

## DETECTION OF THE $\gamma$ -RAY BINARY LS I +61°303 IN A LOW-FLUX STATE AT VERY HIGH ENERGY $\gamma$ -RAYS WITH THE MAGIC TELESCOPES IN 2009

J. ALEKSIĆ<sup>1</sup>, E. A. ALVAREZ<sup>2</sup>, L. A. ANTONELLI<sup>3</sup>, P. ANTORANZ<sup>4</sup>, M. ASENSIO<sup>2</sup>, M. BACKES<sup>5</sup>, J. A. BARRIO<sup>2</sup>, D. BASTIERI<sup>6</sup>, J. BECERRA GONZÁLEZ<sup>7,8</sup>, W. BEDNAREK<sup>9</sup>, A. BERDYUGIN<sup>10</sup>, K. BERGER<sup>7,8</sup>, E. BERNARDINI<sup>11</sup>, A. BILAND<sup>12</sup>, O. BLANCH<sup>1</sup>, R. K. BOCK<sup>13</sup>, A. BOLLER<sup>12</sup>, G. BONNOLI<sup>3</sup>, D. BORLA TRIDON<sup>13</sup>, V. BOSCH-RAMON<sup>14</sup>, I. BRAUN<sup>12</sup>, T. BRETZ<sup>15,26</sup>, A. CAÑELLAS<sup>14</sup>, E. CARMONA<sup>13</sup>, A. CAROSI<sup>3</sup>, P. COLIN<sup>13</sup>, E. COLOMBO<sup>7</sup>, J. L. CONTRERAS<sup>2</sup>, J. CORTINA<sup>1</sup>, L. COSSIO<sup>16</sup>, S. COVINO<sup>3</sup>, F. DAZZI<sup>16,27</sup>, A. DE ANGELIS<sup>16</sup>, G. DE CANEVA<sup>11</sup>, E. DE CEA DEL POZO<sup>17</sup>, B. DE LOTTO<sup>16</sup>, C. DELGADO MENDEZ<sup>7,28</sup>, A. DIAGO ORTEGA<sup>7,8</sup>, M. DOERT<sup>5</sup>, A. DOMÍNGUEZ<sup>18</sup>, D. DOMINIS PRESTER<sup>19</sup>, D. DORNER<sup>12</sup>, M. DORO<sup>20</sup>, D. ELSAESSER<sup>15</sup>, D. FERENC<sup>19</sup>, M. V. FONSECA<sup>2</sup>, L. FONT<sup>20</sup>, C. FRUCK<sup>13</sup>, R. J. GARCÍA LÓPEZ<sup>7,8</sup>, M. GARCZARCZYK<sup>7</sup>, D. GARRIDO<sup>20</sup>, G. GIAVITTO<sup>1</sup>, N. GODINOVIĆ<sup>19</sup>, D. HADASCH<sup>17</sup>, D. HÄFNER<sup>13</sup>, A. HERRERO<sup>7,8</sup>, D. HILDEBRAND<sup>12</sup>, D. HÖHNE-MÖNCH<sup>15</sup>, J. HOSE<sup>13</sup>, D. HRUPEC<sup>19</sup>, B. HUBER<sup>12</sup>, T. JOGLER<sup>13</sup>, H. KELLERMANN<sup>13</sup>, S. KLEPSEK<sup>1</sup>, T. KRÄHENBÜHL<sup>12</sup>, J. KRAUSE<sup>13</sup>, A. LA BARBERA<sup>3</sup>, D. LELAS<sup>19</sup>, E. LEONARDO<sup>4</sup>, E. LINDFORS<sup>10</sup>, S. LOMBARDI<sup>6</sup>, A. LÓPEZ<sup>1</sup>, M. LÓPEZ<sup>2</sup>, E. LORENZ<sup>12,13</sup>, M. MAKARIEV<sup>21</sup>, G. MANEVA<sup>21</sup>, N. MANKUZHIYIL<sup>16</sup>, K. MANNHEIM<sup>15</sup>, L. MARASCHI<sup>3</sup>, M. MARIOTTI<sup>6</sup>, M. MARTÍNEZ<sup>1</sup>, D. MAZIN<sup>1,13</sup>, M. MEUCCI<sup>4</sup>, J. M. MIRANDA<sup>4</sup>, R. MIRZOYAN<sup>13</sup>, H. MIYAMOTO<sup>13</sup>, J. MOLDÓN<sup>14</sup>, A. MORALEJO<sup>1</sup>, P. MUNAR-ADROVER<sup>14</sup>, D. NIETO<sup>2</sup>, K. NILSSON<sup>10,29</sup>, R. ORITO<sup>13</sup>, I. OYA<sup>2</sup>, D. PANEQUE<sup>13</sup>, R. PAOLETTI<sup>4</sup>, S. PARDO<sup>2</sup>, J. M. PAREDES<sup>14</sup>, S. PARTINI<sup>4</sup>, M. PASANEN<sup>10</sup>, F. PAUSS<sup>12</sup>, M. A. PEREZ-TORRES<sup>1</sup>, M. PERSIC<sup>16,22</sup>, L. PERUZZO<sup>6</sup>, M. PILIA<sup>23</sup>, J. POCHON<sup>7</sup>, F. PRADA<sup>18</sup>, P. G. PRADA MORONI<sup>24</sup>, E. PRANDINI<sup>6</sup>, I. PULJAK<sup>19</sup>, I. REICHARDT<sup>1</sup>, R. REINTHAL<sup>10</sup>, W. RHODE<sup>5</sup>, M. RIBÓ<sup>14</sup>, J. RICO<sup>1,25</sup>, S. RÜGAMER<sup>15</sup>, A. SAGGION<sup>6</sup>, K. SAITO<sup>13</sup>, T. Y. SAITO<sup>13</sup>, M. SALVATI<sup>3</sup>, K. SATALECKA<sup>11</sup>, V. SCALZOTTO<sup>6</sup>, V. SCAPIN<sup>2</sup>, C. SCHULTZ<sup>6</sup>, T. SCHWEIZER<sup>13</sup>, M. SHAYDUK<sup>13</sup>, S. N. SHORE<sup>24</sup>, A. SILLANPÄÄ<sup>10</sup>, J. SITAREK<sup>9</sup>, D. SOBCZYNSKA<sup>9</sup>, F. SPANIER<sup>15</sup>, S. SPIRO<sup>3</sup>, A. STAMERRA<sup>4</sup>, B. STEINKE<sup>13</sup>, J. STORZ<sup>15</sup>, N. STRAH<sup>5</sup>, T. SURIĆ<sup>19</sup>, L. TAKALO<sup>10</sup>, H. TAKAMI<sup>13</sup>, F. TAVECCHIO<sup>3</sup>, P. TEMNIKOV<sup>21</sup>, T. TERZIĆ<sup>19</sup>, D. TESCARO<sup>24</sup>, M. TESHIMA<sup>13</sup>, O. TIBOLLA<sup>15</sup>, D. F. TORRES<sup>17,25</sup>, A. TREVES<sup>23</sup>, M. UELLENBECK<sup>5</sup>, H. VANKOV<sup>21</sup>, P. VOGLER<sup>12</sup>, R. M. WAGNER<sup>13</sup>, Q. WEITZEL<sup>12</sup>, V. ZABALZA<sup>14</sup>, F. ZANDANEL<sup>18</sup>, AND R. ZANIN<sup>1</sup>

