Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

MNRAS **440,** 530–535 (2014)
Advance Access publication 2014 March 11

doi:10.1093/mnras/stu227

Search for very high energy gamma-rays from the $z = 0.896$ quasar 4C +55.17 with the MAGIC telescopes

J. Aleksić,[1] S. Ansoldi,[2] L. A. Antonelli,[3] P. Antoranz,[4] A. Babic,[5] P. Bangale,[6] U. Barres de Almeida,[6] J. A. Barrio,[7] J. Becerra González,[8] W. Bednarek,[9] K. Berger,[8] E. Bernardini,[10] A. Biland,[11] O. Blanch,[1] R. K. Bock,[6] S. Bonnefoy,[7] G. Bonnoli,[3] F. Borracci,[6] T. Bretz,[12,⋆] E. Carmona,[13] A. Carosi,[3] D. Carreto Fidalgo,[12] P. Colin,[6] E. Colombo,[8] J. L. Contreras,[7] J. Cortina,[1] S. Covino,[3] P. Da Vela,[4] F. Dazzi,[14] A. De Angelis,[2] G. De Caneva,[10] B. De Lotto,[2] C. Delgado Mendez,[13] M. Doert,[15] A. Domínguez,[16,†,§] D. Dominis Prester,[5] D. Dorner,[12] M. Doro,[14] S. Einecke,[15] D. Eisenacher,[12] D. Elsaesser,[12] E. Farina,[17] D. Ferenc,[5] M. V. Fonseca,[7] L. Font,[18] K. Frantzen,[15] C. Fruck,[6] R. J. García López,[8] M. Garczarczyk,[10] D. Garrido Terrats,[18] M. Gaug,[18] G. Giavitto,[1] N. Godinović,[5] A. González Muñoz,[1] S. R. Gozzini,[10] D. Hadasch,[19] M. Hayashida,[20] A. Herrero,[8] D. Hildebrand,[11] J. Hose,[6] D. Hrupec,[5] W. Idec,[9] V. Kadenius,[21] H. Kellermann,[6] M. L. Knoetig,[11] K. Kodani,[20] Y. Konno,[20] J. Krause,[6] H. Kubo,[20] J. Kushida,[20] A. La Barbera,[3] D. Lelas,[5] N. Lewandowska,[12] E. Lindfors,[21,‡] S. Lombardi,[3] M. López,[7] R. López-Coto,[1] A. López-Oramas,[1] E. Lorenz,[6] I. Lozano,[7] M. Makariev,[22] K. Mallot,[10] G. Maneva,[22] N. Mankuzhiyil,[2] K. Mannheim,[12] L. Maraschi,[3] B. Marcote,[23] M. Mariotti,[14] M. Martínez,[1] D. Mazin,[6] U. Menzel,[6] M. Meucci,[4] J. M. Miranda,[4] R. Mirzoyan,[6] A. Moralejo,[1] P. Munar-Adrover,[23] D. Nakajima,[20] A. Niedzwiecki,[9] K. Nilsson,[21,‡] K. Nishijima,[20] N. Nowak,[6] R. Orito,[20] A. Overkemping,[15] S. Paiano,[14] M. Palatiello,[2] D. Paneque,[6,§] R. Paoletti,[4] J. M. Paredes,[23] X. Paredes-Fortuny,[23] S. Partini,[4] M. Persic,[2] F. Prada,[16,24] P. G. Prada Moroni,[25] E. Prandini,[14] S. Preziuso,[4] I. Puljak,[5] R. Reinthal,[21] W. Rhode,[15] M. Ribó,[23] J. Rico,[1] J. Rodriguez Garcia,[6] S. Rügamer,[12] A. Saggion,[14] T. Saito,[20] K. Saito,[20] M. Salvati,[3] K. Satalecka,[7] V. Scalzotto,[14] V. Scapin,[7] C. Schultz,[14] T. Schweizer,[6] S. N. Shore,[25] A. Sillanpää,[21] J. Sitarek,[1,§] I. Snidaric,[5] D. Sobczynska,[9] F. Spanier,[12] V. Stamatescu,[1] A. Stamerra,[3] T. Steinbring,[12] J. Storz,[12] S. Sun,[6] T. Surić,[5] L. Takalo,[21] H. Takami,[20,§] F. Tavecchio,[3] P. Temnikov,[22] T. Terzić,[5] D. Tescaro,[8] M. Teshima,[6] J. Thaele,[15] O. Tibolla,[12] D. F. Torres,[19] T. Toyama,[6] A. Treves,[17] P. Vogler,[11] R. M. Wagner,[6,¶] F. Zandanel[16,‖] and R. Zanin[23]

[1] *IFAE, Edifici Cn., Campus UAB, E-08193 Bellaterra, Spain*
[2] *Università di Udine, and INFN Trieste, I-33100 Udine, Italy*

[⋆] Present address: Ecole polytechnique fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland.

