
**Discovery of VHE gamma-rays from the blazar 1ES 1215+303 with the MAGIC telescopes and simultaneous multi-wavelength observations**

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Discovery of VHE $\gamma$-rays from the blazar 1ES 1215+303 with the MAGIC telescopes and simultaneous multi-wavelength observations


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ABSTRACT

Context. We present the discovery of very high energy (VHE, $E > 100 \text{ GeV}$) $\gamma$-ray emission from the BL Lac object 1ES 1215+303 by the MAGIC telescopes and simultaneous multi-wavelength data in a broad energy range from radio to $\gamma$-rays.

Aims. We study the VHE $\gamma$-ray emission from 1ES 1215+303 and its relation to the emissions in other wavelengths.

Methods. Triggered by an optical outburst, MAGIC observed the source in 2011 January–February for 20.3 h. The target was monitored in the optical $R$-band by the KVA telescope that also performed optical polarization measurements. We triggered target of opportunity observations with the Swift satellite and obtained simultaneous and quasi-simultaneous data from the Fermi Large Area Telescope and from the Metsähovi radio telescope. We also present the analysis of older MAGIC data taken in 2010.

Results. The MAGIC observations of 1ES 1215+303 carried out in 2011 January–February resulted in the first detection of the source at VHE with a statistical significance of 9.4 $\sigma$. Simultaneously, the source was observed in a high optical and X-ray state. In 2010 the source was observed in a high state in both bands. The radio flux were comparable in 2010 and 2011. The spectral energy distribution obtained with the 2011 data can be modeled with a simple one zone SSC model, but it requires extreme values for the Doppler factor or the electron energy distribution.

Key words. BL Lacertae objects: individual: 1ES 1215+303 – gamma-rays: galaxies

1. Introduction

Most of the extragalactic sources from which very high energy (VHE, >100 GeV) $\gamma$-ray emissions have been detected are blazars. These objects are commonly believed to be a subtype of active galactic nuclei (AGN) whose relativistic jet points very close to the line of sight of the observer. Blazars are characterized by high amplitude variability at all wavebands from radio to $\gamma$-rays. The correlations between the different energy bands are complicated, but in general it seems that high states in lower
energy bands (e.g. optical) are accompanied by high states in the higher energies (i.e. γ-rays) at least in some sources (see e.g. Reintfeld et al. 2012).

The spectral energy distribution (SED) of blazars exhibits a generic two-bump structure: one peak with a maximum in the spectral range from radio to X-rays and a second peak in the interval from X-ray to γ-ray. The radiation is produced in a highly beamed plasma jet and the double peaked SED is often explained by a single population of relativistic electrons. The first peak is due to synchrotron emission in the magnetic field of the jet and the second peak is caused by inverse Compton (IC) scattering of low-energy photons (Rees 1967). The low-energy photons can originate externally to the jet (external Compton scattering, Dermer & Schlickeiser 1993) or be produced within the jet via synchrotron radiation (synchrotron self-Compton scattering, SSC; Maraschi et al. 1992).

Blazar is a common term used for flat spectrum radio quasars (FSRQs) and BL Lac objects (BL Lacs), which are thought to be intrinsically different. The FSRQs show broad emission lines in their optical spectra while the BL Lacs have featureless spectra with weak or no emission lines possibly masked by a strong emission from the jet. This indicates that in BL Lac objects the main population of seed photons for Compton scattering should originate from the synchrotron emission. Indeed most of the SEDs of BL Lacs are well described with simple SSC model (e.g. Bloom & Marscher 1996; Tavecchio et al. 1998).

MAGIC has been successfully performing optically triggered VHE γ-ray observations of AGN since the start of its operations. The triggers have been provided by the Tuorla blazar monitoring program1 and the target of opportunity (ToO) observations with MAGIC have resulted in the discovery of five new VHE γ-ray emitting sources (Mrk 180, Albert et al. 2006b; 1ES 1011+496, Albert et al. 2007; SS 0716+714, Andeurhub et al. 2009; B3 2247+381, Aleksić et al. 2012a; and 1ES 1215+303, this paper). However, in many cases it has not been possible to confirm with high statistical significance if the sources were in higher VHE γ-ray state than usual during the observations. The long-term studies of individual VHE γ-ray blazars like Mrk 421 (Acciari et al. 2011) and PG 1553+113 (Aleksić et al. 2012b) have also yielded controversial results on the correlation between the two broad energy ranges. Thus, to date, the connection between the optical and VHE γ-ray states has remained an open question.