<sup>1</sup> IFAE, Edifici Cn., Campus UAB, E-08193 Bellaterra, Spain; [blanch@ifae.es](mailto:blanch@ifae.es)

<sup>2</sup> Universidad Complutense, E-28040 Madrid, Spain

<sup>3</sup> INAF National Institute for Astrophysics, I-00136 Rome, Italy

<sup>4</sup> Università di Siena and INFN Pisa, I-53100 Siena, Italy

<sup>5</sup> Technische Universität Dortmund, D-44221 Dortmund, Germany

<sup>6</sup> Università di Padova and INFN, I-35131 Padova, Italy

<sup>7</sup> Inst. de Astrofísica de Canarias, E-38200 La Laguna, Tenerife, Spain

<sup>8</sup> Depto. de Astrofísica, Universidad de La Laguna, E-38206 La Laguna, Spain

<sup>9</sup> University of Łódź, PL-90236 Lodz, Poland

<sup>10</sup> Tuorla Observatory, University of Turku, FI-21500 Piikkiö, Finland

<sup>11</sup> Deutsches Elektronen-Synchrotron (DESY), D-15738 Zeuthen, Germany

<sup>12</sup> ETH Zurich, CH-8093, Switzerland

<sup>13</sup> Max-Planck-Institut für Physik, D-80805 München, Germany; [jogler@mppmu.mpg.de](mailto:jogler@mppmu.mpg.de)

<sup>14</sup> Universitat de Barcelona (ICC/IEEC), E-08028 Barcelona, Spain

<sup>15</sup> Universität Würzburg, D-97074 Würzburg, Germany

<sup>16</sup> Università di Udine and INFN Trieste, I-33100 Udine, Italy

<sup>17</sup> Institut de Ciències de l'Espai (IEEC-CSIC), E-08193 Bellaterra, Spain

