MAGIC discovery of VHE γ-rays from the BL Lac object 1ES 0033+595

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Abstract: We present the discovery at very high energy (VHE, $E > 100$ GeV) of the BL Lac 1ES 0033+595, as measured with the MAGIC stereoscopic system. We also discuss its simultaneous broad-band Spectral Energy Distribution (SED). The source was detected in X-rays by the Einstein (1992), *BeppoSAX* (1999), *INTEGRAL* (2003), and *Swift*–BAT (2005) orbiting telescopes. Long considered to be a promising TeV emitter, it was detected at VHE with the MAGIC telescopes, which observed the source for nearly 24 h between August and October 2009. For the study of the SED we used simultaneous optical R-band data from the KVA telescope, archival X-ray data, and simultaneous high-energy (HE, $E > 300$ MeV) data from the *Fermi*–LAT. The redshift of this source is uncertain. Using an empirical approach based on comparing the spectral slopes in the HE and VHE ranges, we constrained the source redshift to be $z = 0.34 \pm 0.08 \pm 0.05$. Using that value, we modeled the SED by fitting a single-zone Synchrotron Self-Compton (SSC) emission to the data by χ^2-minimization.

Keywords: icrc2013, MAGIC, γ-rays, AGN, 1ES 0033+595.

1 Introduction

Blazars are a subclass of Active Galactic Nuclei (AGN) characterized by strong continuum emission (extending from the radio all the way to the γ-ray regime), high radio and optical polarization, and rapid variability at all frequencies. These objects are thought to be AGN with jets closely aligned with our line-of-sight emitting a characteristic Spectral Energy Distribution (SED) with at least two broad emission components: one peak with a maximum in optical to X-ray band (related to synchrotron emission process in magnetic fields of the jets) and a second peak located in the γ-ray band (explained as inverse Compton (IC) scattering of low-energy photons) [1]. Blazars are the most commonly detected extragalactic sources at very high energy (VHE, $E > 100$ GeV), with steadily increasing numbers in the past 15 years.

The blazar 1ES 0033+595 is classified as extreme high-frequency peaked (HBL) object with synchrotron emission peaking near 10^{19} Hz [2]. It was detected for the first time as a hard X-ray source by the Einstein Slew Survey in 1992 [3] and later by the X-ray satellite *BeppoSAX* in 1999 [4], by the *INTEGRAL* satellite in 2003 [5], and by the Burst Alert Telescope (BAT) instrument on-board *Swift* satellite in 2005 [6].

So far, optical observations of 1ES 0033+595 were not able to resolve the host galaxy to determine a photometric redshift leaving its value uncertain. In the literature only a secure lower limit of $z > 0.24$ can be found [7]. Furthermore, no lines have been detected in the optical spectra.

At high-energy (HE, $E > 300$ MeV) 1ES 0033+595 was first detected with the *Fermi*–LAT (Large Area Telescope) and the source currently has been included in the *Fermi*–LAT bright AGN catalog, with a spectrum consistent with a power law with $\Gamma = -2.00 \pm 0.13$ and a flux of $F_\gamma(> 200\,\mathrm{MeV}) = (20.30 \pm 5.11) \times 10^{-9}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ [8].

In the VHE γ-ray band 1ES 0033+595 was observed in 1995 for 12 h with the Whipple 10-m telescope yielding only an upper limit of 17% of the Crab Nebula flux above 430 GeV [9]. MAGIC observed this source in 2006 and later in 2008 for about 5 h. The latter observations yielded only a flux upper limit of 10% of the Crab Nebula flux above 170 GeV [10]. Finally, new observations in 2009 during the commissioning phase of the MAGIC stereoscopic system led to the discovery of the source in the VHE γ-ray range [11].

2 Multi-wavelength Observations

Simultaneous observations of 1ES 0033+595 were performed in 2009 in optical, HE, and VHE γ-ray bands. No simultaneous data were available for the radio and X-ray energy ranges, so archival data were considered.

