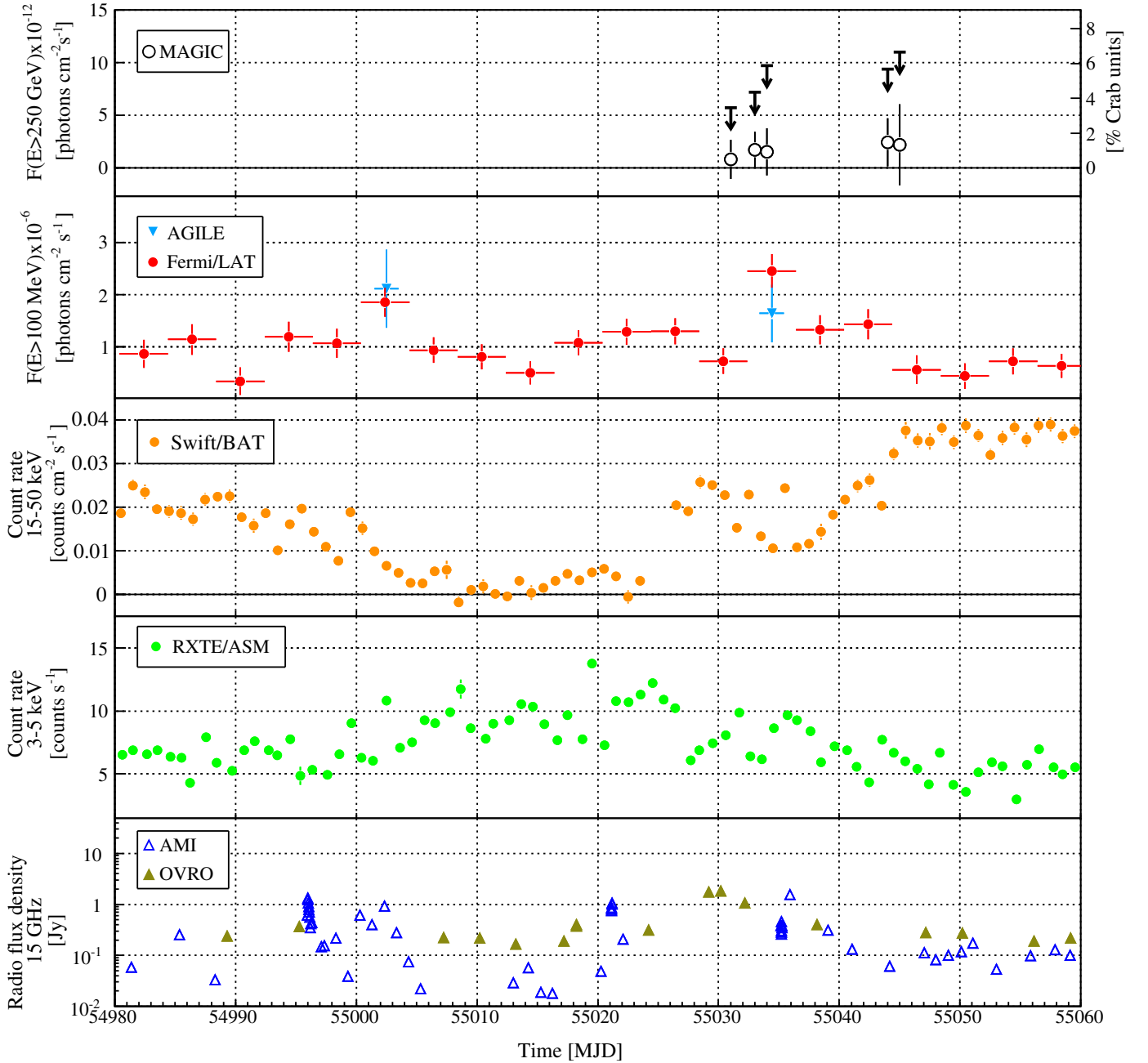


FIG. 3.— Zoom of Figure 2 around cycle V campaign between 2009 May 29 and August 17. The open circle points in the VHE MAGIC panel show the non-significant measured integral fluxes with their statistical error bars (whereas the upper limits take into account also the systematic errors).

occurs only in this X-ray spectral state. During the second alert, in 2009 July (MJD 55030), MAGIC recorded some data simultaneous with a GeV peak emission and did not detect any VHE signal. This important result will be discussed in detail in section 4.1.

Microquasars are expected to produce VHE emission inside the jets either when they are compact and persistent, mainly in the HS, or in the presence of strong radio-emitting-blobs, which most likely happen during a SS. Therefore, the results of the MAGIC observations were divided according to the X-ray spectral state of the source, as described in sections 4.2 and 4.3 for the SS and HS, respectively. Besides, in the scenario where the VHE radiation is emitted during

powerful synchrotron radio ejections, there might be a correlation between these two wavelengths (Atoyan & Aharonian 1999). Therefore, in section 4.4 the X-ray/radio states during the MAGIC observations are quoted.

4.1. Results during high-energy γ -ray emission

Abdo *et al.* (2009) presented the *Fermi*/LAT observations of Cygnus X-3 between 2008 August 4 and 2009 September 2. They detected a strong signal above 100 MeV, with an overall significance of more than 29 standard deviations, which is mainly dominated by two active periods (MJD 54750–54820 and 54990–55045). These active periods coincide with the X-ray SS of the source, indicating that Cygnus X-3 emits

high-energy γ -rays during this spectral state, with an average flux of 1.2×10^{-6} photons $\text{cm}^{-2} \text{s}^{-1}$ and a photon index $2.70 \pm 0.05_{\text{stat}} \pm 0.20_{\text{sys}}$ (under the assumption of a power-law spectrum). They also estimated that the peak flux can be as high as 2×10^{-6} photons $\text{cm}^{-2} \text{s}^{-1}$ without providing any photon index.

The five *AGILE* detections between 100 MeV and 3 GeV (Tavani et al. 2009; Bulgarelli et al., in preparation) coincide with the strongest high-energy outbursts, which can be seen overlapping them with the *Fermi*/LAT light-curve. The *AGILE* integral flux averaged over the first four detections is estimated of 1.9×10^{-6} photons $\text{cm}^{-2} \text{s}^{-1}$ with a corresponding photon index of 1.8 ± 0.2 .

In cycle V, MAGIC pointed at Cygnus X-3 during the second period of high-energy enhanced activity detected by *Fermi*/LAT, as shown in the Figure 3. In particular, MAGIC carried out observations simultaneous with a GeV emission peak on 2009 July 21 and 22 (MJD 55033–55034), and it did not detect any VHE emission. The corresponding MAGIC integral flux ULs above 250 GeV are lower than 6% of the Crab Nebula flux.