[†] Present address: Department of Physics, and Astronomy, UC Riverside, CA 92521, USA.

[‡] Present address: Finnish Centre for Astronomy with ESO (FINCA), University of Turku, FI-21500 PIIKKIÖ, Finland.

[§] E-mail: takami@post.kek.jp (HT); jsitarek@ifae.es (JS); albertod@ucr.edu (AD); dPaneque@mppmu.mpg.de (DP)

[¶] Present address: Oskar Klein Centre for Cosmoparticle Physics, Stockholm University, SE-106 91 Stockholm, Sweden.

[‖] Present address: GRAPPA Institute, University of Amsterdam, 1098XH Amsterdam, the Netherlands.

Published by Oxford University Press on behalf of the Royal Astronomical Society

[3]*INAF National Institute for Astrophysics, I-00136 Rome, Italy*
[4]*Università di Siena, and INFN Pisa, I-53100 Siena, Italy*
[5]*Croatian MAGIC Consortium, Rudjer Boskovic Institute, University of Rijeka and University of Split, HR-10000 Zagreb, Croatia*
[6]*Max-Planck-Institut für Physik, D-80805 München, Germany*
[7]*Universidad Complutense, E-28040 Madrid, Spain*
[8]*Inst. de Astrofísica de Canarias, E-38200 La Laguna, Tenerife, Spain*
[9]*University of Łódź, PL-90236 Łódź, Poland*
[10]*Deutsches Elektronen-Synchrotron (DESY), D-15738 Zeuthen, Germany*
[11]*ETH Zurich, CH-8093 Zurich, Switzerland*
[12]*Universität Würzburg, D-97074 Würzburg, Germany*
[13]*Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, E-28040 Madrid, Spain*
[14]*Università di Padova and INFN, I-35131 Padova, Italy*
[15]*Technische Universität Dortmund, D-44221 Dortmund, Germany*
[16]*Inst. de Astrofísica de Andalucía (CSIC), E-18080 Granada, Spain*
[17]*Università dell'Insubria, Como, I-22100 Como, Italy*
[18]*Unitat de Física de les Radiacions, Departament de Física, and CERES-IEEC, Universitat Autònoma de Barcelona, E-08193 Bellaterra, Spain*
[19]*ICREA and Institut de Ciències de l'Espai (IEEC-CSIC), E-08193 Bellaterra, Spain*
[20]*Japanese MAGIC Consortium, Division of Physics and Astronomy, Kyoto University, Kyoto 606-8501, Japan*
[21]*Finnish MAGIC Consortium, Tuorla Observatory, University of Turku and Department of Physics, University of Oulu, FI-90014 Oulu, Finland*
[22]*Inst. for Nucl. Research and Nucl. Energy, BG-1784 Sofia, Bulgaria*
[23]*Universitat de Barcelona (ICC, IEEC-UB), E-08028 Barcelona, Spain*
[24]*Instituto de Fisica Teorica, UAM/CSIC, E-28049 Madrid, Spain*
[25]*Università di Pisa, and INFN Pisa, I-56126 Pisa, Italy*

Accepted 2014 January 31. Received 2014 January 24; in original form 2013 November 15

ABSTRACT

The bright gamma-ray quasar 4C +55.17 is a distant source ($z = 0.896$) with a hard spectrum at GeV energies as observed by the Large Area Telescope (LAT) on board the *Fermi* satellite. This source is identified as a good source candidate for very high energy (VHE; >30 GeV) gamma-rays. In general, VHE gamma-rays from distant sources provide a unique opportunity to study the extragalactic background light (EBL) and underlying astrophysics. The flux intensity of this source in the VHE range is investigated. Then, constraints on the EBL are derived from the attenuation of gamma-ray photons coming from the distant blazar. We searched for a gamma-ray signal from this object using the 35 h observations taken by the MAGIC (Major Atmospheric Gamma-ray Imaging Cherenkov) telescopes between 2010 November and 2011 January. No significant VHE gamma-ray signal was detected. We computed the upper limits of the integrated gamma-ray flux at the 95 per cent confidence level of 9.4×10^{-12} and 2.5×10^{-12} cm^{-2} s^{-1} above 100 and 200 GeV, respectively. The differential upper limits in four energy bins in the range from 80 to 500 GeV are also derived. The upper limits are consistent with the attenuation predicted by low-flux EBL models on the assumption of a simple power-law spectrum extrapolated from LAT data.

Key words: radiation mechanisms: non-thermal – galaxies: active – galaxies: nuclei – quasars: individual: 4C +55.17 – gamma-rays: galaxies.

