Detection of very high energy $\gamma$-ray emission from NGC 1275 by the MAGIC telescopes

J. Aleksic$^1$, E. A. Alvarez$^2$, L. A. Antonelli$^3$, P. Antoranz$^4$, M. Asensio$^2$, M. Backes$^5$, U. Barres de Almeida$^6$, J. A. Barrio$^7$, D. Bastieri$^7$, J. Becerra González$^{8,9}$, W. Bednarek$^{10}$, K. Berger$^{8,9}$, E. Bernardini$^{11}$, A. Biland$^{12}$, O. Blanco$^{1}$, R. K. Boch$^{6}$, A. Boller$^{12}$, G. Bonnoli$^{1}$, D. Borla Tridon$^{8}$, T. Bretz$^{13,26}$, A. Cañellas$^{14}$, E. Carmona$^{8}$, A. Carosi$^{1}$, P. Colin$^{15}$, E. Colombo$^{3}$, J. L. Contreras$^{2}$, J. Cortina$^{1}$, L. Cossio$^{15}$, S. Covino$^{7}$, P. Da Vela$^{4}$, F. Dazzi$^{16,27}$, A. De Angelis$^{15}$, G. De Caneva$^{11}$, E. De Cea del Pozo$^{16}$, B. De Lotto$^{15}$, C. Delgado Mendez$^{8,28}$, A. Diago Ortega$^{9}$, M. Doert$^{5}$, A. Dominguez$^{17}$, D. Dominis Prester$^{18}$, D. Dornet$^{12}$, M. Doro$^{19}$, D. Eisenacher$^{13}$, D. Elsaesser$^{15}$, D. Ferenc$^{18}$, M. V. Fonseca$^{2}$, L. Font$^{19}$, C. Fruck$^{6}$, R. J. Garcí−López$^{8,9}$, M. Garzarczyk$^{8}$, D. Garrido$^{19}$, G. Giavitto$^{1}$, N. Godinović$^{18}$, S. R. Gozzi$^{11}$, D. Hafen$^{6}$, A. Herrero$^{8,9}$, D. Hildebrand$^{12,3}$, D. Höhne-Mönch$^{13}$, J. Hose$^{6}$, D. Hrupec$^{18}$, B. Huber$^{12}$, T. Jogle$^{6}$, V. Kadenius$^{20}$, H. Kellermann$^{6}$, S. Klepper$^{1}$, D. Krähenbühl$^{12}$, J. Krause$^{6}$, A. La Barbera$^{3}$, D. Lelas$^{18}$, E. Leonardo$^{4}$, N. Lewandowska$^{13}$, E. Lindfors$^{20}$, S. Lombardi$^{7,3}$, M. López$^{2}$, R. López-Coto$^{1}$, A. López-Oramas$^{1}$, E. Lorenz$^{6,12}$, M. Makariev$^{21}$, G. Maneva$^{21}$, N. Mankuzhiyil$^{15}$, K. Mannheim$^{13}$, L. Maraschi$^{3}$, B. Marcote$^{14}$, M. Mariotti$^{7}$, M. Martínez$^{1}$, D. Mazin$^{1,6}$, M. Meucci$^{3}$, J. M. Miranda$^{4}$, R. Mirzoyan$^{6}$, J. Moldón$^{14}$, A. Moralejo$^{1}$, P. Munar-Adrover$^{14}$, A. Niedzwiecki$^{10}$, D. Nieto$^{2}$, K. Nilsson$^{20,29}$, N. Nowak$^{6}$, R. Origo$^{3}$, S. Patano$^{7}$, D. Paneque$^{6}$, R. Paolletti$^{6}$, S. Parotto$^{3}$, J. M. Pedres$^{14}$, S. Partini$^{3}$, M. A. Perez-Torres$^{1}$, M. Persic$^{15,22}$, L. Peruzzo$^{2}$, M. Pilia$^{23}$, J. Pochon$^{6}$, F. Prada$^{17}$, P. G. Prada Moroni$^{24}$, E. Prandini$^{1}$, I. Puerto Gimenez$^{8}$, I. Puljak$^{18}$, I. Reichardt$^{1}$, R. Reintal$^{20}$, W. Rhode$^{5}$, M. Ribo$^{14}$, J. Rico$^{25,3}$, S. Rügamer$^{13}$, A. Saggion$^{2}$, K. Saito$^{6}$, T. Y. Saito$^{6}$, M. Salvati$^{3}$, K. Satalecka$^{2}$, V. Scalzotto$^{7}$, V. Scapin$^{2}$, C. Schultz$^{2}$, T. Schweizer$^{6}$, M. Shayduk$^{26}$, S. N. Shore$^{24}$, A. Sillanpää$^{20}$, J. Sitarek$^{1,10}$, I. Snidaric$^{18}$, D. Sobczynska$^{10}$, F. Spanier$^{13}$, S. Spiro$^{3}$, V. Stamatescu$^{1}$, A. Stamerra$^{3}$, B. Steinke$^{6}$, J. Storz$^{13}$, N. Stroh$^{3}$, S. Sun$^{6}$, T. Surić$^{18}$, L. Takalo$^{20}$, H. Takami$^{6}$, F. Tavecchio$^{2}$, P. Temnikov$^{21}$, T. Terzić$^{28}$, D. Tescaro$^{1}$, M. Teshima$^{6}$, O. Tibolla$^{13}$, D. F. Torres$^{25,16}$, A. Treves$^{23}$, M. Uellenbeck$^{3}$, P. Vogler$^{12}$, R. M. Wagner$^{6}$, Q. Weitze$^{12}$, V. Zabalza$^{14}$, F. Zandanel$^{18,*}$, and R. Zanin$^{15}$ (The MAGIC Collaboration), C. Pfrommer$^{30}$ and A. Pinzke$^{31}$