<sup>18</sup> Inst. de Astrofísica de Andalucía (CSIC), E-18080 Granada, Spain

<sup>19</sup> Croatian MAGIC Consortium, Rudjer Boskovic Institute, University of Rijeka and University of Split, HR-10000 Zagreb, Croatia

<sup>20</sup> Universitat Autònoma de Barcelona, E-08193 Bellaterra, Spain

<sup>21</sup> Inst. for Nucl. Research and Nucl. Energy, BG-1784 Sofia, Bulgaria

<sup>22</sup> INAF/Osservatorio Astronomico and INFN, I-34143 Trieste, Italy

<sup>23</sup> Università dell'Insubria, Como, I-22100 Como, Italy

<sup>24</sup> Università di Pisa and INFN Pisa, I-56126 Pisa, Italy

<sup>25</sup> ICREA, E-08010 Barcelona, Spain

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### ABSTRACT

We present very high energy ( $E > 100$  GeV)  $\gamma$ -ray observations of the  $\gamma$ -ray binary system LS I +61°303 obtained with the MAGIC stereo system between 2009 October and 2010 January. We detect a  $6.3\sigma$   $\gamma$ -ray signal above 400 GeV in the combined data set. The integral flux above an energy of 300 GeV is  $F(E > 300 \text{ GeV}) = (1.4 \pm 0.3_{\text{stat}} \pm 0.4_{\text{syst}}) \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ , which corresponds to about 1.3% of the Crab Nebula flux in the same energy range. The orbit-averaged flux of LS I +61°303 in the orbital phase interval 0.6–0.7, where a maximum of the TeV flux is expected, is lower by almost an order of magnitude compared to our previous measurements between 2005 September and 2008 January. This provides evidence for a new low-flux state in LS I +61°303. We find that the change to the low-flux state cannot be solely explained by an increase of photon–photon absorption around the compact star.

**Key words:** binaries: general – gamma rays: general – stars: individual (LS I +61°303) – X-rays: binaries – X-rays: individual (LS I +61°303)

## 1. INTRODUCTION

The LS I +61°303 system consists of a Be star and a compact object of still uncertain nature, either a neutron star or a black hole. Its orbital period, which is most precisely measured in radio, is  $26.4960 \pm 0.0028$  days (Gregory 2002). Soft X-ray outbursts modulated with the same period as in the radio waveband were reported by Paredes et al. (1997) and changes in the orbital evolution have been recently studied (Torres et al. 2010). Many other orbital parameters of the system are less precisely known and different solutions have been proposed (see Casares et al. 2005; Grundstrom et al. 2007; Aragona et al. 2009), but observations indicate a highly eccentric orbit ( $e = 0.55 \pm 0.05$ ) with the periastron passage at orbital phase  $\phi_{\text{per}} = 0.275$  (Aragona et al. 2009). These orbital parameters are important for modeling the very high energy (VHE) emission of the system as shown in, e.g., Sierpowska-Bartosik & Torres (2009) or Dubus et al. (2010).

In 2006 the MAGIC Collaboration discovered variable VHE  $\gamma$ -ray emission from LS I +61°303 (Albert et al. 2006). A subsequent extensive observational campaign in Fall 2006 found a period for the VHE emission of  $26.6 \pm 0.2$  days (Albert et al. 2009). The VHE  $\gamma$ -ray emission shows an outburst in the orbital phase interval 0.6–0.7 with no significant  $\gamma$ -ray emission detected during the rest of the orbit. In particular, no VHE  $\gamma$ -ray signal was detected by MAGIC around the periastron passage of the system. The data from Fall 2006 also suggested a correlation between the X-ray and VHE  $\gamma$ -ray flux (Albert et al. 2008a). An extensive multi-wavelength campaign conducted in 2007, including MAGIC, *XMM-Newton*, and *Swift*, provided strong evidence for the X-ray/VHE  $\gamma$ -ray flux correlation in strictly simultaneous data (Anderhub et al. 2009). In contrast, no correlation was found between the radio wavelength flux and the VHE  $\gamma$ -ray flux from the Fall of 2006 campaign (Albert et al. 2008a).

The VHE emission of LS I +61°303 was confirmed by VERITAS observations between 2006 September and 2007 February (Acciari et al. 2008). However, in observations conducted by the VERITAS Collaboration in Fall 2008 and early 2009, no VHE signal was detected. More recent VERITAS observations in Fall 2009 (the same time period as in the present paper) also yielded only upper limits for VHE emission from LS I +61°303 (Acciari et al. 2011). Very recently the VERITAS Collaboration reported a detection of the system with a significance of more than  $5\sigma$  (Acciari et al. 2011) between orbital phases 0.05 and 0.23. This places the detection at superior conjunction and 5.8 to 1.3 days before the periastron passage. No VHE  $\gamma$ -ray emission was previously detected in this phase range.