1 INTRODUCTION

Gamma-ray astronomy has rapidly grown in recent years thanks to the development of Imaging Atmospheric Cherenkov Telescopes (IACTs), which are able to observe gamma-rays at very high energies (VHE; >30 GeV), such as the High Energy gamma-ray Spectroscopic System (HESS; Aharonian et al. 2006a), the Major Atmospheric Gamma-ray Imaging Cherenkov (MAGIC; Aleksić et al. 2012) telescopes and the Very Energetic Radiation Imaging Telescope Array System (VERITAS; Nepomuk Otte & the VERITAS Collaboration 2009). Space telescopes observing in the GeV energy band such as the Large Area Telescope (LAT) on board the *Fermi* satellite (Atwood et al. 2009) have also substantially contributed to progress in the field.

VHE photons, with energies above a characteristic energy, are strongly attenuated through electron–positron pair creation in the extragalactic background light (EBL). This characteristic EBL absorption energy is defined by the photon energy at which the pair creation optical depth is unity. The characteristic energy depends on the source's redshift. The attenuation results in a much softer spectrum at the Earth than that of the intrinsic spectrum of a source (e.g. Nikishov 1962; Gould & Schréder 1966; Stecker, de Jager

& Salamon 1992). The characteristic energy is lower for sources with higher redshift. Thus, the detection of VHE gamma-rays from distant sources is a challenge for IACTs. On the other hand, this absorption process brings a unique opportunity to study the EBL (e.g. Stecker & de Jager 1993; Stanev & Franceschini 1998), which is difficult to be measured directly due to strong Galactic foregrounds (e.g. Hauser & Dwek 2001; Dwek & Krennrich 2013). The EBL is mainly interpreted as stellar and dust emission integrated over the cosmic history. Therefore, VHE gamma-ray observations can be used to extract information on the imprinted cosmic stellar and galaxy evolution.

Observations of VHE gamma-ray sources with different redshifts allow us to investigate the EBL in different wavelengths and hence to examine underlying astrophysics and cosmology at different epochs. In particular, VHE gamma-ray observations of BL Lac objects at $z \lesssim 0.2$ have constrained EBL models from optical to infrared wavelengths (e.g. Aharonian et al. 2006b, 2007). The most distant object ever detected in the VHE range, with firmly confirmed redshift, is the flat spectrum radio quasar (FSRQ) 3C 279 ($z = 0.536$; Albert et al. 2008). This source has also been utilized to constrain EBL models on the assumption that the intrinsic power-law index in the VHE range is softer than -1.5. Recently, two sources with possibly higher redshifts have been detected, namely KUV 00311−1938 (Becherini et al. 2012) with $z \geq 0.506$ (Pita et al. 2012) and PKS 1424+240 with $z \geq 0.6035$ (Acciari et al. 2010; Furniss et al. 2013), but they have not been used to estimate the EBL density due to the uncertainty in their redshift measurements. Moreover, different authors have recently claimed the detection of the EBL imprint by the statistical analyses of the spectra of blazars (Ackermann et al. 2012; Abramowski et al. 2013; Domínguez et al. 2013). In particular, the analysis of Ackermann et al. (2012) covers the wide redshift range ($0.2 \lesssim z \leq 1.6$) using LAT data. Abramowski et al. (2013) focus on lower redshift blazars detected by HESS ($z < 0.2$). Domínguez et al. (2013) use the multiwavelength data of the spectral energy distribution (SED) of blazars to estimate the cosmic gamma-ray horizon from the local Universe to $z \sim 0.5$ by using an EBL model-independent technique. Although the LAT has unveiled the EBL at high redshifts ($z \sim 1$), the detection of sources with high redshifts in the VHE range allows us to test different (longer than in the LAT energy range) wavelengths of the EBL which have not yet been investigated. The MAGIC telescopes have achieved an analysis energy threshold below 100 GeV, and therefore are an ideally suited instrument among existing IACTs to study high-redshift sources.

In this paper, we report the observational results of the distant quasar 4C + 55.17 ($z = 0.896$) by the MAGIC telescopes. This source was recognized as a promising high-redshift candidate for VHE emission from the first LAT AGN Catalog (1LAC; Abdo et al. 2010). Moreover, 4C + 55.17 was also identified as a good source candidate for VHE detection by the *Fermi* LAT collaboration in a dedicated high-energy data analysis (private communication, 2010 September), and by Neronov, Semikoz & Vovk (2011). The spectrum in the LAT energy range is hard and consistent with a power law $\mathrm{d}N/\mathrm{d}E \propto E^{-\alpha}$ with $\alpha = 2.05 \pm 0.03$ in the range from 100 MeV to 100 GeV, not showing significant flux variability in the 1LAC (Abdo et al. 2010). The spectral hardness of gamma-ray sources is particularly important to study the EBL because of the limited sensitivities of IACTs; harder sources can provide more photons with energies above the characteristic EBL absorption energy, allowing for studies with better precision. Even with a spectral break at the energy of several GeV recently reported (Ackermann et al. 2011; McConville et al. 2011; Neronov et al. 2012), this source is still a good candidate for a distant VHE gamma-ray emitter.