2.1 MAGIC

MAGIC is a system of two 17 m dish Imaging Atmospheric Cherenkov Telescopes (IACTs) located at the Roque de los Muchachos observatory in the Canary Island of La Palma. Since 2009 the MAGIC telescopes carry out stereoscopic observations with the lowest trigger energy threshold among the current operating IACTs, with an accessible energy range between 50 GeV and several TeV. The sensitivity of the system in 50 h of observations is $< 1.6\%$ of the Crab Nebula flux for energies above ~ 100 GeV and $< 0.8\%$ for energies above ~ 300 GeV [12].

The MAGIC telescopes observed 1ES 0033+595 for nearly 24 h from August 17^{th} to October 14^{th}, 2009, in wobble mode [13], and with zenith angles ranging between 31°

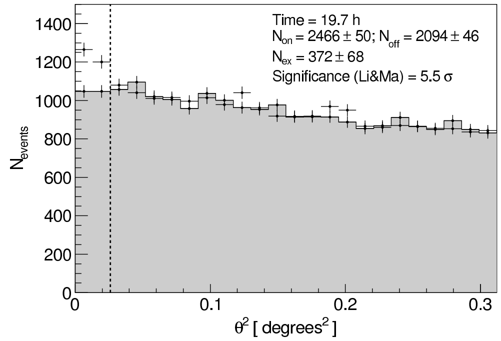

Fig. 1: θ^2 distributions of the 1ES 0033+595 signal and background estimation from 19.7 h of MAGIC stereo observations taken between August 17^{th} and October 14^{th}, 2009, above an energy threshold of 125 GeV. The region between zero and the vertical dashed line (at 0.026 degrees^2) represents the fiducial signal region.

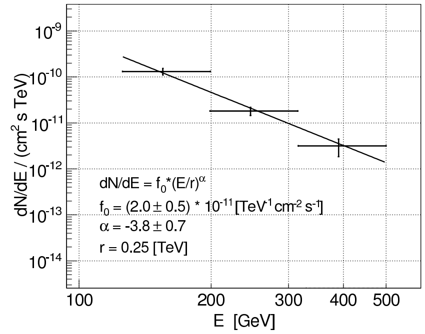

Fig. 2: 1ES 0033+595 differential energy spectrum measured by MAGIC between 125 GeV and 500] GeV. The power-law fit to the data is also shown (black line).

and 35° (which resulted in an analysis energy threshold of 125 GeV). The observations were performed during the commissioning phase of the MAGIC stereoscopic system, with a non-standard stereo trigger configuration, i.e. using the MAGIC-I trigger system and reading out the second telescope simultaneously[1].

The data analysis was performed using the standard software package MARS, including the latest standard routines for the stereoscopic analysis [12, 14]. Standard quality checks based on the rate of the stereo events and the distributions of basic image parameters were applied to the data, resulting in a selected data sample of 19.7 h of effective on-time. The final analysis cuts applied to the 1ES 0033+595 data were optimized by means of contemporaneous Crab Nebula data and MC simulations.

Fig. 1 shows the θ^2 plot for energies above the threshold (125 GeV). We found an excess of 372 ± 68 events in the fiducial signal region ($\theta^2 < 0.026$ degrees^2), corresponding to a significance of 5.5 σ, calculated according to Eq. 17 of [15].

In Fig. 2, the unfolded differential energy spectrum of the source between 125 GeV and 500 GeV derived from the MAGIC observations is shown. The spectrum can be described by a simple power law ($\chi^2/n_{dof} = 2.86/4$):

$$\frac{\mathrm{d}N}{\mathrm{d}E} = N_0 \left(\frac{E}{250\,\mathrm{GeV}} \right)^{\Gamma}, \quad (1)$$

with a photon index of $\Gamma = -3.8 \pm 0.7_{stat} \pm 0.3_{syst}$, and a normalization constant at 250 GeV of $N_0 = (2.0 \pm 0.5_{stat} \pm 0.5_{syst}) \times 10^{-11}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{TeV}^{-1}$. The mean flux above 150 GeV is $\mathrm{F}_\gamma = (7.1 \pm 1.3_{stat} \pm 1.6_{syst}) \times 10^{-12}$ cm^{-2} s^{-1}, corresponding to $(2.2 \pm 0.4_{stat} \pm 0.5_{syst})$% Crab Nebula flux.