1ES 1215+303 (also known as ON 325) is a high synchrotron peaking BL Lac object (Abdo et al. 2010b) with redshift z = 0.130 (Akiyama et al. 2003, however, z = 0.237 is also reported in the literature, e.g. Neddy). The source was classified as a promising candidate TeV blazar (Costamante & Ghisellini 2002; Tavecchio et al. 2010) and has been observed several times in VHE γ-rays before the observations presented here. The previous observations yielded only upper limits, Whipple: F (>430 GeV) < 1.89 × 10^{-11} cm^{-2} s^{-1} (Horan et al. 2004); MAGIC: F (>120 GeV) < 3.5 × 10^{-11} cm^{-2} s^{-1} (Aleksić et al. 2011a). The source was listed in the Fermi Large Area Telescope (LAT) bright AGN catalog (Abdo et al. 2009) as showing a hard spectrum (Γ = 1.89 ± 0.06). It underwent a large outburst in late 2008, and in this catalog 1ES 1215+303 is the only high energy peaking source that shows significant variability. In the second Fermi-LAT AGN catalog (Ackermann et al. 2011) other high synchrotron peaking sources have also been flagged as variable.

In the first days of 2011 January 1ES 1215+303 was observed to be in a high optical state. This triggered MAGIC observations, extending until 2011 February, that resulted in the discovery of VHE γ-rays from the source (Mariotti 2011). In this paper we present the results of the 2011 January–February observations. We also present the previous observations of 1ES 1215+303 with the MAGIC telescopes performed in 2010 January–February and 2010 May–June that produced only a hint of signal. For all epochs we present simultaneous and quasi-simultaneous multi-wavelength data from radio, optical, X-ray, and GeV γ-rays.

2. Observations and data analysis

The observations of 1ES 1215+303 were performed in a broad wavelength range (from radio to VHE γ-rays) by 5 different instruments. This is the first time that such a broad wavelength range is covered for this source in quasi-simultaneous observations.

2.1. MAGIC

MAGIC consists of two 17 m Imaging Air Cherenkov Telescopes (IACTs) sensitive to γ-rays with energy above 50 GeV in standard trigger mode (which is the lowest trigger energy threshold among the existing IACTs). The system is located in the Canary Island of La Palma, 2200 m above sea level. Since fall 2009 the telescopes are working together in stereoscopic mode which ensures a sensitivity of <0.8% of the Crab Nebula flux above 300 GeV in 50 h of observations (Aleksić et al. 2012c). The field of view of each MAGIC camera has a diameter of 3.5°.

1ES 1215+303 was observed by MAGIC in 2010 January–February, 2010 May–June, and 2011 January–February, for a total of 48 h. The observations were done in the so-called wobble mode (i.e. with the source offset by 0.4° from the camera center), which provides a simultaneous estimate of the background from the same data set (Fomin et al. 1994). While most of the data were taken in dark night conditions, a small fraction were taken in presence of moderate moonlight. The data span a range of zenith angle from 1° to 40° with most of the data taken below 25° (in 2010 the mean zenith angle was ~13°, and in 2011 ~8°). The data were analyzed using the standard MAGIC software and analysis package (Aleksić et al. 2012c). Another VHE γ-ray emitter, 1ES 1218+304 (Albert et al. 2006a) is present in the same field of view as 1ES 1215+303. The sources are separated by ~0.8°, which is much larger than the point spread function (PSF) of the MAGIC telescopes (~0.1°), so there was no source confusion or contamination. However, these sources have nearly the same Right Ascension, so in the standard wobble setup used in the 2010 January–February observations, the background estimation region partially overlapped with the 1ES 1218+304 position. This would result in an overestimate of the background, so this region was excluded from the background estimate. In the later observations (2010 May–June, and 2011 January–February) the wobbling offset direction was changed to have the standard background estimation regions far from the second source.

After the data quality selection, based mainly on the rate of stereo events, the data samples of January–February 2010, May–June 2010 and January–February 2011 contain 19.4, 3.5, and 20.6 h of good quality data respectively. Because of the different positions of the source in the camera, and the variable nature of AGN, we decided to split the analysis into these 3 periods.