Figure 4 shows the spectral energy distribution (SED) of Cygnus X-3 between 100 MeV and 5 TeV including MAGIC 95% CL upper limits at VHE, and the power-law spectrum in the high-energy range reported by both *AGILE* and *Fermi*/LAT. The spectra take into account the error on the photon index and the one on the integral flux, which is 30% and 40% for *Fermi*/LAT and *AGILE*, respectively. The SED for the average SS was obtained considering the average *Fermi*/LAT flux and MAGIC results of the SS data set. On the other hand, to obtain the SED during a high-energy emission peak, the MAGIC measurements simultaneous with the GeV emission peak and both *Fermi*/LAT and *AGILE* spectral power-law fits were used. The *Fermi*/LAT photon index during the peak was assumed to be the same as the one for the SS average flux. Being the latter dominated by the brightest phases of the γ -ray outburst, it can be considered representative also of the flaring activity. Both MAGIC upper limits are consistent with the extrapolation of the *Fermi*/LAT spectra up to VHE, but not with the extrapolation of the harder *AGILE* spectrum, which would suggest a cut-off between some tens and 250 GeV.

4.2. Results during the soft state

The MAGIC telescope pointed at Cygnus X-3 when it was in SS during the observational cycles I, II, IV and V, corresponding to a total of 30.8 hours. For these observations, soft X-ray measurements in the 3–5 keV band are always above the transitional level set at 3 counts s^{-1} by Szostek et al. (2008).

After having analyzed each data cycle separately, the data sets were combined in order to obtain a global UL to the integral flux for the SS. The upper limit at 95% CL for energies greater than 250 GeV is 4.1×10^{-12} photons $\text{cm}^{-2} \text{s}^{-1}$, i.e. $\sim 2.5\%$ of the Crab Nebula flux. The differential flux upper limits for this spectral state are shown in Table 4 and in the left panel of Figure 5.

Due to the highly anisotropic radiation from the companion star, the predicted γ -ray emission above 250 GeV would be modulated according to the orbital phase (Bednarek 1997). Absorption might play an important role making the VHE orbital modulation difficult to be detected by the current sensitivity instrumentation (Bednarek 2010). The orbital modulation of the GeV γ -ray emission was detected only when the

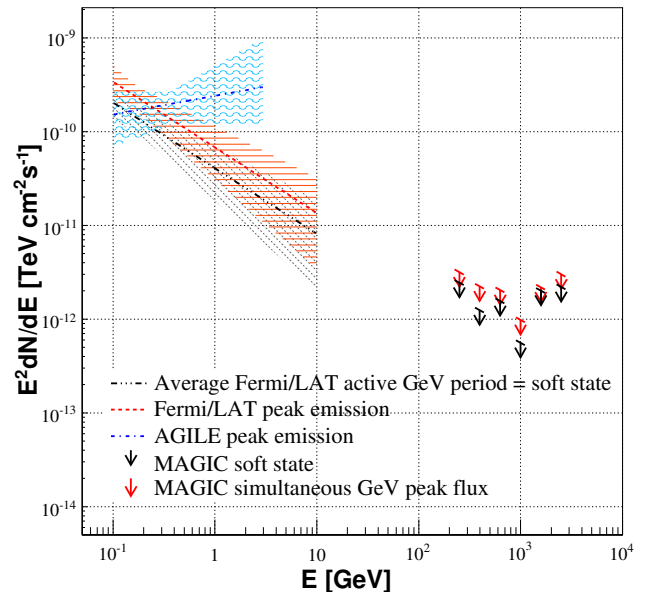


FIG. 4.— Cygnus X-3 spectral energy distribution in the high-energy and VHE bands. The lines indicate the power-law spectra derived from *Fermi*/LAT and *AGILE* integral fluxes and photon indices, where the corresponding errors were taken into account and are shown in shadowed areas. The arrows display the 95% CL MAGIC differential flux upper limits and their slope indicates the assumed power-law spectrum with a photon index 2.6. The black indicators show the SED during the period of enhanced GeV activity coinciding with the SS, whereas, the colorful (colors in the online version) ones during the high-energy peak emission (MJD 55031–55034).

source was in the SS (Abdo et al. 2009). MAGIC searched for such modulation in this spectral state. A phase-folded analysis was performed assuming the parabolic ephemeris in Singh et al. (2002). The results are shown in the left panel of Figure 6 and in Table 5. No evidence of VHE γ -ray signal was found in any phase bin. The obtained integral flux ULs are smaller than 10% of the Crab Nebula flux for all of them.

4.3. Results during the hard state

The 25.9 hours of MAGIC cycle III data sample were obtained when Cygnus X-3 was in HS. *Swift*/BAT count rates during this cycle are rather high, greater than 0.05 counts $\text{cm}^{-2} \text{s}^{-1}$, whereas the soft X-ray fluxes in the 3–5 keV band are below 2 counts s^{-1} .

For this spectral state, the integral flux upper limit for energies greater than 250 GeV is 1.1% of the Crab Nebula flux (1.8×10^{-12} photons $\text{cm}^{-2} \text{s}^{-1}$). The differential flux upper limits are quoted in Table 4 and plotted in the right panel of Figure 5. The performed phase-folded analysis for this spectral state did not yield any significant detection. The computed upper limits to the integral flux are, on average, at the level of 5% of the Crab Nebula flux (see right panel in Figure 6 and Table 5).

4.4. Results during X-ray/radio states

MAGIC observed Cygnus X-3 in both X-ray main spectral states (see section 4.2 and 4.3). However, the state of the source can be further characterized by simultaneous radio flux. Szostek et al. (2008) identified six different X-ray/radio states studying simultaneous observations of the Green Bank Interferometer at 8.3 GHz and *RXTE*/ASM in the energy

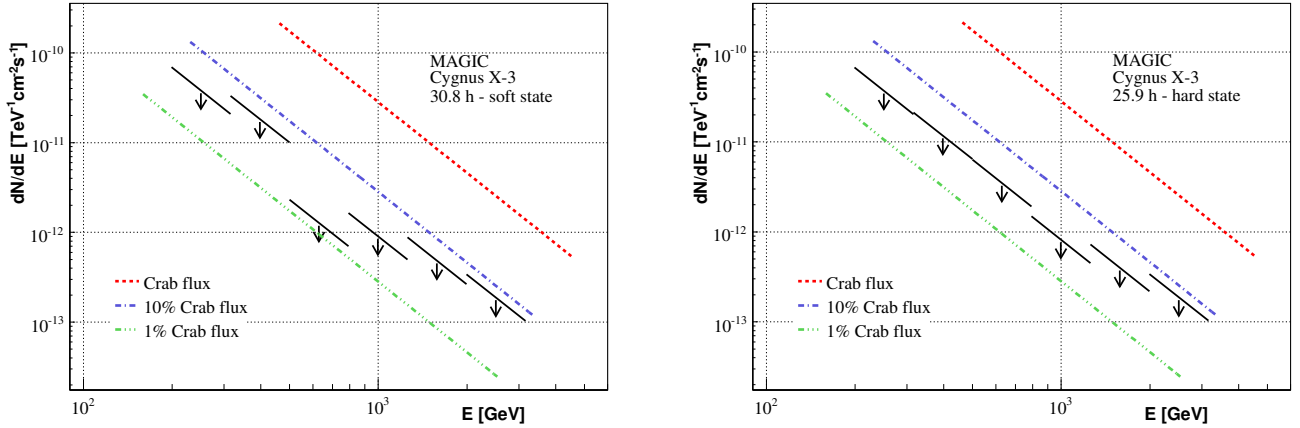


FIG. 5.— 95% differential flux upper limits for the SS (left panel), and for HS (right panel) observations. The slope of the arrows indicates the assumed power-law spectrum with a photon index 2.6.