The binary system was observed in high energy (HE, 0.1 – 100 GeV)  $\gamma$ -rays by EGRET (Kniffen et al. 1997) but the large position uncertainty of the source and inconclusive variability studies of the emission prevented its unambiguous identification. The positional association with LS I +61°303 was only achieved following HE  $\gamma$ -ray observations by AGILE (Pittori et al. 2009). More recently, *Fermi*/LAT found that the HE  $\gamma$ -rays are periodically modulated in very good agreement

with the (radio) orbital period (Abdo et al. 2009) establishing beyond doubt that the signal origins from LS I +61°303. The HE outburst was not, however, observed at the same phases as the VHE outburst but occurred between phase 0.3 and 0.45 just after the periastron passage. This difference in phase may indicate that different processes are responsible for the HE and VHE  $\gamma$ -ray emission. On the other hand, the same process might produce both emissions if the GeV  $\gamma$ -rays are produced by cascading inverse Compton (IC) pairs developing in the radiation field of the star. This cascade would reduce the TeV emission and enhance the GeV emission when the compact object is close to the star. For more details on such a scenario see Bednarek (2006b). Another possibility is that the shift in the peak emission could be caused by a different location of the  $\gamma$ -ray production site in the system (Zabalza et al. 2011). We note that no simultaneous VHE observations are available at the same epoch (2008 August to 2009 January) of the first reported *Fermi* observations (Abdo et al. 2009). An unambiguous interpretation of the non simultaneous SED from MeV to TeV energies of LS I +61°303 is not possible because the system might have changed its VHE emission in the meantime.

Two principal scenarios have been proposed to explain the non-thermal emission from LS I +61°303: an accretion powered microquasar (e.g., Romero et al. 2005; Bednarek 2006a; Gupta & Böttcher 2006; Bosch-Ramon et al. 2006) and a rotation-powered compact pulsar wind (e.g., Dubus 2006; Sierpowska-Bartosik & Torres 2009; Zdziarski et al. 2010). An alternative model assumes that the compact object is an accreting magnetar and that the  $\gamma$ -rays are produced along the accretion flow onto the magnetar (Bednarek 2009). High resolution radio measurements (Dhawan et al. 2006) show an extended structure varying in shape and position as a function of the orbital phase. While this was taken as evidence for a pulsar wind interacting with that of the Be star other interpretations were suggested as well (Romero et al. 2007). Neither of the two proposed scenarios could be validated by accretion disk features, e.g., a thermal component in the X-ray spectrum or the presence of pulsed emission at any wavelength. Thus the engine behind the VHE emission remains an open question.

Here, we present new observations of LS I +61°303 conducted with the MAGIC stereo system. This has twice the sensitivity of the previous MAGIC campaigns and results in a significant detection of the binary system during a newly identified low-flux state. We briefly discuss the observational technique and the data analysis procedure, present the VHE  $\gamma$ -ray light curve of the source, and put the results in context of the previous VHE  $\gamma$ -ray observations of this system.

## 2. OBSERVATIONS

The observations were performed between 2009 October 15 and 2010 January 22 using the MAGIC telescopes on the Canary island of La Palma (28°75N, 17°86W, 2225 m a.s.l.), from where LS I +61°303 is observable at zenith distances above 32°. The MAGIC stereo system consists of two imaging air Cherenkov telescopes, each with a 17 m diameter mirror. The observations were carried out in stereo mode, meaning only shower images which trigger simultaneously both telescopes are recorded. The stereoscopic observations provide a  $5\sigma$  signal above 300 GeV from a source which exhibits 0.8% of the Crab Nebula flux in 50 hr observation time, a factor of two more sensitive than our single telescope campaign on LS I +61°303 in 2007. Further details on the design and performance of the MAGIC stereo system can be found in Aleksić et al. (2011).

<sup>26</sup> Now at École polytechnique fédérale de Lausanne (EPFL), Lausanne, Switzerland.

<sup>27</sup> Supported by INFN Padova.

<sup>28</sup> Now at Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain.

<sup>29</sup> Now at Finnish Centre for Astronomy with ESO (FINCA), University of Turku, Finland.