1 http://users.utu.fi/kanilm/
2 http://nedww.ipac.caltech.edu/
2.2. Fermi-LAT

The Fermi-LAT is a pair conversion telescope designed to cover the energy band from 20 MeV to greater than 300 GeV. It operates in all-sky survey mode and therefore can provide observations of 1ES 1215+303 simultaneous to MAGIC. In this paper the standard LAT Science Tools (version v9r23p0) were used to analyze the data collected in the time interval from 2008 August 5 to 2011 March 22. For this analysis, only events belonging to the “Diffuse” class (which have the highest probability of being photons) and located in a circular Region Of Interest (ROI) of 7° radius, centered at the position of 1ES 1215+303, were selected (using Pass 6 event selection). In addition, we applied a cut on the zenith angle (<100°) limb γ-rays and a cut on the rocking angle (>52°) to limit Earth limb contamination.

The data analysis of 1ES 1215+303 is very challenging due to the presence of several γ-ray emitting sources in the same ROI. 1ES 1218+304 is located at a distance of just 0.8° from the source of interest. Another well known VHE emitter, W Comae, is located at ∼2° from the latter source. Thus, the LAT analysis was restricted to energies above 1 GeV where the Fermi-LAT PSF is sufficiently narrow to separate 1ES 1215+303 from the other sources in the ROI. The unbinned likelihood method was applied to events in the energy range from 1 GeV to 300 GeV. All point sources from the 2FGL catalog (Nolan et al. 2012) located within 12° of 1ES 1215+303 were included in the model of the region. Sources located within a 5° radius centered on 1ES 1215+303 position had their flux and photon index left as free parameters. The diffuse Galactic and isotropic components (including residual instrumental background) were modeled with the publicly available files gll_iem_v02_P6_V11_DIFFUSE.fit and isotropic iem_v02_P6_V11_DIFFUSE.txt. The normalizations of the components comprising the total background model were allowed to vary freely during the spectral point fitting. The instrument response functions P6_V11_DIFFUSE were used. The successful separation of flux between 1ES 1215+303 and 1ES 1218+304 was verified by the absence of any significant correlation between their light curves. The systematic uncertainty in the flux is estimated as 5% at 560 MeV and 20% at 10 GeV and above.

2.3. Swift

The Swift satellite (Gehrels et al. 2004) is equipped with three telescopes, the Burst Alert Telescope (BAT; Barthelmy et al. 2005) covering the 15–150 keV energy range, the X-ray telescope (XRT; Burrows et al. 2005) covering the 0.2–10 keV energy band, and the UV/Optical Telescope (UVOT; Roming et al. 2005) covering the 180–600 nm wavelength range. A Swift ToO request was submitted on 2011 January 3. The Swift observations started on January 4 until January 12 with four ∼5 ks exposures in photon counting mode. The data were processed with standard procedures using the FTOOLS task XRTPIPELINE (version 0.12.6) distributed by HEASARC within the HEASoft package (v.6.10). Events with grades 0–12 were selected for the data (see Burrows et al. 2005) and the latest response matrices available in the Swift CALDB (v.20100802) were used. For the spectral analysis, we extracted the source events in the 0.3–10 keV range within a circle with a radius of 20 pixels (∼47 arcsec). The background was extracted from an off-source circular region with a radius of 40 pixels.

The spectra were extracted from the corresponding event files and binned using GRPPHA to ensure a minimum of 25 counts per energy bin, in order to obtain reliable χ² statistics. Spectral analysis was performed using XSPEC version 12.6.0. The neutral hydrogen-equivalent column density was fixed to the Galactic value in the direction of the source 1.74 × 10²⁰ cm⁻² (Kalberla et al. 2005).

Swift/UVOT observed the source with all filters (V, B, U, UVW1, UVM2, UVW2) for four nights. UVOT source counts were extracted from a circular region 5 arcsec-sized centered on the source position, while the background was extracted from a larger circular nearby source–free region. These data were processed with the uvtomaghist task of the HEASOFT package. The observed magnitudes have been corrected for Galactic extinction E(B-V) = 0.024 mag (Schlegel et al. 1998), applying the formulae by Pei (1992) and finally converted into fluxes following Poole et al. (2008).

2.4. KVA

The KVA optical telescopes are located in La Palma, but are operated remotely from Finland. The two telescopes are attached to the same fork. The larger telescope has a mirror diameter of 60 cm and the smaller 35 cm.