(Affiliations can be found after the references)

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ABSTRACT

We report on the detection of very high energy ($\gamma$-ray, $E > 100$ GeV) emission from NGC 1275, the central radio galaxy of the Perseus cluster of galaxies. The source has been detected by the MAGIC telescopes with a statistical significance of 6.6 $\sigma$ or above 100 GeV in 46 hr of stereo observations carried out between August 2010 and February 2011. The measured differential energy spectrum between 70 GeV and 500 GeV can be described by a power-law with a steep spectral index of $\Gamma = -4.1 \pm 0.7_{\text{stat}} \pm 0.3_{\text{syst}}$, and the average flux above 100 GeV is $F_{\gamma} = (1.3 \pm 0.2_{\text{stat}} \pm 0.3_{\text{syst}}) \times 10^{-11}$ cm$^{-2}$ s$^{-1}$. These results, combined with the power-law spectrum measured in the first two years of observations by the Fermi-LAT above 100 MeV, with a spectral index of $\Gamma = -2.1$, strongly suggest the presence of a break or a cut-off around tens of GeV in the NGC 1275 spectrum. The light curve of the source above 100 GeV does not show hints of variability on month time-scale. Finally, we report on the non-detection in the present data of the radio galaxy IC 310, previously discovered by the Fermi-LAT and MAGIC. The derived flux upper limit $F_{\gamma}^{\text{UL}}(< 300 \text{ GeV}) = 1.2 \times 10^{-12}$ cm$^{-2}$ s$^{-1}$ is a factor $\sim 3$ lower than the mean flux measured by MAGIC between October 2009 and February 2010, thus confirming the year time-scale variability of the source at VHE.

Key words. galaxies: active — galaxies: jets — galaxies: individual (NGC 1275) — galaxies: individual (IC 310) — gamma rays: galaxies

1. Introduction

NGC 1275 ($z = 0.0179$), the central dominant galaxy of the Perseus cluster, harbors one of the closest active galactic nuclei (AGN), already included in the original Seyfert list (Seyfert, 1943). The AGN is a very bright radio source showing an extended jet with Fanaroff-Riley I morphology (e.g. Vermeulen et al., 1994, Buttiglione et al., 2010). The optical emission of the nucleus is variable and strongly polarized, from 3% to 6% (Mazá, 1979, Martin et al., 1983), implying that the relativistic jet contributes significantly to the optical continuum (Angel & Stockman, 1980). The source has been also classified as a BL Lac object (Veron, 1978). However, the jet increases its brightness and proximity this source is ideally suited to study the
physics of relativistic outflows and the ‘feedback’ effects on the cluster environment (e.g. Fabian et al. 2008; Gallagher 2009).

In fact, NGC 1275 is one of the closest γ-ray emitting AGN. It was first unambiguously detected in the high energy (HE, 100 MeV < E < 100 GeV) γ-ray range by the Fermi Large Area Telescope (LAT) (Abdo et al. 2009), during the first four months of all-sky-surveys observations, with an average flux above 100 MeV of \( F_\gamma = (2.10 \pm 0.23) \times 10^{-7} \text{ cm}^{-2} \text{s}^{-1} \). The differential energy spectrum between 100 MeV and 25 GeV was well described by a power-law with spectral index of \( \Gamma = -2.17 \pm 0.05 \). While no variability was observed during these four months of observations, subsequent results based on the first year of Fermi-LAT observations (Kataoka et al. 2010) showed evidence of flux variability on time-scales of months. Furthermore, the average γ-ray spectrum showed a significant deviation from a simple power-law, giving indications of an exponential cut-off at the break photon energy of \( E_b = (42.2 \pm 19.6) \text{ GeV} \).