This source is a radio-loud active galaxy with the firmly confirmed redshift of $z = 0.896$ estimated from broad optical emission lines in its spectrum (Wills et al. 1995; Adelman-McCarthy et al. 2008). It had been categorized as an FSRQ, but interestingly the classification has recently been questioned due to its morphological and spectroscopic properties which are distinct from those of other FSRQs (Rossetti et al. 2005). FSRQs are characterized by a centrally concentrated radio core with high brightness temperature and highly variable flux. However, the brightness temperature of this source is 2×10^8 K at 5 GHz (Taylor et al. 2007), which is much lower than that of the other known quasar-hosted gamma-ray blazars (McConville et al. 2011), and a light curve in the LAT energy range is consistent with steady emission (Furniss & McConville 2013). Note that only strong variability can be significantly detected due to the limited number of detected photons by the LAT. Radio morphology has indicated that 4C +55.17 belongs to a family of young radio galaxies, that is, compact symmetric objects (see O'Dea 1998 for a review), which are a smaller version of classical Fanaroff–Riley (FR) II radio galaxies (Rossetti et al. 2005). The low flux variability of this source also supports this indication. Importantly, this type of compact objects is a promising source candidate of ultra-high-energy cosmic rays (Takami & Horiuchi 2011) similarly to the lobes of FR II radio galaxies (e.g. Biermann & Strittmatter 1987; Takahara 1990; Rachen & Biermann 1993). McConville et al. (2011) model the multiwavelength SED of this source by using both compact symmetric object and FSRQ interpretations. The authors suggest that infrared and hard X-ray observations can help to distinguish between the two models, but VHE gamma-rays also provide a clue for the distinction despite the significant EBL absorption. Also, a hadronic interpretation predicts a hard intrinsic spectrum in the VHE range (Kino & Asano 2011). Therefore, observations of this source in the VHE range can provide an important clue to its nature and radiation mechanism.

This paper is laid out as follows. We describe the details of the MAGIC observations and data analysis in Section 2. Then, results are shown in Section 3. Implications from the results are discussed in Section 4 and a summary is presented in Section 5.

2 OBSERVATIONS AND ANALYSIS

The MAGIC stereoscopic system consists of two IACTs each with a mirror dish diameter of 17 m, located at 2200 m above sea level at the Roque de los Muchachos, La Palma in Canary Island (28°.75N, 17°.86W). The MAGIC telescopes have been operating in stereoscopic mode since the end of 2009, which provided an analysis energy threshold below 100 GeV and an integral sensitivity of 0.76 ± 0.03 per cent of the Crab nebula flux above 300 GeV for 50 h observations (Aleksić et al. 2012).

4C +55.17 was observed from 2010 November to 2011 January for 21 dark nights and a total of 35 h in stereoscopic mode. The data were taken at medium zenith angles (from 27° to 37°) to achieve an energy threshold below 100 GeV. The observations were performed in the so-called wobble mode (Fomin et al. 1994), i.e. the target source direction has the offset of 0°.4 from the camera centre, allowing for taking both signal and background data simultaneously. The observations were performed with two pointing directions, different positions from the source with the same declination as the source but at an angular distance of ±0°.4 in right ascension. The direction of the wobble offset is inverted every 20 min to minimize systematic errors originating from possible exposure inhomogeneities.

Data were selected based on the rate of background events being in a regular range for MAGIC observations. The data selection yielded 27.73 h of effective time. Those data were analysed following the standard procedure (Aleksić et al. 2012) with the MAGIC Analysis and Reconstruction Software (MARS; Moralejo et al. 2009). The analysis cuts to extract gamma-ray signals from the hadronic background were optimized independently of these observational data by means of data from Crab nebula and dedicated Monte Carlo simulations of gamma-ray-induced showers.

3 RESULTS

An initial check of the energy threshold, for these observations, was made using Monte Carlo simulations of gamma-ray-induced showers. We selected Monte Carlo events simulated under an assumed spectrum following the telescope responses after application of the same experimental cuts that were applied to the data, and made the histogram of the events as a function of input energies. The energy at the maximum of the histogram is defined as the analysis threshold. This is the standard definition of the analysis threshold for IACTs.

We assume the incident gamma-ray spectrum to be a power law with index $\alpha = 4$. This is expected by the LAT spectrum and plausible EBL models at around 100 GeV. Note that the spectral index of the LAT spectrum above 2 GeV (up to 60 GeV) is $\alpha = 2.2$ in McConville et al. (2011) and the spectrum above 10 GeV can be characterized with a power-law function of $\alpha = 2.43 \pm 0.18$ (Ackermann et al. 2013). As a result, the energy threshold was found to be ~100 GeV. A gamma-ray signal from 4C +55.17 was searched for following the standard method using the so-called θ^2 distribution, i.e. a distribution of the squared angular distance between the reconstructed arrival directions of the events and the source nominal position (Daum et al. 1997).