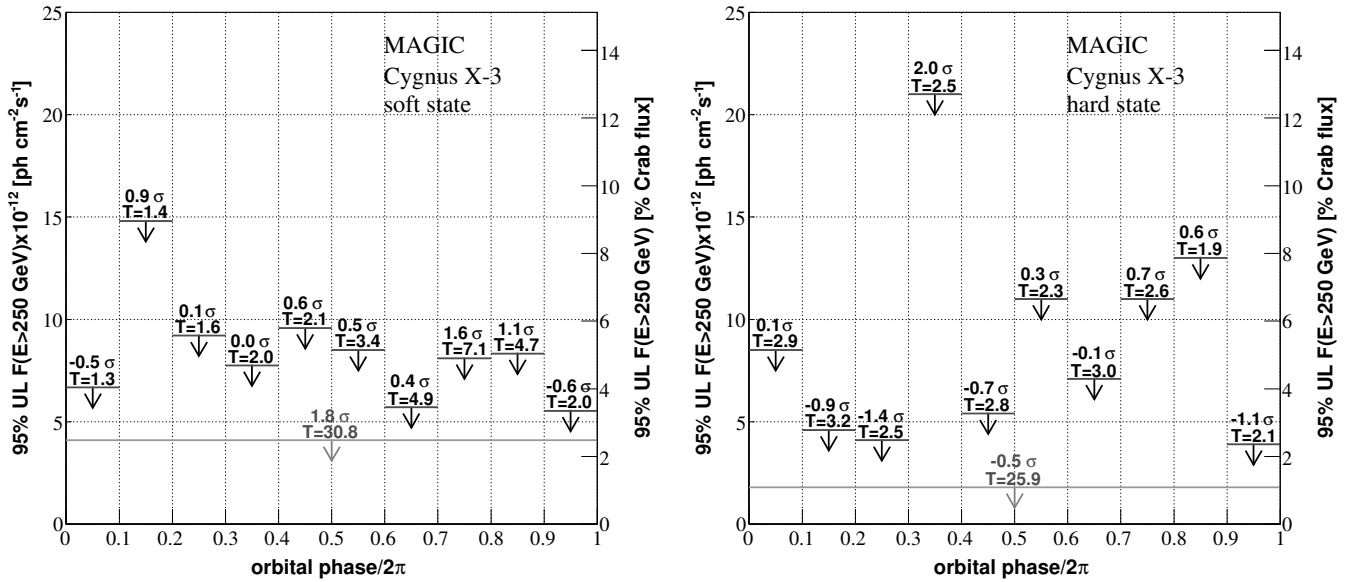


FIG. 6.— Phase-wise integral flux upper limits for $E > 250$ GeV for the SS (left panel) and HS (right panel). The effective observation time (in hours) and the signal significance for each phase bin are written on top of each arrow. The grey arrow indicates the integral flux UL on the VHE time-integrated emission.

range 3–5 keV. The relation between these two energy bands is shown in the so-called “saxophone” plot (see Figure 7). It was noted that the use of other radio frequencies yield similar results. This gives us the confidence that a direct comparison between their and our results using 15 GHz (RT, and AMI) and 11.2 GHz (RATAN-600) is reasonable. The OVRO and AMI 15 GHz data generally agree well, but for a ~ 0.12 Jy offset apparent during steady periods, probably due to unrelated extended emission resolved out by AMI. Thus, only the AMI 15 GHz were used in this analysis, although our conclusions are not substantially affected by this choice.

Figure 7 shows the soft X-ray [3–5 keV] *RXTE*/*ASM* count rates versus radio flux densities corresponding either to the nights of *MAGIC* observations for the five observational cycles, or to the *AGILE* flux peaks (only the last four *AGILE* detections were considered, since no simultaneous radio data

were available for the first one). Unfortunately, no radio data simultaneous with cycle III and cycle IV *MAGIC* observations were available. Nevertheless, in case of cycle III data, this does not prevent us from pointing out that Cygnus X-3 was in a quiescent state, just by using the soft X-ray measurements. For cycle IV data, quasi simultaneous radio observations (one day before *MAGIC* observations) were used. This latter choice does not affect our qualitative result, since the source had already entered a post-flaring state. As shown in Figure 9, in 2008 April, *AGILE* detected Cygnus X-3 (MJD 54572–54573) one day before a major radio flare (Trushkin et al. 2008) lasting a few days, but *MAGIC* started pointing at the microquasar ten days after the peak radio emission.

All the high-energy flux peaks were detected in the right branch of the “saxophone”, before, after or during a flaring state. Although Abdo et al. (2009) quoted a time lag between

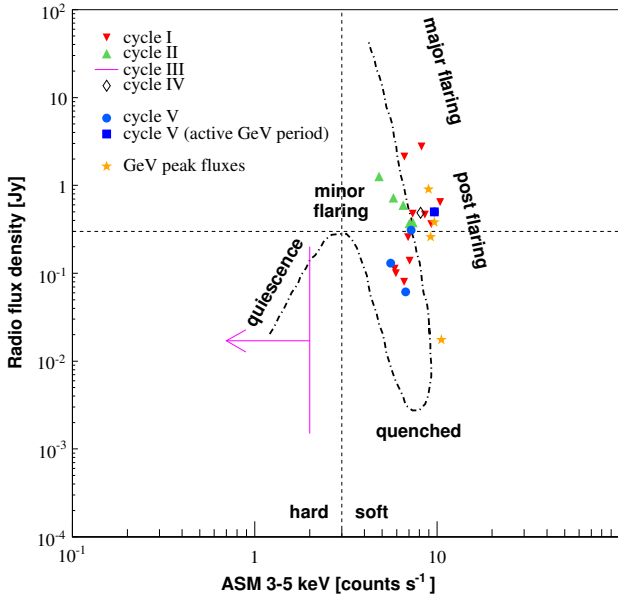


FIG. 7.— Soft X-ray counts versus radio fluxes simultaneous with the GeV peak fluxes (yellow stars) and MAGIC observations, where the different marker colors identify the five MAGIC observational cycles. The arrow shows the X-ray flux level during cycle III MAGIC campaign, for which radio data are not available. Radio measurements are at 11.2 GHz from RATAN-600 and at 15 GHz from RT/AMI. The dot-dashed line shows the expected “saxophone” shape (adapted from Szostek et al. (2008)).

the radio and the γ -ray peaks of 5 ± 7 days, the correlation between the two energy bands is not yet clear. On the other hand, MAGIC observed Cygnus X-3 in its SS some days after the radio flare occurred, although for the first nights of cycle V observations, the radio flux densities are rather high and oscillating between two small flares (see Figure 3).