No evidence of weekly variability above 150 GeV could be derived from the MAGIC measurements. Fitting the weekly light curve with a constant flux hypothesis yielded a $\chi^2/n_{dof} = 3.7/3$, corresponding to a probability $P(\chi^2) = 0.3$.

2.2 *Fermi*–LAT

The *Fermi*–LAT is a pair conversion telescope designed to cover the energy band from 20 MeV to more than 300 GeV. The data presented here belong to two data sets: the first sample is contemporaneous to MAGIC data (August 17^{th} – October 14^{th}, 2009), whereas the second sample spans from August 4^{th}, 2008 (beginning of scientific operation of LAT) to October 28^{th}, 2011, that is 38 months of integrated data. LAT data were analyzed with the *Fermi* Science Tools package version 09-27-01 and the P7SOURCE_V6 Instrument Response Functions (IRFs) were used. Only events belonging to the "Source" class and located in a circular Region of Interest (ROI) within 10° radius, centered at the position of 1ES 0033+595, were selected. In addition, we excluded photons with zenith angles $> 100°$ to limit contamination from Earth limb γ-rays, and photons with rocking angle $> 52°$ to avoid time intervals during which Earth entered the LAT Field of View (FoV). Due to the location of the source near the Galactic center we decided to restrict the analysis to the 300 MeV – 300 GeV energy range. In such way, on the one hand, we benefit of excluding part of the strong galactic diffuse background (whose spectrum follows a power law with index of about -2.4, concentrating its main contribution at low LAT energies). On the other hand, since the source of interest has a hard spectrum (with spectral index of about -1.9) excluding the contribution of low energy photons will not affect significantly the analysis while ensuring more reliable results. The analysis in the time interval simultaneous with MAGIC observations was performed using an unbinned maximum likelihood method [16]. For the 38 months data set, instead, a binned maximum likelihood technique was used, since the unbinned method was not able to handle the large amount of data (due to the Galactic plane and the wide time interval). A background model and all point sources from the 2FGL catalog [17] located within 15° of 1ES 0033+595 were included in the model of the region. The background model used for the analysis includes a Galactic diffuse emission component and an isotropic component (including residual instrument background), modeled with the files ring_2year_P76_v0.fits and isotrop_2year_P76_source_v0.txt. In the full energy range analysis, all point sources within the 10° radius ROI were fitted with their parameters set free, while sources beyond

1. Compared to the standard trigger mode adopted for regular stereoscopic observations, where the Cherenkov events are triggered simultaneously by both telescopes, this configuration turned out to have slightly less sensitivity at the energies below ~ 150 GeV, but the same energy threshold. In order to take into account the non-standard trigger condition, dedicated Monte Carlo (MC) γ-ray simulations have been generated and adopted in the analysis.

10° radius ROI had their parameters frozen to the values reported in 2FGL. The normalizations of the background components were allowed to vary freely.

For the data set simultaneous with MAGIC observations we found a flux of $(8.0 \pm 3.6) \times 10^{-9}$ cm^{-2} s^{-1} and a spectral index of -1.7 ± 0.2, whereas for the 38 months time interval sample the flux is $(6.6 \pm 1.0) \times 10^{-9}$ cm^{-2} s^{-1} and the spectral index is -1.9 ± 0.1.

For the spectral analysis, the simultaneous data sample was divided in 4 energy bins (2 bins in the 300 MeV – 10 GeV range and 2 bins in the 10 GeV – 300 GeV range), whereas the 38 months data sample was divided in 6 equal energy bins. A separate fit in each energy bin was performed fixing the spectral index of all the sources and the isotropic normalization to the values obtained from the likelihood analysis of the full energy range. For each energy bin, if the Test Statistic (TS) value for the source of interest was TS < 9, the values of the fluxes were replaced by 2 σ confidence level upper limits.