The 35 cm telescope is used for simultaneous photometric observations with MAGIC, but also to monitor potential VHE γ-ray candidate AGN in order to trigger MAGIC observations if the sources are in high optical states. The observations are performed in the R-band and the magnitude of the source is measured from CCD images using differential photometry. The comparison star magnitudes for 1ES 1215+303 are from Fiorucci & Tosti (1996), and the magnitudes are converted to flux using the formula and values from Bessell (1979). 1ES 1215+303 has been observed regularly as part of the Tuorla blazar monitoring program since 2002.

The 60 cm telescope is used for polarimetric observations (see e.g. Pirola et al. 2005; Aleksić et al. 2011b). For 1ES 1215+303 polarimetric observations were performed on six nights from 2011 January 7 to January 17. The degree of polarization and position angle were calculated from the intensity ratios of the ordinary and extraordinary beams using standard formulae and semiautomatic software specially developed for polarization monitoring purposes.

2.5. Metsähovi radio telescope

37 GHz radio observations were made with the 13.7 m Metsähovi radio telescope located in Kylmälä, Finland. The telescope, the observation methods, and the data analysis procedure are described in e.g. Terasranta et al. (1998). The telescope detection limit is ∼0.2 Jy under optimal conditions and since 1ES 1215+303 is a rather weak source at 37 GHz it can only be observed under good weather conditions. Typically, an acceptable measurement of the source is obtained approximately once per month. Data were obtained simultaneously with the MAGIC observations in 2010 June, but in 2011 January–February the weather did not allow simultaneous observations with MAGIC, the closest points being from 2010 December and 2011 March.
3. Results

3.1. MAGIC results

The MAGIC data were divided in three samples corresponding to three observation epochs: 2010 January–February, 2010 May–June, and 2011 January–February. The so-called $\theta^2$ plots (the distribution of the squared angular distance between the arrival direction of the events and the real position), for energies above 300 GeV, corresponding to the three observation epochs, are shown in Fig. 1. The computation of the number of the ON (signal) and OFF (background) events was performed in a fiducial signal region of $\theta^2 < 0.01$ deg$^2$, and using 5 background regions (4 in case of the January–February 2010 data).

In 2010 January–February (left panel) 194 ON events were detected over 144.6 ± 6.0 OFF events, with a significance level of 3.5$\sigma$ (using Eq. (17) in Li & Ma 1983). In 2010 May–June (middle panel) the observation time was much shorter and no excess events were present. For 2011 data (right panel) the numbers were 251 ON over 119 ± 4.8 OFF corresponding to a ~9.4$\sigma$ significance, which is the first detection of VHE γ-rays from this source.

In Fig. 2, we show the significance map of the sky region for energies above 300 GeV for the 2010 (January–February and May–June combined) and 2011 observations. 1ES 1218+304 is clearly visible in both maps while 1ES 1215+304 was fainter in 2010 than in 2011. The 1ES 1218+304 data analysis and results will be addressed in a separate paper.

For the light curve and spectrum determinations softer cuts were applied that have a higher γ-ray efficiency. The light curve (in a 5-days bins) above 200 GeV of the 2011 data is well described by a constant flux of $(7.7 \pm 0.9) \times 10^{-12}$ cm$^{-2}$ s$^{-1}$ ($\chi^2/\nu_{d.o.f.} = 0.56/3$), which corresponds to about 3.5% of the Crab Nebula flux. Assuming that the hint of a signal seen in the 2010 data is a γ-ray excess the corresponding flux was $F(>200 \text{ GeV}) = (3.4 \pm 1.0) \times 10^{-12}$ cm$^{-2}$ s$^{-1}$, which is less than half of the flux measured in 2011. The hypothesis of constant flux between 2010 and 2011 is excluded at the level of 3.1$\sigma$.

The derived VHE γ-ray spectrum for the 2011 observations can be described by a single power law ($\chi^2/\nu_{d.o.f.} = 5.2/3$, see Fig. 3):

$$\frac{dN}{dE} = (2.27 \pm 0.25) \times 10^{-11} \left(\frac{E}{300 \text{ GeV}}\right)^{-2.96\pm0.14} \text{TeV}^{-1} \text{cm}^{-2} \text{s}^{-1}$$  