5. DISCUSSION

MAGIC observations of Cygnus X-3 cover all X-ray spectral states of the source in which VHE emission is thought to be likely produced, either from a persistent jet in the HS, or during powerful ejections in the SS. However, no significant excess events were found in any of the inspected samples.

VHE γ rays have been predicted from microquasar jets (Atoyan & Aharonian 1999; Romero et al. 2003; Bosch-Ramon et al. 2006). A robust prediction of modeling is that photon-photon absorption cannot be neglected if the γ rays are produced close to a massive star (Bednarek 1997; Orellana et al. 2007). In particular for Cygnus X-3 the presence of a Wolf-Rayet companion, with temperature $T_* \approx 10^5$ K and radius $R_* \approx 10^{11}$ cm, leads to an optical depth $\tau \geq 1$ for VHE γ rays for an emitter located at several orbital radii from the star (Bednarek 2010). Even under very efficient electromagnetic cascading, i.e. a radiation to magnetic energy density ratio $8\pi u_*/B^2 \gg 1$, the expected VHE fluxes are below the sensitivity of the present instruments (Bednarek 2010). Therefore, in order to detect VHE photons the emitter should be located far from the binary system.

Fermi/LAT detected Cygnus X-3 when it was in the SS, and found orbital modulation for the radiation above 100 MeV with a photon index 2.7 for the periods of enhanced-activity (Abdo et al. 2009). For the epochs outside these high-activity periods, the GeV flux decreases significantly (Fig-

ure 2 in Abdo et al. (2009)) and no modulation is found. The GeV orbital light curve of Cygnus X-3 in the high-energy active periods can be explained in the context of anisotropic inverse Compton scattering with the stellar photons (Abdo et al. 2009; Bosch-Ramon & Khangulyan 2009; Dubus et al. 2010), which is also energetically more efficient than hadronic mechanisms such as pp interactions or photomeson production. Since very bright X-ray emission is produced in the inner accretion disk or at the base of the jets in Cygnus X-3, the GeV radiation would be absorbed unless it is originated beyond $\sim 10^{10}$ cm above the compact object. This implies that the GeV radiation is produced in the jet of Cygnus X-3 rather than in the inner accretion disk/corona region. On the other hand, the GeV emitter cannot be too high in the jet, since otherwise there would not be strong orbital modulation (see also Abdo et al. 2009). Therefore, the observed GeV and the predicted detectable VHE emission cannot be explained by one particular population because the former should be produced in/close to the system and the latter farther from it. The location of a hypothetical VHE emitter could coincide with the innermost region of the radio emitting jet, which, to avoid synchrotron self-absorption, should start relatively far from the binary system. This is consistent with the fact that MAGIC did not detect Cygnus X-3 during the high-activity GeV period, even though the flux upper limits are close to a power-law extrapolation of the *Fermi*/LAT spectrum to energies greater than 100 GeV and well below an extrapolation of the *AGILE* spectrum.

During the periods of GeV high-activity of the source, as by the synchrotron self Compton scenario (Atoyan & Aharonian 1999), a detectable TeV signal could arise during the first hours of a radio outburst. Unfortunately, MAGIC has never observed the source during this phase of the flare, but always some days before or after the maximum radio flux. This radiation would not be strongly modulated, due to its origin far from the system. The two times more sensitive two telescopes arrangement, MAGIC phase II, may indeed detect Cygnus X-3 if it observes the source for longer time at the very maximum of a GeV flare, which might be even earlier than the onset of the radio outburst (Abdo et al. 2009).

In the HS, the VHE emission is expected to be produced inside the compact and persistent jets, whose total luminosity is estimated to be at least 10^{37} erg s^{-1} (Martí et al. 2005). The MAGIC VHE γ -ray upper limit set at 1.1×10^{-12} erg cm^{-2} s^{-1} is equivalent to a VHE luminosity of $\simeq 7 \times 10^{33}$ erg s^{-1} at 7 kpc. Thus, the maximum conversion efficiency of the jet power into VHE γ rays is 0.07% which is similar to that of Cygnus X-1 for the upper limit on the VHE steady emission, but one order of magnitude greater than that of GRS 1915+105 (Albert et al. 2007a; Acero et al. 2009). These upper limits are in good agreement with the theoretical expectations which generally predict a VHE steady luminosity of $\simeq 10^{32}$ erg s^{-1} . Persistent galactic jets do not seem to be good candidate sources to be detected at VHEs by the current sensitivity instrumentation. Only ten times more sensitive future instruments, such as Cherenkov Telescope Array (CTA), may have a chance to detect such VHE emission. This would provide a new handle on the emission mechanisms of compact jets.

6. ACKNOWLEDGMENTS

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TABLE 2
DIFFERENTIAL FLUX UPPER LIMITS FOR THE VHE TIME-INTEGRATED EMISSION AT 95% CL.

Energy Range (GeV)	N_{on} Evt.s. ^a	N_{bg} Evt.s. ^b	Excess Evt.s.	Norm.Fact. ^c	Signif. ^d (σ)	UL Evt.s. ^e	Flux UL ($\text{TeV}^{-1}\text{cm}^{-2}\text{s}^{-1}$)
199–315	4416	4384.5 ± 39.0	31.5 ± 77.0	0.34	0.4	237.8	$2.6\text{E}-11$
315–500	2057	1980.6 ± 28.6	76.4 ± 53.6	0.36	1.5	264.2	$1.2\text{E}-11$
500–792	769	800.8 ± 21.1	-31.8 ± 34.9	0.39	-0.9	51.3	$1.1\text{E}-12$
792–125	289	299.9 ± 12.9	-10.9 ± 21.4	0.38	-0.3	39.2	$5.1\text{E}-13$
1256–1991	102	98.3 ± 6.9	3.7 ± 12.2	0.37	0.5	36.2	$3.0\text{E}-13$
1991–3155	38	32.3 ± 3.5	5.7 ± 7.1	0.35	0.7	27.4	$1.3\text{E}-13$

^aNumber of signal events.

^bNumber of normalized background events.

^cNormalization factor.

^dSignificance.

^eMaximum number of excess events computed by using Rolke's method.