The θ^2 distributions of the observed data with the corresponding energy threshold of 100 GeV (i.e. images with the total number of reconstructed photoelectrons $\gtrsim$50 in each telescope), shown in Fig. 1, indicate no significant excess of gamma-rays compared to background in the direction of 4C +55.17. The significance estimated using equation 17 of Li & Ma (1983) is close to zero. Here, a region with $\theta^2 < 0.026$ deg^2 is used to estimate the significance.

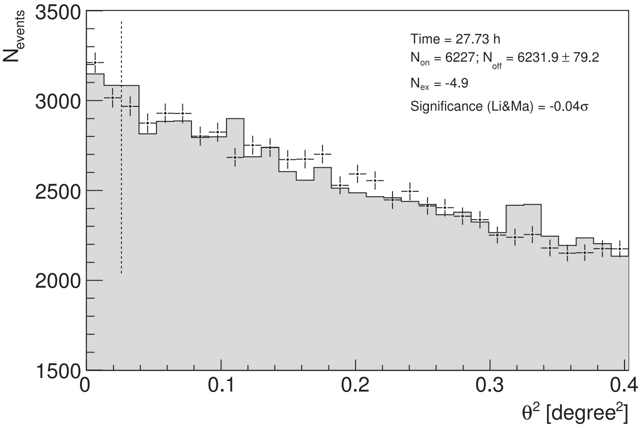

Figure 1. Theta-squared distributions of events computed with respect to the positions of 4C +55.17 (data points) and the anti-source, i.e. one off-position, used for background estimation (shaded region) computed from 27.73 h (effective time) of the MAGIC stereo observations.

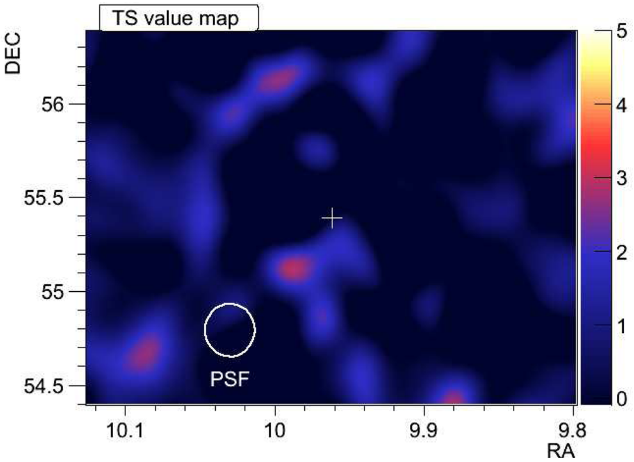

Figure 2. Significance skymap of 4C +55.17 from the data corresponding to those used in Fig. 1. There is no significant signal in the direction of 4C +55.17 (cross).

This choice is standard for θ^2 cut for low-energy ($\lesssim$100 GeV) sources. The corresponding significance map is shown in Fig. 2. It also confirms that there is no significant signal from 4C +55.17.

The upper limits on the gamma-ray flux are calculated by adding a cut in estimated photon energy to the data. The upper limits of integrated gamma-ray flux were estimated on the assumption of $\alpha = 4$. The integral upper limit above 100 GeV is 9.4×10^{-12} cm^{-2} s^{-1} at the 95 per cent confidence level. A flux upper limit above 200 GeV is also calculated as 2.5×10^{-12} cm^{-2} s^{-1} at the 95 per cent confidence level for comparison with a recent upper limit by VERITAS (2.6×10^{-12} cm^{-2} s^{-1} for $E > 200$ GeV; Errando & VERITAS Collaboration 2011). The MAGIC upper limit is slightly lower than the upper limit of VERITAS due to the longer observation time; the VERITAS observations were performed for 17.7 h. Further observations with VERITAS (for a total observation time of 45 h; Furniss & McConville 2013) result in a more constraining upper limit above 150 GeV. Thanks to the lower energy threshold of MAGIC, here we report an upper limit at lower energies.

We calculate differential upper limits in the four energy bins of equal width in logarithmic scale in the energy range between 80 and 500 GeV. The spectral indices of the gamma-ray distributions were assumed to be $\alpha = 4$ in the first bin and $\alpha = 5$ in the other following bins because of a sharp cutoff at ~100 GeV predicted from recent EBL models (e.g. Franceschini, Rodighiero & Vaccari 2008; Domínguez et al. 2011; Gilmore et al. 2012; Inoue et al. 2013). As discussed above, the analysis threshold for IACTs is not a sharp threshold, and thus we can report on the energy range >80 GeV. The results are tabulated in Table 1 and plotted in Fig. 3 at characteristic energies.