in the fitting range 70 GeV–1.8 TeV. Since the spectral index of 1ES 1215+303 is similar to that of the Crab Nebula and the source is relatively bright, we can directly use the systematic errors estimated in Aleksić et al. (2012c). The systematic error of the slope is ±0.15 and in the energy range of the 1ES 1215+303 spectrum, the error in the flux normalization (without the energy scale uncertainty) was estimated to be 11%. The systematic error in the energy scale is 15%. Finally, the MAGIC spectrum was deabsorbed using different EBL models (Domínguez et al. 2011; Kneiske & Dole 2010; Franceschini et al. 2008; Primack et al. 2005) and the maximum high UV EBL model described in Albert et al. (2008) for $z = 0.130$. The results are shown in Fig. 3. As denoted in the figure by the shaded area, at this redshift the EBL models agree well. The EBL model of Domínguez et al. (2011) was used to calculate the final intrinsic spectrum since this model is based on an observational approach.
Table 1. Data summary and results for the Swift/XRT ToO observations.

<table>
<thead>
<tr>
<th>MJD</th>
<th>Obs. time [ks]</th>
<th>Flux (2−10 keV) [10^{-12} erg/cm^2/s]</th>
<th>a (Γ for PL)</th>
<th>b</th>
<th>\chi^2/\nu</th>
<th>n_{d.o.f}</th>
</tr>
</thead>
<tbody>
<tr>
<td>55 168.699</td>
<td>4.99</td>
<td>1.21 ± 0.19</td>
<td>2.56 ± 0.10</td>
<td>0.34 ± 0.34</td>
<td>1.99/25</td>
<td></td>
</tr>
<tr>
<td>55 565.0340</td>
<td>4.39</td>
<td>2.74 ± 0.25</td>
<td>2.41 ± 0.08</td>
<td>0.37 ± 0.24</td>
<td>0.87/42</td>
<td></td>
</tr>
<tr>
<td>55 569.1281</td>
<td>2.38</td>
<td>3.02 ± 0.40</td>
<td>2.29 ± 0.16</td>
<td>–</td>
<td>1.23/18 (PL)</td>
<td></td>
</tr>
<tr>
<td>55 571.1327</td>
<td>4.07</td>
<td>1.69 ± 0.17</td>
<td>2.65 ± 0.14</td>
<td>–</td>
<td>1.23/18 (PL)</td>
<td></td>
</tr>
<tr>
<td>55 572.1361</td>
<td>4.27</td>
<td>1.45 ± 0.20</td>
<td>2.64 ± 0.09</td>
<td>0.28 ± 0.27</td>
<td>1.15/32</td>
<td></td>
</tr>
<tr>
<td>55 573.1396</td>
<td>2.99</td>
<td>1.73 ± 0.25</td>
<td>2.46 ± 0.11</td>
<td>0.66 ± 0.37</td>
<td>1.26/25</td>
<td></td>
</tr>
<tr>
<td>55 674.2438</td>
<td>2.34</td>
<td>1.30 ± 0.30</td>
<td>2.67 ± 0.25</td>
<td>–</td>
<td>0.48/8 (PL)</td>
<td></td>
</tr>
</tbody>
</table>

Notes. The datasets in the first/last rows are prior/subsequent to the MAGIC observations and are reported for comparison. For each dataset the following quantities are reported: the MJD time of the beginning of the observations; the exposure time; the integral flux in the 2−10 keV band; the a and b parameters for the log parabola fit (or the photon index Γ in case a simple power-law is used, see text); the reduced \chi^2 with number of degrees of freedom n_{d.o.f}. PL indicates when the simple power law is used instead of the log parabola.

Fig. 3. Observed and deabsorbed VHE γ-ray spectra. The EBL model of Domínguez et al. (2011) was used, the gray area shows the spread of the EBL models. The arrow shows the systematic error of the measurement.

Fig. 4. Long-term light curve of 1ES 1215+303 from Fermi-LAT between 1 and 100 GeV.