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REFERENCES

- Abdo, A. A., et al. 2009, *Science*, 326, 1512
 Acero, F., et al. 2009, *A&A*, 508, 1135
 Aharonian, F. A., et al. 2004, *ApJ*, 614, 897A
 Aharonian, F. A., et al. 2005a, *A&A*, 442, 1
 Aharonian, F. A., et al. 2005b, *Science*, 309, 746
 Aharonian, F. A., et al. 2006, *A&A*, 460, 743
 Acciari, V. A., et al. 2008, *ApJ*, 679, 1427
 Acciari, V. A., et al. 2009, *ApJ*, 700, 1034
 Albert, J., et al. 2006, *Science*, 312, 1771
 Albert, J., et al. 2007, *ApJ*, 665, L51
 Albert, J., et al. 2007a, *astro-ph/0702475*
 Albert, J., et al. 2008a, *ApJ*, 675, L25
 Albert, J., et al. 2008b, *ApJ*, 684, 1351
 Albert, J., et al. 2008c, *ApJ*, 674, 1037
 Albert, J., et al. 2008d, *NIM*, 594, 407
 Albert, J., et al. 2008e, *NIM*, A588, 424
 Albert, J., et al. 2009, *ApJ*, 693, 303
 Aliu, E., et al. 2009, *Astropart. Phys.*, 30, 293
 Anderhub H., et al. 2009, *ApJ*, 706, L27
 Atoyan A. M., & Aharonian F. A. 1999, *MNRAS*, 302, 253
 Becklin, E. E., Neugebauer, O., Hawkins, F., et al. 1973, *Nature*, 245, 302
 Bednarek W. 1997, *A&A*, 322, 523
 Bednarek W. 2010, submitted to *MNRAS* (arXiv:1002.1563)
 Bhat C. L., Sapru M. L., & Razdan H. 1986, *ApJ*, 306, 587
 Bosch-Ramon, V., Romero, G. E., & Paredes, J. M. 2006, *A&A*, 447, 263
 Bosch-Ramon, V., & Khangulyan, D. 2009, *IJMPD*, 18, 347
 Braes, L., & Miley, G. 1972, *Nature*, 237, 506
 Breiman, L. 2001, *Machine Learning*, 45, 5
 Britzger, D., et al. 2009, in Proc. 31st International Cosmic Ray Conference, Lodz
 Cawley M. F., et al. 1985, *ApJ*, 296, 185
 Chadwick P. M., et al. 1985, *Nature*, 318, 642
 Chardin G., & Gerbier G. 1989, *A&A*, 210, 52
 Danaher S., Fegan D. J., & Weekes T. C. 1981, *Nature*, 289, 568
 Douthwaite J. C. 1983, *A&A*, 126, 1
 Dubus, G. 2006, *A&A*, 456, 801
 Dubus, G., Cerutti, B., Henri, G. 2010, *MNRAS*, in press (arXiv:1002.3888)
 Fomin, V. P., Stepanian, A. A., Lamb, R. C., Lewis, D. A., Punch, M., & Weekes, T. C. 1994, *Astropart. Phys.*, 2, 137
 Geldzahler, B. J., Johnston, K. J., Spencer, J. H., et al. 1983, *ApJ*, 273, L65
 Giacconi, R., et al. 1967, *ApJ*, 148, L119
 Gregory, P. C., Kronberg, P. P., Seaquist, E. R., et al. 1972, *Nature Physical Science*, 239, 114
 Hanson, M. M., Still, M. D., & Fender, R. P. 2000, *ApJ*, 541, 308
 Hillas, A. M. 1985, in Proc. 19th International Cosmic Ray Conference, La Jolla, 3, 445
 Hjalmarsdotter L., et al. 2004, *ESASP*, 552, 223
 Hjalmarsdotter L., et al. 2008, *MNRAS*, 384, 278
 Koljonen K. I. I., et al. 2010, submitted to *MNRAS* (arXiv:1003.4351)
 Lamb, R. C., et al. 1982, *Nature* 296, 543
 Levinson, A., & Blandford, R. 1996, *ApJ*, 456, L29
 Ling, Z., Zhang, S. N., & Tang, S. 2009, *ApJ*, 695, 1111
 Maraschi, L., & Treves, A. 1981, *MNRAS*, 194, 1
 Martí, J., Paredes, J. M., & Peracaula, M. 2001, *A&A*, 375, 476
 Martí, J., Perez-Ramírez, D., et al. 2005, *A&A*, 439, 279
 Miller-Jones, J. C. A., et al. 2004, *ApJ*, 600, 368
 Mioduszewski, A. J., Rupen, M. P., Hjellming, R. M., Pooley, G. G., & Waltman, E. B. 2001, *ApJ*, 553, 766
 Mori, M., Bertsch, D. L., Dingus, B. L., et al. 1997, *ApJ*, 476, 842
 Orellana M., Bordas P., Bosch-Ramon, V., Romero, G. E., & Paredes, J. M. 2007, *A&A*, 476, 90
 Parsignault, D. R., Gursky, H., Kellogg, E. M., et al. 1972, *Nature*, 239, 123
 Rico, J. 2008, *ApJ*, 683, L55
 Rolke, W., Lopez, A., Conrad, J., & James, F. 2005, *NIM A*, 551,493
 Romero, G. E., Torres, D. F., Kaufman Bernardo, M. M., & Mirabel, I. F. 2003, *A&A*, 410, L1
 Sabatini, S., et al. 2010, *ApJ*, 712, L10
 Saito, T., Zanin, R., et al. 2009, in Proc. 31st International Cosmic Ray Conference, Lodz
 Samorski, M., & Stamm, W. 1983, *ApJ*, 268, L17
 Shilling, M., et al. 2001, in Proc. 27th International Cosmic Ray Conference, Hamburg, 2521
 Singh, N. S., et al. 2002, *A&A*, 392, 161
 Stark M. J., & Saia M. 2003, *ApJ*, 587, L101
 Szostek, A., Zdziarski, A. A., & McCollough, M. 2008, *MNRAS*, 388, 1001
 Tavani, M. & Arons, J. 1997, *ApJ*, 477, 439
 Tavani, M., et al. 2009, *Nature*, 462, 620
 Trushkin, S. A., Nizhelskij, N. A., & Bursov, N. N. 2008, Proc. 7th Microquasar Workshop, Foca (Turkey)
 Tudose, V., et al. 2010, *MNRAS*, 401, 890
 van Kerkwijk, M. H., Charles, P. A., Geballe, T. R., et al. 1992, *Nature*, 355, 703
 Vladimirovsky, B. M., Stepanian, A. A., & Fomin, V. P. 1973, Proc. 13th International Cosmic Ray Conference, Denver, 1, 456
 Waltman, E. B., et al. 1994, *ApJ*, 108, 179
 Zdziarski A. A., & Gierlinski M. 2004, *Progr. Theor. Phys. Suppl.*, 155, 99

TABLE 3
INTEGRAL FLUX UPPER LIMITS FOR ENERGIES ABOVE 250 GeV CALCULATED ON A DAILY BASIS AT 95% CL.