The upper limits on the flux depend on the assumed spectral indices for gamma-ray spectra. In order to evaluate the uncertainty of the upper limits due to this dependence, we calculate the upper limits on the assumption of harder spectra by one unit, i.e. the spectral index of $\alpha = 3$ for integral upper limits, and $\alpha = 3$ in the first bin and $\alpha = 4$ in the following bins for differential limits. As a result, the integral upper limits change by less than 10 per cent for both >100 GeV and >200 GeV. On the other hand, the resultant differential upper limits change within ~30 per cent in the three high-energy bins and by about a factor of 2 in the first bin. The latter is because of a rapid change of collection area as a function of the gamma-ray energy. The collection area of IACTs depends

Table 1. Differential upper limits of the flux and the numbers of events in on- and off-positions.

Range (GeV)	U.L. (cm^{-2} s^{-1})	U.L. (erg cm^{-2} s^{-1})	α assumed	N_{on}	N_{off}	Sign. of excess
79–126	1.0×10^{-10}	1.3×10^{-11}	4	6874	6711	1.4σ
126–200	1.6×10^{-11}	3.0×10^{-12}	5	1846	1847	0.0σ
200–316	5.7×10^{-11}	2.0×10^{-12}	5	714	706	0.2σ
316–501	3.8×10^{-12}	2.1×10^{-12}	5	311	293	0.7σ

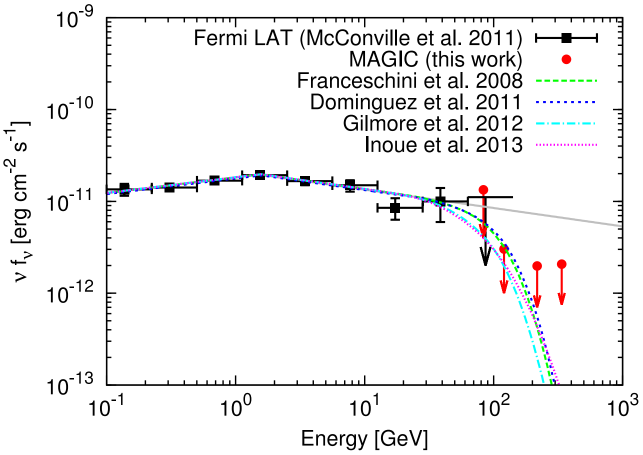

Figure 3. Upper limits of differential flux at the 95 per cent C.L. obtained in this work (circle, red). Locations of the arrows correspond to characteristic energies in the energy ranges where the differential upper limits are calculated. The LAT spectrum derived by McConville et al. (2011, square, black) and its spectral fit with a broken power-law function (assumed to be the intrinsic spectrum) are depicted with black square points and the solid grey line. The intrinsic spectrum attenuated with four state-of-the-art EBL models is also shown, Franceschini et al. (2008) with a long-dashed green curve, Domínguez et al. (2011) with a dashed blue curve, Gilmore et al. (2012) with a dash–dotted light-blue curve and Inoue et al. (2013) with a dotted magenta curve.

strongly on the primary gamma-ray energy. The average number of Cherenkov photons is smaller for lower energy gamma-rays, making it less probable to trigger IACTs even if the shower falls within the light pool. This results in a very steep collection area around the energy threshold, and therefore strong dependence on the collection area in a finite energy bin on the assumed spectral shape.

4 DISCUSSIONS

We interpret the derived upper limits of the gamma-ray flux with 'low-flux' EBL models (Kneiske et al. 2004; Franceschini et al. 2008; Domínguez et al. 2011; Gilmore et al. 2012; Inoue et al. 2013). Note that 'low-flux' means that the flux in the EBL models is close to that given by galaxy counts (e.g. Madau & Pozzetti 2000; Fazio et al. 2004; Keenan et al. 2010).

A recent study shows that the LAT spectrum of 4C +55.17 up to ~60 GeV can be well fitted by a broken power-law function with a break at ~2 GeV and $\alpha = 2.2$ above the break (McConville et al. 2011, see Fig. 3). We adopt this result and assume simple spectral extension beyond the characteristic EBL absorption energy (~100 GeV) up to 1 TeV. This can be considered to give a plausible upper limit of the intrinsic spectrum unless another new component dominates above 60 GeV. The assumed maximum energy up to which the source emits gamma-rays is not important for our analysis because secondary photons created in electromagnetic cascades between the source and the observer will not contribute to the gamma-ray flux significantly due to the intrinsic spectral index softer than 2.

Fig. 3 shows our differential upper limits and the fitted spectra corrected for EBL attenuation. The latter were calculated according to four low-flux EBL models (Franceschini et al. 2008; Domínguez et al. 2011; Gilmore et al. 2012; Inoue et al. 2013). The upper limits are close to the attenuated power-law spectra and interestingly the upper limit at ~120 GeV is slightly below the predictions of Franceschini et al. (2008) and Domínguez et al. (2011). This strong upper limit was possible thanks to the low energy threshold of the MAGIC telescopes. However, we note that the flux should be regarded as consistent with the upper limit because of the dependence of the chosen binning and the statistical errors involved in the spectral fit of the LAT data. The integral upper limits above 100 and 200 GeV provide similar results. Thus, the power-law extension is consistent with the MAGIC upper limits under the low-flux EBL models (and also higher flux EBL models not shown). Given the redshift of 4C +55.17 ($z = 0.896$), the energies of our upper limits (~100 GeV), and the properties of the pair production interaction, the gamma-ray photons that we are discussing are mainly attenuated by EBL photons in the ultraviolet range.