**Table 1**  
Observation Time, Orbital Phase, Integral Flux (Above 300 GeV)

Middle Time (MJD)	Obs. Time (minutes)	Phase	Significance (pre-trial)	Flux $10^{-12}$ ( $\text{cm}^{-2} \text{s}^{-1}$ )	Upper Limit $10^{-12}$ ( $\text{cm}^{-2} \text{s}^{-1}$ )
55119.07	138	0.57	0.8	$1.1 \pm 1.4$	4.0
55121.08	176	0.64	0.6	$0.7 \pm 1.2$	3.2
55122.08	194	0.68	1.0	$0.7 \pm 0.8$	2.4
55126.06	104	0.83	0.6	$0.8 \pm 1.3$	3.6
55127.06	137	0.87	1.9	$2.5 \pm 1.4$	5.5
55128.07	137	0.91	1.4	$1.8 \pm 1.4$	4.9
55129.06	132	0.95	3.8	$5.7 \pm 1.7$	...
55130.06	135	0.98	2.5	$3.5 \pm 1.5$	...
55145.97	140	0.58	2.0	$2.8 \pm 1.5$	...
55147.01	221	0.62	4.9	$6.1 \pm 1.4$	...
55148.00	216	0.66	-1.8	$-1.8 \pm 0.9$	1.0
55149.02	171	0.70	-0.5	$-0.5 \pm 1.1$	1.9
55153.99	123	0.89	0.5	$0.3 \pm 0.6$	1.8
55154.98	149	0.92	-0.2	$-0.2 \pm 1.2$	2.5
55155.98	115	0.96	-0.3	$-0.5 \pm 1.6$	2.9
55156.95	73	1.00	-0.7	$-1.2 \pm 1.7$	2.9
55157.97	82	0.04	0.9	$1.0 \pm 1.1$	3.6
55215.90	134	0.22	1.0	$1.3 \pm 1.4$	4.2
55216.90	161	0.26	0.6	$0.6 \pm 1.2$	3.2
55217.90	165	0.30	2.0	$2.0 \pm 1.1$	...

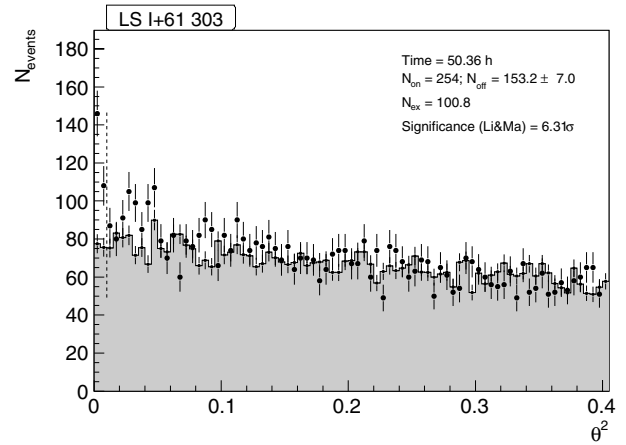
**Notes.** Flux upper limit at the 95% confidence level is quoted in case flux significance is  $\lesssim 2\sigma$  (Rolke et al. 2005). All errors are statistical only we estimate an additional systematic uncertainty of about 40%. The systematic uncertainty is only important in case of comparing between different experiments.

The LS I +61°303 data set spans four orbits of the system, with two observed for only one and three nights, respectively. The data taken in 2009 October and 2009 November were restricted to moonless nights. The data sample the orbital phases 0.55 to 0.98 for 2009 October, and 0.58 to 1.02 for 2009 November, the last night of which is in the next orbital cycle. The data recorded in 2010 January cover the phases 0.22 to 0.32 and were obtained during moonlight conditions (see Table 1). All data were taken at zenith angles between 32° and 48°. After pre-selection of good quality data a total of 48.4 hr of data remained for the analysis. The observation strategy aimed to cover consecutive nights with at least 3 hr of observation in each individual night. Due to adverse observation conditions such as bad weather, the data set does not have uniform coverage during the orbital phases and some nights have shorter observation times than the planned 3 hr.

### 3. DATA ANALYSIS

The data analysis was performed with the standard MAGIC reconstruction software. The recorded shower images were calibrated, cleaned, and used to calculate image parameters individually for each telescope. The energy of each event was then estimated using look up tables generated by Monte Carlo (MC) simulated  $\gamma$ -ray events. The events that simultaneously triggered both telescopes (the so-called stereo events) were then selected<sup>30</sup> and further parameters, e.g., the height of the shower maximum and the impact parameter from each telescope, were calculated. The gamma hadron classifications and reconstructions of the incoming direction of the primary shower particles were then performed using the Random Forest (RF)

<sup>30</sup> This step is only needed for the 2009 October data where no hardware stereo trigger was yet available.