3.2. Fermi-LAT results

The light curve of 1ES 1215+303 was obtained in the energy range from 1 to 100 GeV, in 14-day bins from 2008 August to 2011 March (Fig. 4). It shows the major flare reported in Abdo et al. (2009) at the beginning of the Fermi mission. There is a hint of enhanced flux during 2010 November (MJD 55 500, duration only one bin, i.e. 14 days) but very little variability otherwise, especially at the two MAGIC observation epochs (2010 January–June and 2011 January–February). To maximize the number of photons the SED was derived using the whole MAGIC dataset (2010 January–June and 2011 January–February). The SEDs are shown in Fig. 5. In 2010 January–June the integral flux, \( F (1−100 \text{ GeV}) = (4.9 ± 0.7) \times 10^{-9} \text{ cm}^2 \text{ s}^{-1} \) and the photon index 2.1 ± 0.1, while in 2011 January–February \( F (1−100 \text{ GeV}) = (7.3 ± 1.6) \times 10^{-9} \text{ cm}^2 \text{ s}^{-1} \) and the photon index 2.0 ± 0.2. The mean detected flux was ~50% higher in 2011 January–February than in 2010 January–June, but due to large error bars the increase was not statistically significant. The spectral index was constant within the error bars.

Fig. 5. Spectral energy distribution from Fermi-LAT derived for 2011 January–June (top) and 2011 January–February (bottom). The upper limits have been computed when the test statistics (see e.g. Mattox et al. 1996) in the energy band were lower than 4. The bow-ties are derived from the unbinned likelihood analysis.

3.3. Swift results

The results of the Swift/XRT observations are summarized in Table 1. The source showed the highest flux on 2011 January 8 (MJD 55 569.1) and previous/subsequent observations from 2009 December (MJD 55 168.7)/ 2011 April (MJD 55 674.2) show significantly lower flux. For the X-ray spectra both log parabola (in the form \(-E^{−\alpha−\beta \log(E)}\), with \(E\) being the energy in keV) and a simple power-law fit were tested. The best fit was...
achieved with a log parabola law model in the range 0.3–10 keV for four observations while a simple power law, in the range 0.5–10 keV, provided a better fit for three of the observations. Generally, a log parabolic fit suggests that there is curvature in the X-ray spectra but for 1ES 1215+303, the difference between log parabolic and power law fits is small so no strong conclusions can be drawn. Because of the different fits a comparison between the spectral slopes is difficult, but for the highest flux night the spectral index is marginally harder than for the low state observations.

The Swift/UVOT results from 2011 January ToO observations show constant brightness with V-band magnitude $= 15.06 \pm 0.10$, $B = 15.95 \pm 0.10$, $U = 15.12 \pm 0.08$, $U$VW1 = 14.53 $\pm$ 0.08, $U$VM2 = 14.35 $\pm$ 0.06, and $U$VVW2 = 14.46 $\pm$ 0.06. However, in all bands the source is clearly brighter than in the previous observation (2009 December: $V = 15.60 \pm 0.10$, $B = 15.95 \pm 0.10$, $U = 15.12 \pm 0.08$, $U$VW1 = 15.07 $\pm$ 0.08, $U$VM2 = 15.00 $\pm$ 0.06, and $U$VVW2 = 15.15 $\pm$ 0.06).

### 3.4. KVA and Metsähovi results

In the optical $R$-band the source is clearly variable on daily and yearly time-scales. The host galaxy contributes a flux of 0.99 $\pm$ 0.09 mJy (Nilsson et al. 2007) and when this contribution was subtracted from the measured flux, the AGN core was found to be $\sim 40\%$ brighter in 2011 January–February (average total flux 3.64 mJy) than in 2010 January–June (average total flux 2.55 mJy). Similarly, it was found that during the 2011 January–February observations the flux varied by $\sim 25\%$ (core flux between 3.2 mJy and 4.1 mJy).

During 2011 January the optical polarization was $\sim 9\%$ while during the follow up observation in 2011 April it was higher $\sim 15\%$. The position angle (PA) was only slightly variable between 140 and 150 degrees.

In the radio band the source is rather weak and does not show strong variability. The 37 GHz flux from the Metsähovi radio telescope has a similar level (0.3–0.4 Jy) in 2010 and 2011, although there were no radio observations during 2011 January–February.

### 4. Interpretation

In this section we discuss the quasi-simultaneous light curves, showing how they establish connections between different energy regimes and locate the emission region. The SED is reconstructed for the first time from radio frequencies to TeV energies for 1ES 1215+303, allowing us to study the capability of the one-zone synchrotron self Compton model to reproduce the constructed SED.