The SED of 4C +55.17 can be modelled by both an external Compton model for blazars (e.g. Dermer & Schlickeiser 1993; Sikora, Begelman & Rees 1994) and emission from compact radio lobes (Stawarz et al. 2008). Spectral modelling in McConville et al. (2011) indicates that the compact lobe model predicts a power-law spectrum above several GeV up to several hundred GeV, while the blazar model has a sharp spectral steepening at several GeV. Thus, the simple power-law intrinsic spectrum extended above 100 GeV is an optimistic model. Since the simple power-law spectrum is allowed even for the low-flux EBL models, both models are still consistent with the upper limits. Stronger upper limits or detection in the future will allow us to test the compact symmetric object model under the low-flux EBL models.

5 SUMMARY AND CONCLUSION

The MAGIC telescopes observed 4C +55.17 for 35 h (27.73 h of effective time with good quality data) from 2010 November to 2011 January in a wobble mode. No significant gamma-ray signal was found above 100 GeV. Instead, both integral and differential upper limits of gamma-ray flux were derived. The integral upper limits are 9.4×10^{-12} cm^{-2} s^{-1} above 100 GeV and 2.5×10^{-12} cm^{-2} s^{-1} above 200 GeV. The differential upper limits are tabulated in Table 1. The derived limits are close to and consistent with the power-law spectrum extended from the LAT energy range attenuated by low-flux EBL models.

McConville et al. (2011) claimed that a 50 h observation with MAGIC would suffice to detect this source. However, the strict upper limits from ~30 h of observation do not confirm this prediction, due to the medium zenith angle of the observations ($\gtrsim 27°$), which increases the analysis threshold and suppresses the performance at lowest energies (Aleksić et al. 2012). In fact, according to our estimates, MAGIC would require ∼100 h in order to have a 5σ detection from 4C +55.17 under the optimistic assumption of the power-law extension adopted in this study and relatively optically thin EBL models such as Franceschini et al. (2008) and Domínguez et al. (2011). After the observation of 4C +55.17, the camera of the MAGIC I telescope was upgraded, which improved the sensitivity for the lowest energies (Sitarek et al. 2013). A new trigger system for stereoscopic observations, so-called sum-trigger (Haefner et al. 2011), will improve the sensitivity below 100 GeV significantly. These may help detect this source in the VHE range. Detailed studies on its spectrum beyond detection would require a sensitivity several times better than current ground-based gamma-ray instruments, and hence it may be a task for the next generation of instruments such as the Cherenkov Telescope Array (Actis et al. 2011; Acharya et al. 2013).

ACKNOWLEDGEMENTS

We would like to thank the Instituto de Astrofísica de Canarias for the excellent working conditions at the Observatorio del Roque de los Muchachos in La Palma. The support of the German BMBF and MPG, the Italian INFN, the Swiss National Fund SNF and the Spanish MICINN is gratefully acknowledged. This work was also supported by the CPAN CSD2007-00042 and MultiDark CSD2009-00064 projects of the Spanish Consolider-Ingenio 2010 programme, by grant 127740 of the Academy of Finland, by the DFG Cluster of Excellence ‘Origin and Structure of the Universe’, by the DFG Collaborative Research Centers SFB823/C4 and SFB876/C3, and by the Polish MNiSzW grant 745/N-HESS-MAGIC/2010/0.