More recently, the results obtained from the first two years of Fermi-LAT observations (Brown & Adamo 2011), have given clear evidence for variability on time-scales of days above 800 MeV, revealing that several major flaring events occurred during the two years observation period. A harder-when-brighter behaviour was found. Brighter and therefore harder > GeV states are then promising for triggering observations at very high energy (VHE, \( E > 100 \text{ GeV} \)). Finally, present upper limits at VHE provided by MAGIC-I (Aleksić et al. 2010a) and VERITAS (Acciari et al. 2009) combined with the Fermi-LAT results mentioned above suggested that NGC 1275 may have a break or a cut-off in the spectrum around tens of GeV.

The Perseus galaxy cluster contains another γ-ray source, the radio galaxy IC 310, located at ≈ 0.6° from NGC 1275. It was discovered in 2010 by the Fermi-LAT at HE (Neronov et al. 2010) and by MAGIC at VHE (Aleksić et al. 2010b). The combined MAGIC and Fermi-LAT spectrum is consistent with a flat spectral energy distribution (SED) stretching without a break over more than 3 orders of magnitude in energy (2 GeV – 7 TeV). The spectrum at VHE measured by MAGIC has a spectral index of \( \Gamma = -2.00 \pm 0.14 \), and the mean flux above 300 GeV, during October 2009 – February 2010, was \( F_\gamma = (3.1 \pm 0.5) \times 10^{-12} \text{ cm}^{-2} \text{s}^{-1} \). Strong hints from week to year time-scale variability were seen in the MAGIC data.

In this letter we present the results of the observations of NGC 1275 at VHE performed with the MAGIC telescopes between August 2010 and February 2011, which resulted in the first detection of the source above 100 GeV. The same observational campaign provided also results on the variability at VHE of IC 310. This letter is accompanied by a separate paper dedicated to the study of the Perseus cluster environment, focusing on possible VHE γ-ray emission induced by cosmic rays (Aleksić et al. 2011b). The multi-wavelength emission of NGC 1275 from radio to VHE will be addressed in future work.

2. Observations and Analysis

The MAGIC system consists of two 17 m dish Imaging Air Cherenkov Telescopes (IACTs) located at the Roque de los Muchachos observatory, in the Canary Island of La Palma (28.8°N, 17.8°W, 2200 m a.s.l.). Since fall 2009 the telescopes are working in stereoscopic mode providing an excellent sensitivity of < 0.8% of the Crab flux (C.U. for energies above ~ 300 GeV in 50 hr of observations (Aleksić et al. 2011a), and a trigger energy threshold of 50 GeV, which is the lowest among the existing IACTs. The MAGIC telescopes are currently the most suitable world-wide instrument between 50 GeV and 200 GeV, allowing to extend up to the TeV scale, and without energy gaps, the observations carried out by the Fermi-LAT.

The Perseus galaxy cluster region was observed by the MAGIC telescopes during two campaigns. The first one was carried out between October 2009 and February 2010, for a total observation time of 45.3 hr. This survey resulted in the discovery of the radio galaxy IC 310 as VHE emitter (Aleksić et al. 2010b). The latest campaign (total observation time of 53.6 hr), which resulted in the detection of NGC 1275 at VHE presented in this letter, was performed between August 2010 and February 2011. The source was observed in the wobble mode (Fomin et al. 1994), with data equally split in four pointing positions located symmetrically at 0.4° from NGC 1275, in order to ensure optimum sky coverage and background estimation. The survey was carried out during dark time at low zenith angles (from 12° to 36°), which guaranteed the lowest energy threshold.

The data analysis was performed using the standard MAGIC software package (Albert et al. 2008b; Aliu et al. 2009), taking advantage of newly developed stereoscopic analysis routines (Morojele et al. 2009; Aleksić et al. 2011a; Lombardi et al. 2011). The analysis cuts applied to NGC 1275 data were optimized by means of contemporaneous Crab Nebula data and Monte Carlo (MC) simulations.

After the application of standard quality checks, 7.9 hr of data were rejected mainly due to non-optimal atmospheric conditions. The selected sample used for deriving the results presented here is therefore composed by 45.7 hr of good quality stereo data.