2.3 KVA

The KVA (Kungliga Vetenskaplika Academy) telescopes are a 60 cm telescope used for polarimetric observations and a 35 cm telescope which performed simultaneous photometric observations in the R-band with MAGIC. These telescopes, located at La Palma and remotely operated by the Tuorla Observatory, are mainly used for optical support observations for the MAGIC telescopes. Such observations are performed in the R-band and the magnitude of the source is measured from CCD images using differential photometry.

The average optical flux (simultaneous to MAGIC observation) of 1ES 0033+595 measured by KVA was 0.207 mJy which corresponds to R=17.93 mag. To derive the νF_ν in the optical band a contribution from near-by stars of 0.22 mJy was subtracted from the measured flux [18]. Furthermore, the brightness was corrected for galactic absorption by R= 2.353 mag [19]. The average νF_ν during the MAGIC observations corresponds to $8.47 \pm 0.5 \times 10^{-11}$ cm^{-2} s^{-1}. No significant variability was found during the MAGIC observation window.

2.4 *Swift* and *INTEGRAL*

The *Swift* Gamma-Ray Burst observatory [20], launched in 2004, is equipped with three telescopes: the Burst Alert Telescope (BAT [21], 15 keV – 150 keV), the X-Ray Telescope (XRT, 300 eV – 10 keV), and the Ultraviolet/Optical Telescope (UVOT, 170 nm – 650 nm). The *INTEGRAL* observatory [22], launched in 2002, is equipped with four telescopes. In the present work we used data from the detector ISGRI of the telescope IBIS [23] in the energy range from 20 keV – 100 keV. This instrument provides the best combination of FoV, sensitivity and angular resolution for our study.

Unfortunately, during the MAGIC observing window in 2009, there were no simultaneous *Swift* and *INTEGRAL* available data. We hence used archival data by NED (http://ned.ipac.caltech.edu/) from the observation periods 2004 – 2008 from both experiments, as listed in Tab. 1.

Experiment	Energy [keV]	Flux [10^{11} erg cm^{-2} s^{-1}]	Frequency [10^{19} Hz]
Swift	14 – 195	1.96±0.34	2.53
Swift	15 – 150	2.50±0.40	1.99
INTEGRAL	40 – 100	0.30	1.69
INTEGRAL	20 – 100	1.87	1.45
INTEGRAL	17 – 60	1.03±0.15	0.93

Table 1: Results of X-ray observations performed by *Swift* and *INTEGRAL* between 2004 and 2008 (from `http://ned.ipac.caltech.edu`).

3 Redshift from HE and VHE γ-ray data

The redshift of 1ES 0033+595 is uncertain. However, we can derive an estimation of this parameter using the intrinsic VHE γ-ray spectrum after Extragalactic Background Light (EBL) deabsorption. For its estimate, we used the VHE and HE observations to constrain the redshift of the source by the empirical approach reported in [24]. The method assumes that the intrinsic spectrum at TeV energies (e.g. observed with MAGIC) cannot be harder than that in the GeV band (observed with the *Fermi*–LAT). The spectrum shown in Fig. 2 was hence corrected using the EBL model by [25] in fine steps of redshift until the slope of the deabsorbed spectrum equals the one in the GeV-band. In this case an upper limit on the redshift of $z^* = 0.58 \pm 0.12$ was obtained. In addition, an estimate of the distance can be achieved using the linear relation between z and the true redshift [24]. The extracted redshift of 1ES 0033+595 using the inverse formula (for more details see [24]) resulted in $z_{rec} = 0.34 \pm 0.08 \pm 0.05$ (where the first error is purely statistical while the second corresponds to the uncertainty of the method), which is compatible with the lower limit $z > 0.24$ reported in [7]. In the SED modeling of 1ES 0033+595 the redshift value of $z = 0.34$ was used.