REFERENCES

Abdo A. A. et al., 2010, ApJ, 715, 429
Abramowski A. et al., 2013, A&A, 550, A4
Acciari V. A. et al., 2010, ApJ, 708, L100
Acharya B. S. et al., 2013, Astropart. Phys., 43, 3
Ackermann M. et al., 2011, ApJ, 743, 171
Ackermann M. et al., 2012, Science, 338, 1190
Ackermann M. et al., 2013, ApJS, 209, 34
Actis M. et al., 2011, Exp. Astron., 32, 193
Adelman-McCarthy J. K. et al., 2008, ApJS, 175, 297
Aharonian F. et al., 2006a, A&A, 457, 899
Aharonian F. et al., 2006b, Nature, 440, 1018
Aharonian F. et al., 2007, A&A, 475, L9
Albert J. et al., 2008, Science, 320, 1752
Aleksić J. et al., 2012, Astropart. Phys., 35, 435
Atwood W. B. et al., 2009, ApJ, 697, 1071
Becherini Y., Boisson C., Cerruti M. H. E. S. S. Collaboration, 2012, in Aharonian F. A., Hofmann W., Rieger F. M., eds, AIP Conf. Proc. Vol. 1505, High Energy Gamma-Ray Astronomy: 5th International Meeting on High Energy Gamma-Ray Astronomy. Am. Inst. Phys., New York, p. 490
Biermann P. L., Strittmatter P. A., 1987, ApJ, 322, 643
Daum A. et al., 1997, Astropart. Phys., 8, 1
Dermer C. D., Schlickeiser R., 1993, ApJ, 416, 458
Domínguez A. et al., 2011, MNRAS, 410, 2556
Domínguez A., Finke J. D., Prada F., Primack J. R., Kitaura F. S., Siana B., Paneque D., 2013, ApJ, 770, 77
Dwek E., Krennrich F., 2013, Astropart. Phys., 43, 112
Errando M. (VERITAS Collaboration), 2011, in Hu H., Ma X., eds, Proc. 32nd Int. Cosmic Ray Conf., Vol. 8, Beijing, p. 133
Fazio G. G. et al., 2004, ApJS, 154, 39
Fomin V. P., Stepanian A. A., Lamb R. C., Lewis D. A., Punch M., Weekes T. C., 1994, Astropart. Phys., 2, 137
Franceschini A., Rodighiero G., Vaccari M., 2008, A&A, 487, 837
Furniss A., McConville W., 2013, preprint (arXiv:1303.1103)
Furniss A. et al., 2013, ApJ, 768, L31
Gilmore R. C., Somerville R. S., Primack J. R., Domínguez A., 2012, MNRAS, 422, 3189
Gould R. J., Schréder G., 1966, Phys. Rev. Lett., 16, 252
Haefner D., Schweizer T., Dazzi F., Corti D., 2011, in Hu H., Ma X., eds, Proc. 32nd Int. Cosmic Ray Conf., Vol. 9, Beijing, p. 251
Hauser M. G., Dwek E., 2001, ARA&A, 39, 249
Inoue Y., Inoue S., Kobayashi M. A. R., Makiya R., Niino Y., Totani T., 2013, ApJ, 768, 197
Keenan R. C., Barger A. J., Cowie L. L., Wang W.-H., 2010, ApJ, 723, 40
Kino M., Asano K., 2011, MNRAS, 412, L20
Kneiske T. M., Bretz T., Mannheim K., Hartmann D. H., 2004, A&A, 413, 807
Li T.-P., Ma Y.-Q., 1983, ApJ, 272, 317
Madau P., Pozzetti L., 2000, MNRAS, 312, L9
McConville W. et al., 2011, ApJ, 738, 148
Moralejo A. et al., 2009, in Szabelski J., Giller M., eds, Proc. 31st Int. Cosmic Ray Conf. (Łótź), preprint (arXiv:0907.0943)
Nepomuk Otte A. (VERITAS Collaboration), 2009, in Szabelski J., Giller M., eds, Proc. 31st Int. Cosmic Ray Conf. Pub. ID 1408, preprint (arXiv:0907.4826)
Neronov A., Semikoz D., Vovk I., 2011, A&A, 529, A59
Neronov A., Semikoz D. V., Taylor A. M., Vovk I., 2012, preprint (arXiv:1207.1962)
Nikishov A. I., 1962, Sov. Phys. JETP, 14, 393 [1961, Zh. Eksp. Teor. Fiz., 41, 549]
O’Dea C. P., 1998, PASP, 110, 493
Pita S., Goldoni P., Boisson C., Becherini Y., Gérard L., Lenain J.-P., Punch M., 2012, in Aharonian F. A., Hofmann W., Rieger F. M., eds, AIP Conf. Proc. Vol. 1505, High Energy Gamma-Ray Astronomy: 5th International Meeting on High Energy Gamma-Ray Astronomy. Am. Inst. Phys., New York, p. 566
Rachen J. P., Biermann P. L., 1993, A&A, 272, 161
Rossetti A., Mantovani F., Dallacasa D., Fanti C., Fanti R., 2005, A&A, 434, 449
Sikora M., Begelman M. C., Rees M. J., 1994, ApJ, 421, 153
Sitarek J. et al., 2013, Proc. of 33rd Int. Cosmic Ray Conf. (Rio de Janeiro), preprint (arXiv:1308.0141)
Stanev T., Franceschini A., 1998, ApJ, 494, L159
Stawarz Ł., Ostorero L., Begelman M. C., Moderski R., Kataoka J., Wagner S., 2008, ApJ, 680, 911
Stecker F. W., de Jager O. C., 1993, ApJ, 415, L71
Stecker F. W., de Jager O. C., Salamon M. H., 1992, ApJ, 390, L49
Takahara F., 1990, Prog. Theor. Phys., 83, 1071
Takami H., Horiuchi S., 2011, Astropart. Phys., 34, 749
Taylor G. B. et al., 2007, ApJ, 671, 1355
Wills B. J. et al., 1995, ApJ, 447, 139

This paper has been typeset from a TEX/LATEX file prepared by the author.