Date (MJD)	Time (h)	N_{on} Evt.s.	N_{bg} Evt.s.	Excess Evt.s.	Norm.Fact.	Signif. (σ)	UL Evt.s.	Flux UL ($\text{cm}^{-2}\text{s}^{-1}$)	(% C.U.)
53817	0.46	42	41.4 ± 1.8	0.6 ± 6.7	0.07	0.1	18.7	$1.2\text{E}-11$	7.5
53818	0.26	43	27.0 ± 0.7	16.0 ± 6.6	0.05	2.8	46.7	$5.7\text{E}-11$	34.2
53820	0.54	85	83.8 ± 4.6	1.2 ± 10.2	0.15	0.1	27.4	$1.5\text{E}-11$	9.3
53822	0.70	132	111.4 ± 3.5	20.6 ± 12.0	0.19	1.7	67.9	$2.9\text{E}-11$	17.4
53824	0.80	84	84.8 ± 2.4	-0.8 ± 9.5	0.15	-0.1	24.3	$9.1\text{E}-12$	5.5
53825	0.80	83	64.3 ± 2.1	18.7 ± 9.3	0.15	2.1	58.0	$2.2\text{E}-11$	13.1
53826	1.00	37	34.3 ± 0.6	2.7 ± 6.1	0.06	0.4	20.9	$6.1\text{E}-12$	3.7
53827	0.92	79	76.5 ± 1.9	2.5 ± 9.1	0.13	0.3	28.4	$9.1\text{E}-12$	5.5
53828	1.05	42	49.3 ± 1.1	-7.3 ± 6.6	0.09	-1.0	10.9	$3.1\text{E}-12$	1.8
53943	3.10	257	274.3 ± 9.5	-17.3 ± 18.6	0.33	-0.9	27.9	$4.1\text{E}-12$	2.5
53944	2.54	232	235.7 ± 8.8	-3.7 ± 17.6	0.33	-0.2	38.6	$7.1\text{E}-12$	4.3
53945	1.73	122	125.7 ± 6.4	-3.7 ± 12.7	0.33	-0.3	27.1	$8.4\text{E}-12$	5.1
53946	1.37	127	108.0 ± 5.9	19.0 ± 12.7	0.33	1.5	65.0	$2.5\text{E}-11$	15.3
53948	0.90	82	65.7 ± 4.6	16.3 ± 10.2	0.33	1.7	54.3	$3.2\text{E}-11$	19.4
53949	1.79	138	143.3 ± 6.9	5.3 ± 13.6	0.33	0.4	42.1	$1.3\text{E}-11$	7.8
54286	2.16	299	314.0 ± 10.2	-15.0 ± 20.1	0.33	-0.74	62.1	$1.1\text{E}-11$	6.8
54287	4.53	547	547.0 ± 13.4	-0.7 ± 27.0	0.33	-0.03	150.3	$1.3\text{E}-11$	8.1
54288	1.07	176	208.0 ± 8.3	-32.0 ± 15.6	0.33	-1.99	20.3	$7.0\text{E}-12$	4.3
54289	0.38	86	84.3 ± 5.3	1.7 ± 10.7	0.33	0.16	41.3	$3.9\text{E}-11$	23.5
54295	1.82	189	176.3 ± 7.6	12.7 ± 15.7	0.33	0.82	76.4	$2.1\text{E}-11$	13.0
54296	1.93	219	209.0 ± 8.3	10.0 ± 17.0	0.33	0.59	74.9	$2.0\text{E}-11$	11.8
54297	1.93	151	138.7 ± 6.7	12.3 ± 14.0	0.33	0.89	65.9	$1.7\text{E}-11$	10.4
54305	1.75	179	167.7 ± 7.4	11.3 ± 15.3	0.33	0.75	111.6	$3.1\text{E}-11$	19.0
54307	0.98	115	117.0 ± 6.2	-2.0 ± 12.4	0.33	-0.16	52.9	$2.4\text{E}-11$	14.5
54308	0.5	71	59.3 ± 4.4	11.7 ± 9.5	0.33	1.27	100.1	$8.1\text{E}-11$	48.8
54316	0.73	85	88.7 ± 5.4	-3.7 ± 10.7	0.33	-0.34	33.0	$1.8\text{E}-11$	11.0
54318	2.72	262	277.3 ± 9.6	-15.3 ± 18.8	0.33	-0.81	39.2	$6.7\text{E}-12$	4.1
54319	1.93	184	184.0 ± 7.8	0.0 ± 15.6	0.33	0.00	61.8	$1.5\text{E}-11$	8.8
54320	1.58	146	152.3 ± 7.1	-6.3 ± 14.0	0.33	-0.95	38.8	$1.1\text{E}-11$	6.8
54346	1.86	182	200.0 ± 8.1	-18.0 ± 15.7	0.33	-1.12	45.3	$1.0\text{E}-11$	6.3
54584	0.31	17	23.0 ± 2.7	-5.0 ± 5.0	0.33	-1.0	8.0	$1.0\text{E}-11$	6.2
54585	1.07	89	75.3 ± 5.0	13.7 ± 10.7	0.33	1.3	50.2	$2.0\text{E}-11$	11.9
54586	1.33	60	66.7 ± 4.7	-6.7 ± 9.1	0.33	-0.7	15.5	$5.1\text{E}-11$	3.1
55031	3.48	186	183.3 ± 7.8	2.7 ± 15.7	0.33	0.2	43.2	$5.7\text{E}-12$	3.4
55033	2.21	71	63.7 ± 4.6	7.3 ± 9.6	0.33	0.8	36.2	$7.2\text{E}-12$	4.4
55034	1.63	50	43.3 ± 3.8	6.7 ± 8.0	0.33	0.9	31.4	$9.7\text{E}-12$	5.8
55044	1.81	88	80.0 ± 5.1	8.0 ± 10.7	0.33	0.8	40.0	$9.4\text{E}-12$	5.7
55045	0.88	69	69.0 ± 4.8	0.0 ± 9.6	0.33	0.0	24.2	$1.1\text{E}-11$	6.6

NOTE. — Refer to Table 2 for the meaning of the columns.

TABLE 4
DIFFERENTIAL FLUX UPPER LIMITS FOR THE SS AND HS OBSERVATIONS.