4 Spectral Energy Distribution

The 1ES 0033+595 SED is reconstructed for the first time from optical to TeV energies, allowing us to study the compatibility with a single zone Synchrotron Self-Compton (SSC) model [26] using the χ^2-minimization method [27]. The emission characteristics of BL Lac objects is generally well reproduced by the one-zone leptonic model, in which a population of relativistic electrons inside a region moving down the jet emit through synchrotron and synchrotron self-Compton mechanisms [28]. The spectral energy distribution of 1ES 0033+595 was modeled with such one-zone leptonic model using the χ^2-minimization method fully described in [27]. The emission region was assumed to be spherical, with radius R, filled with a tangled magnetic field of intensity B and relativistic electrons, emitting synchrotron and synchrotron self-Compton radiation. The energy distribution of the electrons follows a smoothed broken power law with normalization K between the Lorentz factors γ_{min} and γ_{max}, with slopes n_1 and n_2 below and above the break at γ_{break}. The relativistic boosting is represented by the Doppler factor δ.

In Fig. 3 we present the reconstructed SED from optical to TeV energies of 1ES 0033+595 using the multiwavelength data as described in Sec. 2. The MAGIC data were corrected for the extragalactic absorption using the EBL model by [25] and an assumed redshift of 0.34.

The obtained values of the model parameters are summarized in Tab. 2. The model parameters used for the SED fitting of 1ES 0033+595 are compatible with those

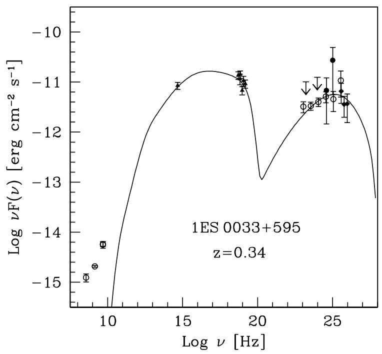

Fig. 3: SED of 1ES 0033+595 with an assumed redshift of $z = 0.34$. From lower to higher photon energies: simultaneous KVA data in the R-band, where the contribution of nearby stars has been subtracted and the flux has been corrected for galactic extinction (filled triangle); *INTEGRAL* and *Swift*–BAT archival data from 2004 – 2008 (filled triangle); simultaneous *Fermi*–LAT data (filled circle); MAGIC data corrected for the extragalactic absorption (filled diamond). The 38 months *Fermi*–LAT data (open circle) and archival radio data from the Green Bank and Texas observatories (open circle) are also shown. Radio data have not been included in the fitting due the opacity of the emission region in the radio band.

obtained for other HBL class objects (see e.g. [28, 29, 30]).

γ_{min}	γ_{break}	γ_{max}	n_1	n_2	B[G]	K[cm^{-3}]	R[cm]	δ
1000	$3.7{\cdot}10^4$	$2.9{\cdot}10^6$	2.0	3.2	0.2	$3.7{\cdot}10^2$	$6.5{\cdot}10^{16}$	36

Table 2: Model parameters used for fitting the SED in Fig. 3. For the χ^2 fitting the value of γ_{min} was fixed. The assumed redshift is $z = 0.34$.

5 Summary and Conclusions

In this contribution we reported the discovery of 1ES 0033+595 at VHE with the MAGIC telescopes, which made possible for the first time the characterization of the SED from optical to VHE. The MAGIC detection of 1ES 0033+595 also confirmed the prediction of the source to be a promising VHE γ-ray emitter, as reported in [31].

From the comparison of data from different wavelengths, from optical to VHE, we found that 1ES 0033+595 behaves like a typical HBL, namely marginal variability at optical frequencies, significant variability at X-rays, and a hard spectrum (power-law index > -2) at HE.

Since the redshift of this source is unknown, but crucial for an accurate SED modeling, we used the approach reported in [24] to obtain a redshift estimate of $0.34 \pm 0.08 \pm 0.05$. This result is in a good agreement with the lower limit of $z > 0.24$ reported in [7].

Finally, we presented for the first time the SED of 1ES 0033+595 from optical to VHE bands (using the redshift value of $z = 0.34$) and the achieved model parameters.

A comparison with other HBL type objects (e.g. [28, 29, 30]) shows that the model parameters used here for the SED fitting are compatible with those obtained for other HBL class objects, thus supporting the classification of 1ES 0033+595 as a HBL type object.

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