**Figure 1.** Squared angular distance between the pointing direction of the shower and the source position ( $\theta^2$ -plot) for the position of LS I +61°303 (points) and the simultaneous determined background regions (gray shaded histogram) for the total 2009/2010 MAGIC data set.  $N_{\text{on}}$  is the number of events at the source position,  $N_{\text{off}}$  is the number of background events,  $N_{\text{ex}}$  is the number of excess events ( $N_{\text{ex}} = N_{\text{on}} - N_{\text{off}}$ ), and the significance was calculated according to Li & Ma (1983).

method (Albert et al. 2008b). The RF calculates a variable called hadronness which is a measure of the probability that an event is of hadronic origin. Finally, the signal selection used cuts in the hadronness (calculated by the RF) and in the squared angular distance between the shower pointing direction and the source position ( $\theta^2$ ). The energy dependent cut values were determined by optimizing them on a sample of events recorded from the Crab Nebula under the same zenith angle range and similar epochs than the LS I +61°303 data. For the energy spectrum and flux, the effective detector area was estimated by applying the same cuts used on the data sample to a sample of MC simulated  $\gamma$ -rays. Finally, the energy spectrum was unfolded, accounting for the energy resolution and possible energy reconstruction bias (Albert et al. 2007).

In this analysis we use for the estimation of the detection significance a set of cuts optimized to yield the highest significance on a sample of Crab Nebula data under similar observation conditions as the LS I +61°303 data set. These cuts are then applied to a set of simulated MC  $\gamma$ -rays to estimate the energy threshold of the detection plot ( $E_{\text{th}} = 400 \text{ GeV}$ ). For the light curve and spectrum determination softer cuts are used to reduce systematic effects and provide a lower energy threshold by sacrificing the highest significance.

### 4. RESULTS

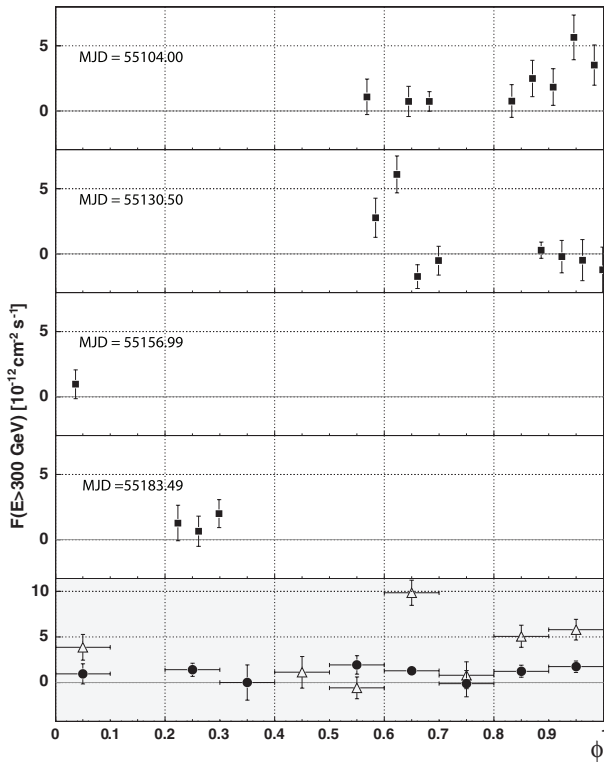
The integral data set of 48.8 hr presented here results in a  $6.3\sigma$  detection of VHE  $\gamma$ -ray emission above 400 GeV from LS I +61°303 (see Figure 1). The integrated flux above 300 GeV is

$$F(E > 300 \text{ GeV}) = (1.4 \pm 0.3_{\text{stat}} \pm 0.4_{\text{sys}}) \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$$

corresponding to about 1.3% of the Crab Nebula flux in the same energy range.

#### 4.1. Light Curve

We derived a nightly light curve above an energy of 300 GeV that is shown in Figure 2. The measured fluxes and upper limits are quoted in Table 1. A constant flux fit to the light curve yields a  $\chi^2/\text{dof} = 42.15/19$  ( $p = 1.5 \times 10^{-3}$ ) and hence