3. Results

The \( \theta^2 \) distributions with respect the signal region and the background (estimated from 3 distinct regions), for energies above 100 GeV, are shown in Fig. 1 We found an excess of 522 ± 81 events, corresponding to a significance of 6.6 standard deviations (\( \sigma \)), calculated according to the Eq. 17 in Li & Ma (1983).

The NGC 1275 differential energy spectrum measured by MAGIC between 70 GeV and 500 GeV can be described by a simple power-law (\( \chi^2/\nu_{df} = 0.76/1 \))

\[
\frac{dN}{dE} = (3.1 \pm 1.0\text{stat} \pm 0.7\text{syst}) \times 10^{-10} \left( \frac{E}{100 \text{ GeV}} \right)^{\Gamma},
\]

in units of \( \text{cm}^{-2} \text{s}^{-1} \text{TeV}^{-1} \), with \( \Gamma = -4.1 \pm 0.7\text{stat} \pm 0.3\text{syst} \)).

The mean flux above 100 GeV is \( F_\gamma = (1.3 \pm 0.2\text{stat} \pm 0.3\text{syst}) \times 10^{-11} \text{ cm}^{-2} \text{s}^{-1} \), corresponding to (2.5±0.4stat±% C.U.). The steepness of the spectral index measured by MAGIC strongly supports the presence of a break or a cut-off in the NGC 1275 spectrum around tens of GeV, as already suggested by the Fermi-LAT.

1 In this letter C.U. stands for Crab Units, defined as the fraction of the Crab Nebula flux given in Eq. 1 of Aleksić et al. (2011a), that corresponds for energies above 100 GeV to 5.4 × 10^{-16} \text{ cm}^{-2} \text{s}^{-1} .

2 The \( \theta^2 \) is the squared angular distance between the arrival direction of the events and a given nominal position (e.g. Daum et al. 1997).

3 The systematic errors of the flux normalization and the energy spectral slope considered here have been estimated to be respectively 23% and ±0.3, whereas the systematic error on the energy scale is 17%. These values are more conservative than those presented in Aleksić et al. (2011a), given the flux weakness and the spectral steepness of NGC 1275, as measured by MAGIC.
results (Kataoka et al., 2010, Brown & Adams, 2011), and is consistent with the upper limits on the flux at VHE provided by MAGIC-I (Aleksić et al., 2010a) and VERITAS (Acciari et al., 2009). The rapid decline of the spectrum, which causes the NGC 1275 signal to vanish above approximately 500 GeV, permits to investigate possible VHE γ-ray emissions induced by cosmic rays in the Perseus cluster environment above that energy (Aleksić et al., 2011b).

In Fig. 2, the SED measured by MAGIC is compared with the results in the 100 MeV – 100 GeV range provided by the Fermi–LAT, averaging Fermi data over the first year (filled circles, Kataoka et al., 2010) and the first two years (open circles, Brown & Adams, 2011). The comparison suggests that a significant spectral steepening occurs around ~100 GeV. However the present non-simultaneous data do not allow to discuss whether the spectral change corresponds to a break between two power-laws or an exponential cut-off.

The August 2010 – February 2011 light curve of NGC 1275 taken between August 2010 and February 2011 above an energy threshold of 100 GeV and with a monthly binning is shown in Fig. 3. No evidence of variability can be derived from these measurements. In fact, fitting the light curve with a constant flux hypothesis yields a probability $P(\chi^2) = 0.29$.

The significance skymap of the central region of the Perseus cluster above 100 GeV is shown in Fig. 4. A hot spot at ~6σ significance level consistent with the sky position of NGC 1275 is present. The position of the radio galaxy IC 310 is also shown and marked with a green star. No significant excess events coming from IC 310 have been found in the observations presented here. The corresponding integral flux upper limit above 300 GeV (performed using the Rolke et al., 2005 method, with a confidence level of 95%, and a total systematic uncertainty of 30%) is $F_{\gamma} > 300 \text{ GeV} = 1.2 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$, for a spectral index of $\Gamma = -2.0$ (i.e. the spectral index of the source previously measured by MAGIC). This value is about a factor 3 lower than the average integral flux $F_{\gamma} > 300 \text{ GeV} = (3.1 \pm 0.5) \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ measured by MAGIC during October 2009 – February 2010 (Aleksić et al., 2010b), hence confirming the variability of the latter source on a year time-scale.