Spectral State	Energy Range (GeV)	N_{on} Evt.s.	N_{bg} Evt.s.	Excess Evt.s.	Norm.Fact.	Signif. (σ)	UL Evt.s.	Flux UL ($\text{TeV}^{-1}\text{cm}^{-2}\text{s}^{-1}$)
HS	199–315	1709	1677.54 ± 24.6	31.5 ± 48.1	0.36	0.7	169.2	$3.5\text{E}-11$
	315–500	926	858.3 ± 18.5	67.7 ± 35.6	0.40	1.9	212.3	$1.7\text{E}-11$
	500–792	324	357.5 ± 12.9	-33.5 ± 22.2	0.47	-1.1	30.3	$1.2\text{E}-12$
	792–1256	125	124.9 ± 7.7	0.1 ± 13.6	0.48	0.4	38.0	$8.4\text{E}-13$
	1256–1991	41	33.7 ± 3.9	7.3 ± 7.5	0.46	1.4	32.7	$4.5\text{E}-13$
	1991–3155	14	8.7 ± 1.8	5.3 ± 4.2	0.40	1.3	20.3	$1.7\text{E}-13$
LH	199–315	2707	2707.0 ± 29.9	0.0 ± 60.0	0.33	0.0	146.2	$3.4\text{E}-11$
	315–500	1131	1122.3 ± 19.2	8.7 ± 38.7	0.33	0.2	108.5	$1.1\text{E}-11$
	500–792	445	443.3 ± 12.1	1.7 ± 24.3	0.33	0.1	62.5	$3.3\text{E}-12$
	792–1256	164	175.0 ± 7.5	-11.0 ± 14.9	0.33	-0.7	24.7	$7.7\text{E}-13$
	1256–1991	61	64.7 ± 4.6	-3.7 ± 9.1	0.33	-0.4	18.4	$3.7\text{E}-13$
	1991–3155	24	23.7 ± 2.7	0.3 ± 5.6	0.33	0.1	15.2	$1.7\text{E}-13$

NOTE. — Refer to Table 2 for the meaning of the columns.

TABLE 5
 INTEGRAL FLUX UPPER LIMITS FOR ENERGIES ABOVE 250 GeV FOR THE PHASE-FOLDED ANALYSES OF THE OBSERVATIONS IN THE SS
 AND THE HS.

Spectral State	Phase	Time (h)	N_{on} Evt.s.	N_{bg} Evt.s.	Excess Evt.s.	Norm.Fact.	Signif. (σ)	UL Evt.s.	Flux UL ($\text{cm}^{-2}\text{s}^{-1}$)	(% C.U.)
SS	0.0–0.1	1.34	64	68.0 ± 4.7	-4.3 ± 9.3	0.33	-0.5	18.2	$6.7\text{E}-12$	4.0
	0.1–0.2	1.40	75	67.3 ± 4.7	8.3 ± 9.8	0.33	0.9	38.6	$1.5\text{E}-11$	8.9
	0.2–0.3	1.63	108	107.0 ± 5.9	1.3 ± 12.0	0.33	0.1	32.1	$9.2\text{E}-12$	5.6
	0.3–0.4	2.05	162	162.0 ± 7.3	0.3 ± 14.6	0.33	0.0	37.1	$7.7\text{E}-12$	4.7
	0.4–0.5	2.11	113	106.0 ± 5.9	7.3 ± 12.1	0.33	0.6	42.3	$9.6\text{E}-12$	5.8
	0.5–0.6	3.40	231	222.3 ± 8.5	8.7 ± 17.5	0.33	0.5	57.1	$8.5\text{E}-12$	5.1
	0.6–0.7	4.93	370	361.3 ± 10.2	9.1 ± 21.8	0.29	0.4	68.3	$5.7\text{E}-12$	3.4
	0.7–0.8	7.13	649	600.7 ± 17.1	49.4 ± 30.7	0.49	1.6	163.9	$8.1\text{E}-12$	4.9
	0.8–0.9	4.69	331	310.0 ± 8.4	21.2 ± 20.0	0.23	1.1	86.4	$8.3\text{E}-12$	5.1
	0.9–1.0	2.05	109	116.0 ± 6.2	-7.0 ± 12.1	0.33	-0.6	22.1	$5.5\text{E}-12$	3.3
0–1	30.78	2216	2120.3 ± 29.5	96.3 ± 55.5	0.41	1.8	311.6	$4.1\text{E}-12$	2.5	
HS	0.0–0.1	2.89	511	509.7 ± 12.9	1.3 ± 26.1	0.33	0.0	102.5	$8.6\text{E}-12$	5.2
	0.1–0.2	3.23	477	501.3 ± 12.8	-24.3 ± 25.3	0.33	-0.9	52.5	$4.6\text{E}-12$	2.7
	0.2–0.3	2.53	281	308.0 ± 10.1	-27.0 ± 19.5	0.33	-1.4	33.6	$4.1\text{E}-12$	2.5
	0.3–0.4	2.53	266	230.0 ± 8.7	36.0 ± 18.5	0.33	2.0	218.1	$2.1\text{E}-11$	12.4
	0.4–0.5	2.79	248	261.0 ± 9.2	-13.0 ± 18.3	0.33	-0.7	43.2	$5.4\text{E}-12$	3.3
	0.5–0.6	2.27	210	205.3 ± 8.2	4.7 ± 16.6	0.33	0.3	73.1	$1.1\text{E}-11$	6.8
	0.6–0.7	2.99	242	243.0 ± 8.9	-1.0 ± 17.9	0.33	-0.1	65.8	$7.1\text{E}-12$	4.3
	0.7–0.8	2.63	234	222.7 ± 8.6	11.3 ± 17.5	0.33	0.6	116.3	$1.1\text{E}-11$	6.8
	0.8–0.9	1.95	199	189.7 ± 7.9	9.3 ± 16.2	0.33	0.6	118.5	$1.3\text{E}-11$	7.8
	0.9–1.0	2.13	235	261.3 ± 9.3	-26.3 ± 17.9	0.33	-1.4	33.8	$3.9\text{E}-12$	2.4
0–1	25.9	2903	2932.0 ± 31.1	-29.0 ± 62.2	0.33	-0.5	191.0	$1.8\text{E}-12$	1.1	

NOTE. — Refer to Table 2 for the meaning of the columns.