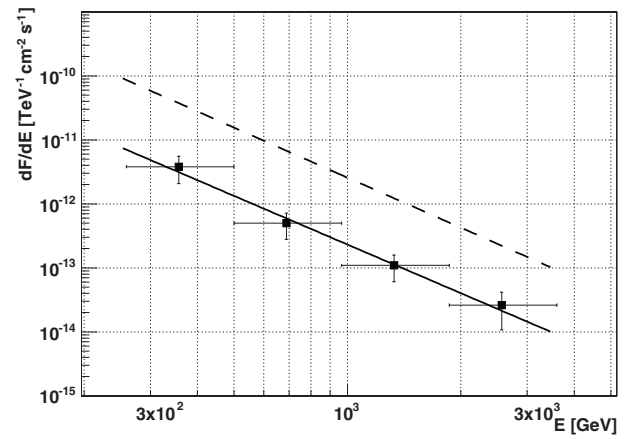


**Figure 2.** VHE ( $E > 300$  GeV)  $\gamma$ -ray flux of LS I +61°303 as a function of the orbital phase for the four observed orbital cycles (four upper panels) and averaged for the entire observation time (lowermost panel, black points). The starting MJD of each orbital cycle is given in the corresponding panel. In the lower most panel we show as hollow triangles the previous published (Anderhub et al. 2009) averaged fluxes per phase bin. Vertical error bars show  $1\sigma$  statistical errors.

is unlikely. Thus, as in previous observations, the emission is variable and reaches a maximum flux around orbital phase 0.62 of  $F(E > 300 \text{ GeV}) = (6.1 \pm 1.4_{\text{stat}} \pm 2.4_{\text{syst}}) \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ , corresponding to 5.4% of the Crab Nebula flux. This is a much lower peak emission than detected in our previous campaigns at the same orbital phases and sampled with very similar cadence. For a more quantitative comparison of the 2009 emission level with the previous MAGIC observations, we included in Figure 2 the light curve of the 2007 data averaged in 0.1 phase bins.

We found that the averaged emission level is dramatically lower than measured in our campaigns from 2005 to 2007 (Albert et al. 2006; Albert et al. 2009; Anderhub et al. 2009). Not only had the flux changed but a VHE  $\gamma$ -ray excess was also observed at phases other than those of the periodic outburst between 0.6 and 0.7. The highest flux is, however, again detected in an outburst during the interval 0.6–0.7, and the measurements in the orbital cycle of 2009 November show the same burst profile as in previous observations but with a reduced flux level. Whether the outburst recurrence is still a periodic property of the VHE emission for LS I +61°303 and whether it shows the same shape as in previous campaigns, cannot be determined with the small number of orbital cycles observed in this campaign. It is noteworthy that the outburst was not detected during the orbit observed in 2009 October.

The mean flux for all phase bins is given in Table 2. The rather low mean values, even in the phase bin 0.6–0.7, of the individual night peak emission indicates that most of the emission of the system is contributed by only few nights instead of a constant flux. A fit to a constant flux in the phase bin 0.6–0.7 yields a  $\chi^2/\text{dof} = 22.4/4$  being strongly disfavored.



**Figure 3.** Spectrum of the complete LS I +61°303 data sample recorded by the MAGIC stereo system in 2009 is shown in black. The vertical errors are  $1\sigma$  statistical errors. The fit to the most precise measured spectrum from Fall 2006 (Albert et al. 2009) is shown as the dashed line. The 2009 spectrum is fitted by a simple power law as well and the fit parameters are compatible to our previous measurements from 2005 to 2008 (see the text for discussion).

**Table 2**  
Average Flux Level Above 300 GeV for Each Orbital 0.1 Phase Bin

Phase Bin	Flux ( $10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ )	Flux Upper Limit ( $10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ )
0.0–0.1	$1.0 \pm 1.1$	1.3
0.1–0.2	...	...
0.2–0.3	$1.4 \pm 0.7$	...
0.3–0.4	$0.0 \pm 1.9$	0.0
0.4–0.5	...	...
0.5–0.6	$1.9 \pm 1.0$	1.3
0.6–0.7	$1.3 \pm 0.5$	...
0.7–0.8	$-0.1 \pm 1.4$	2.0
0.8–0.9	$1.2 \pm 0.7$	1.1
0.9–1.0	$1.7 \pm 0.6$	...

**Notes.** Flux upper limit at the 95% confidence level is quoted in case flux significance is  $\lesssim 2\sigma$  (Rolke et al. 2005). All errors are statistical only we estimate an additional systematic uncertainty of about 40%. The systematic uncertainty is only important in case of comparing between different experiments.