4. Conclusions

The MAGIC telescopes have detected VHE γ-ray emission from NGC 1275, the central radio galaxy in the Perseus cluster, at a statistical significance of 6.6σ from observations performed between August 2010 and February 2011. The corresponding average flux above 100 GeV is $(2.5 \pm 0.4_{\text{stat}})\%$ C.U. This is the fourth nearby radio galaxy detected at VHE, after M 87 (Aharonian et al., 2003, 2006, Albert et al., 2008a, Acciari et al., 2008), Cen A (Aharonian et al., 2009), and IC 310 (Aleksić et al., 2010b). The MAGIC observation yields a spec-
trum which can be fitted between 70 GeV and 500 GeV by a simple power-law with a spectral index of $\Gamma = -4.1 \pm 0.7 \text{stat} \pm 0.3 \text{syst}$. This result combined with previous Fermi-LAT results (Abdo et al. 2009; Kataoka et al. 2010; Brown & Adams, 2011), showing a power-law spectrum with a spectral index of $\Gamma \approx -2.1$ above 100 MeV, strongly suggests the presence of a break or cut-off around tens of GeV in the NGC 1275 spectrum. No evidence of variability on month time-scale has been found above 100 GeV. Finally, the variability on a year time-scale of the source IC 310 (Neronov et al., 2010; Aleksić et al., 2010b) above 100 GeV has been confirmed. The upper limit above 300 GeV presented for the source IC 310 (Neronov et al., 2010; Aleksić et al., 2010b) has been confirmed. The upper limit above 300 GeV presented here in fact about a factor 3 lower than the flux measured by MAGIC between October 2009 and February 2010.

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Fig. 4. Significance skymap of the central region of the Perseus galaxy cluster from 45.7 hr of MAGIC stereo observations taken between August 2010 and February 2011, above an energy threshold of 100 GeV. The NGC 1275 position is marked with a black cross, whereas the position of the radio galaxy IC 310 is shown with a green star. The PSF of about 0.12° is also displayed. The hot spot in the map at a significance level > 6 $\sigma$ is consistent with a point-like emission coming from the NGC 1275 sky position.

1. IFAE, Edifici Cn., Campus UAB, E-08193 Bellaterra, Spain
2. Universidad Complutense, E-28040 Madrid, Spain
3. INAF National Institute for Astrophysics, I-00136 Rome, Italy
4. Università di Siena, and INFN Pisa, I-53100 Siena, Italy
5. Technische Universität Dortmund, D-44221 Dortmund, Germany
6. Max-Planck-Institut für Physik, D-80805 München, Germany
7. Universidad de Padova e INFN, I-35131 Padova, Italy
8. Inst. de Astrofísica de Canarias, E-38200 La Laguna, Tenerife, Spain
9. Depto. de Astrofísica, Universidad de La Laguna, E-38206 La Laguna, Spain
10. University of Lódź, PL-90236 Lódź, Poland
11. Deutsches Elektronen-Synchrotron (DESY), D-15738 Zeuthen, Germany
12. ETH Zurich, CH-8093 Zurich, Switzerland
13. Universität für Bodenkultur Wien, D-1190 Wien, Austria
14. Kavli Institute for Cosmology, University of Cambridge, Cambridge, UK
15. Dipartimento di Fisica, Università di Firenze, I-50019 Sesto Fiorentino, Italy
16. Instituto de Ciencias de la Tierra (CSIC), E-28006 Madrid, Spain
17. Instituto de Ciencias del Espacio (IEEC-CSIC), E-08193 Bellaterra, Spain
18. Univ. ofTsukuba, Ibaraki, Japan
19. University of Turku, Finland
20. Tuorla Observatory, University of Turku, FI-21500 Piikkiö, Finland
21. Croatian MAGIC Consortium, Rudjer Boskovic Institute, University of Rijeka and University of Split, HR-10000 Zagreb, Croatia
22. Universität Autónoma de Barcelona, E-08193 Bellaterra, Spain
23. Tuorla Observatory, University of Turku, FI-21500 Piikkiö, Finland
24. Inst. for Nucl. Research and Nucl. Energy, BG-1784 Sofia, Bulgaria
25. IFAE/Observatorio Astronómico e INFN, I-34143 Trieste, Italy
26. Universidad del’Insubria, Como, I-22100 Como, Italy
27. Universidad de Pisa, and INFN Pisa, I-56126 Pisa, Italy
28. ICREA, E-08010 Barcelona, Spain
29. now at: Ecole polytechnique fédérale de Lausanne (EPFL), Lausanne, Switzerland
30. supported by INFN Padova
31. now at: Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
32. now at: Finnish Centre for Astronomy with ESO (FINCA), University of Turku, Finland
33. HITS, Schloss-Wolfsbrunnenweg 33, 69118 Heidelberg, Germany
34. UC Santa Barbara, CA 93106, Santa Barbara, USA

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