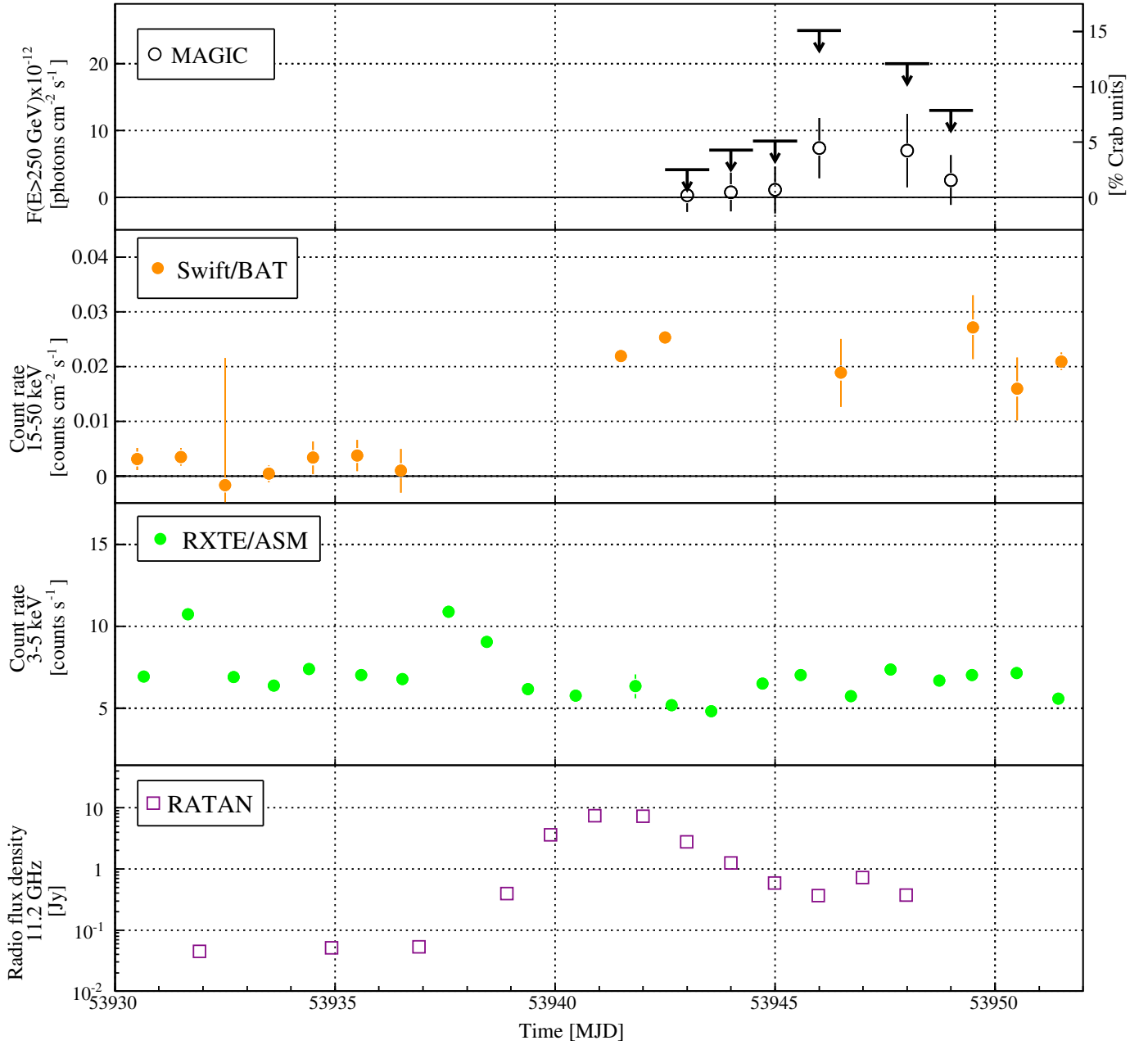


FIG. 8.— Zoom of Figure 2 around cycle II campaign between 2006 July 14 and August 5. The open circle points in the VHE MAGIC panel show the non-significant measured integral fluxes with their statistical error bars (whereas the upper limits take into account also the systematic errors).

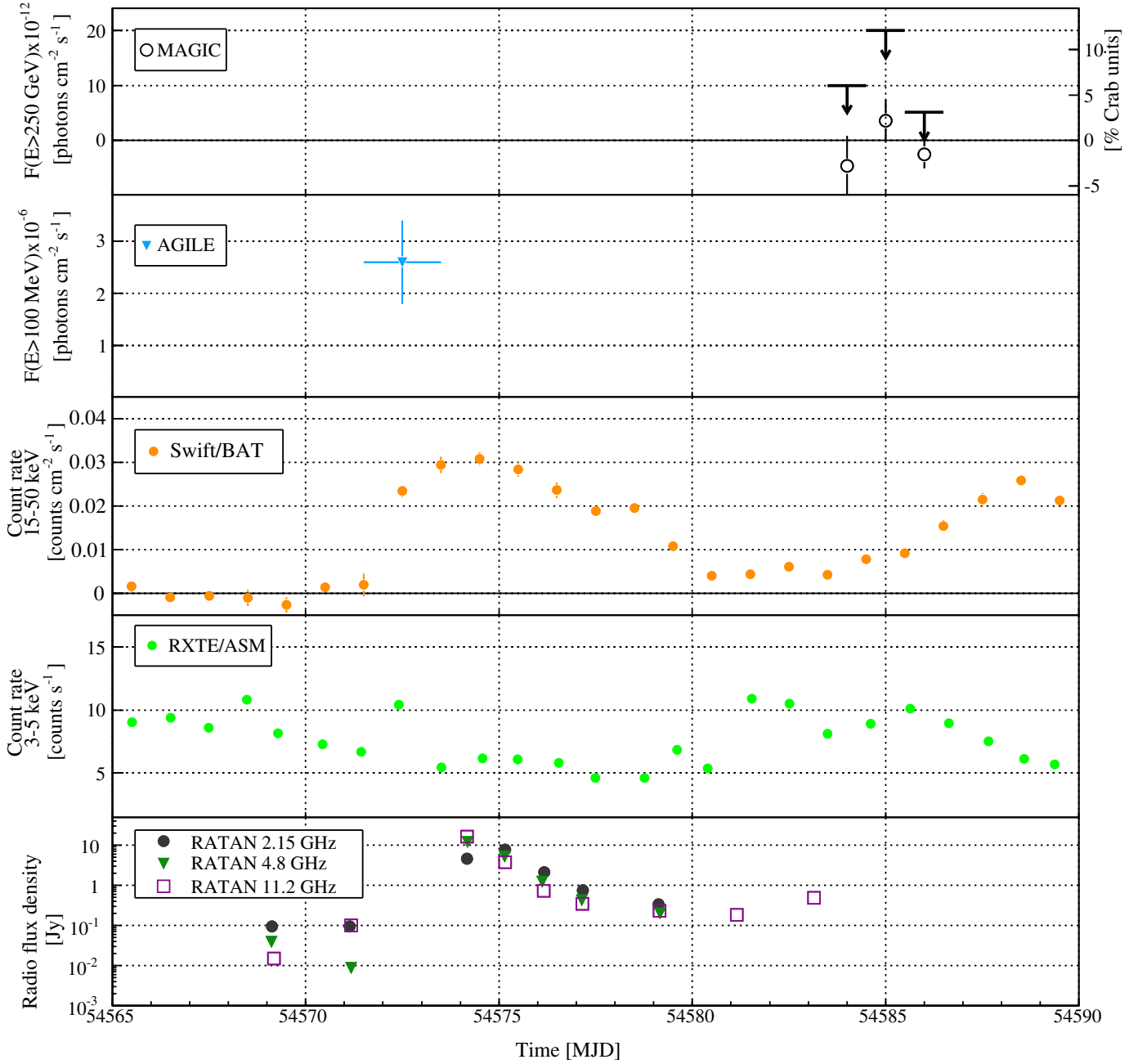


FIG. 9.— Zoom of Figure 2 around cycle IV campaign between 2008 April 9 and May 2. The open circle points in the VHE MAGIC panel show the non-significant measured integral fluxes with their statistical error bars (whereas the upper limits take into account also the systematic errors).