#### 4.2. Spectrum

The emission level of LS I +61°303 was too low during most phases to obtain statistical significant phase-dependent spectra. The total signal, however, was sufficient to form a phase-integrated spectrum with good enough statistic per bin to perform a chi-square test, shown in Figure 3. The spectrum is well described by a simple power law

$$\frac{dF}{dE} = \frac{(2.3 \pm 0.6_{\text{stat}} \pm 0.2_{\text{syst}}) \cdot 10^{-13}}{\text{TeV cm}^2 \text{ s}} \frac{E^{-2.5 \pm 0.5_{\text{stat}} \pm 0.2_{\text{syst}}}}{1 \text{ TeV}},$$

with a  $\chi^2/\text{dof} = 0.42/2$ . The spectral slope is compatible within errors with those previously reported by MAGIC (Albert et al. 2006; Albert et al. 2009; Anderhub et al. 2009). Hence, no evidence for long term spectral variability despite very different fluxes during these different campaigns is observed. Moreover, an exponential cutoff was also fitted allowing the power-law parameters to vary in the  $1\sigma$  range (adding linearly statistical and systematic uncertainties) with respect to the fitted spectra in Anderhub et al. (2009). That leads to a best-fit cutoff at 483 GeV with a reduced  $\chi^2/\text{dof} = 4.8/1$ , which is strongly increased with respect to the power-law fit and hence strongly disfavors a cutoff in the spectra to explain the reduced flux level.

## 5. DISCUSSION

The binary system LS I +61°303 was detected emitting VHE  $\gamma$ -rays in 2009–2010 at a level a factor 10 lower than previously observed in the phase interval 0.6–0.7. The previously observed orbital modulated outburst in this interval was not detected during the first observed orbital cycle, whereas it was observed in the second. From this data set alone it was not possible to determine whether the outburst is still a truly periodic feature of the light curve. There are also other orbital phases, varying from one orbit to another, during which significant emission was observed from 2005 to 2008. These individual nights were rarely observed and contributed only a minor fraction to the integral signal from LS I +61°303 in these campaigns. Although we could not significantly detect emission at individual orbital phases in the here presented observations because of the weakness of the source, it appears that several phase intervals dominate in the integral signal. This is strong evidence for a new behavior in the VHE  $\gamma$ -ray emission of LS I +61°303. In previous observations conducted with MAGIC, the 0.6–0.7 interval dominated the total flux.

Furthermore, it is evident that the flux during that phase interval is considerably reduced compared to the previous campaigns and on a similar level as in other phase intervals (e.g., 0.9–1.0). This suggests that a change in the VHE  $\gamma$ -ray emission of LS I +61°303 has occurred. On the other hand, there was no statistically significant change in the spectrum of the orbit-integrated flux in 2009 compared to the earlier results, suggesting that the same processes continue to produce VHE gamma-rays, but that either fewer are produced or they are more absorbed.

If enhanced opacity causes the observed decreases in the VHE flux, the photons will be redistributed to lower energies and thus might be visible as a flux enhancement. Those VHE  $\gamma$ -rays would thus need to propagate through a circum-source environment with a higher photon energy density and we would expect to detect a cutoff or an absorption feature in our spectrum. A cutoff in our energy range that reduces the integral flux by a factor of 10 compared to our previous measurements (e.g., Anderhub et al. 2009) is incompatible with our spectrum. The spectral fit disfavors an increased photon–photon absorption around the emission region as the explanation for the flux reduction in the VHE domain.

Another possibility is that there might be fewer accelerated particles and/or fewer seed photons or less target matter, resulting in lower VHE  $\gamma$ -rays production, depending on the details of the assumed model (microquasar, pulsar wind, leptonic, or hadronic production). However, regardless of the scenario, a change in the stellar wind density profile might explain the change in the VHE  $\gamma$ -ray emission level: the wind density, velocity, and porosity determine the accretion rate in the microquasar scenario and the location of the termination shock in the pulsar wind scenario. Depending on the magnitude of these changes it might be difficult to explain the large variation in the VHE domain, at least a recent study of the effect of wind clumping in the framework of a microquasar scenario found only variations of about 10% (Owocki et al. 2009). In addition, the effect of possible stellar wind density variations on the VHE emission in LS I +61°303 is not yet well understood.

The VERITAS observations in the same period as we have presented here did not detect VHE  $\gamma$ -ray emission from the system (Acciari et al. 2011). Our measurements are not, however, in contradiction to those of VERITAS. Our longer integration combined with a denser sampling of two orbital cycles yielded

a fainter detection threshold than from previous campaigns expected VHE  $\gamma$ -ray signal from LS I +61°303. Thus, it is evident that a frequent sampling with long individual integrations is required not to miss weak emission from binary systems.

This is the first VHE  $\gamma$ -ray detection of LS I +61°303 in the era of the *Fermi* satellite. The faint emission at VHE  $\gamma$ -rays does not yet permit night by night correlation studies but do show that the emission in LS I +61°303 has changed on longer timescale, since 2007. More sensitive and even deeper VHE  $\gamma$ -ray observations should yield shorter timescale correlation studies.

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Facility: MAGIC

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