#### 4.1. Multi-wavelength behavior

The long-term multi-wavelength light curve, from radio to VHE $\gamma$-rays, is shown in Fig. 6. The MAGIC light curve shows a lower flux in 2010 (January–February and May–June) than in 2011 (by a factor of 2). The large uncertainties in the Fermi-LAT measurement do not allow us to conclusively say whether a similar flux enhancement also occurred in the 1–100 GeV energy range (see Sect. 3.2). In X-rays the source was in a high state (enhanced by a factor of 2) in 2011 January compared with previous observations. In the optical band the average flux during MAGIC observations in 2010 was 3.5 mJy, while in 2011 it was 4.6 mJy. Thus, the source was clearly in outburst during early 2011, at least in VHE $\gamma$-rays, X-rays, and the optical band.

There were no simultaneous radio observations, but both the previous and subsequent observations showed low flux, suggesting that the outburst might have originated rather close to the central engine where the emission region is opaque at radio wavelengths. However, as the simultaneous observations are missing the existence of a simultaneous radio flare cannot be excluded.

During the 2011 January–February observations (Fig. 7), the MAGIC light curve is consistent with a constant flux. The source was in a rather low state in the Fermi-LAT energy range and no short term variability was detected. In X-rays and optical the source was variable during the MAGIC observations: the first two X-ray exposures gave a higher flux than for the latter three. The X-ray spectra show hints of hardening with higher flux, but they are statistically the same. The MAGIC observations started when the optical flux was decreasing, but during 2011 January the optical light curve showed several small flares. The X-ray light curve was more sparse and showed only one flare, but the comparison of simultaneous optical and X-ray points shows the same pattern in the light curves, indicating that the X-ray and optical emissions originate from the same region.

In addition to multi-wavelength variability studies, the optical polarization measurements have proven to be a powerful tool to analyze the emission scenarios in the blazar jets (e.g. Marscher et al. 2008). Polarization traces the magnetic field.
of the jet. A net polarization oriented either parallel or perpendicu-
lar to the projected jet axis can be confused by shocks and the
signatures are visible in optical polarization. The optical po-
larization measurements from 2011 January show little variabili-
ty in polarization degree (average ∼9%) or PA (varying between
∼140°−150°) during the MAGIC observations, but the follow-up
observations from 2011 April (Fig. 6) show a higher polariza-
tion, ∼15%. Unfortunately, the polarization observations missed
the peak of the first optical outburst and our data sample is very
small. Ikejiri et al. (2011) monitored the photo-polarimetric be-
havior of the source in 2008–2009 and their observations seem
to show similar polarization trends (i.e. a decreasing polariza-
tion during outbursts). They also found that the PA was almost
constant at ∼150°, which agrees with our observations and with
the historical data from 1981–1989 (Wills et al. 2011) show-
ing PA values from ∼130–170°. Such preferred position angles
have been observed for several BL Lac objects (e.g. Jannuzi et al.
1994) and implies long-term stability of the structure of the re-
gion producing the polarized emission e.g. the existence of an
optical polarization core. In first order, if the optical outburst
was produced by a shock traveling along the jet, one would expect
the polarization degree to increase during the outburst. However,
if there is a standing shock (optical polarization core) present,
another shock with a different magnetic field orientation colliding
with the standing component could produce an outburst in the to-
tal flux, but decrease the observed level of polarization (Villforth
et al. 2010). A detailed photo-polarimetric study based on more
data would be needed to further test this hypothesis.

4.2. Spectral energy distribution

The SED of 1ES 1215+303 in both MAGIC observation epochs is
shown in Fig. 8. The 2011 high energy bump is constructed using
the MAGIC deabsorbed spectrum (using the EBL model of
Domínguez et al. 2011) and the simultaneous Fermi-LAT spec-
trum (collecting all photons from 2011 January–February). As
stated in Sect. 4.1, the low energy bump was variable during the
period and is constructed for the night MJD 55 569 that showed
the highest Swift flux and for which there are simultaneous KVA
and UVOT observations. The contribution of the host galaxy was
subtracted from the R-band flux following Nilsson et al. (2007).
The host galaxy also contaminates the V, B, and U bands of the
UVOT data, but its contribution should be negligible in the UV.
As we have no direct measurements of the host galaxy contribu-
tion in V, B and U bands we extrapolated the magnitudes from
the R-band value using the galaxy colors of elliptical galaxies at
z = 0.2 (Fukugita et al. 1995).

For the 2010 MAGIC data set, we could not derive a spec-
trum because of the low significance of the signal but we report
the flux between 300 GeV and 1 TeV (assuming the same spec-
tral index as in 2011). The simultaneous Fermi-LAT spectrum
was calculated for the whole interval from 2010 January to June.
There was no simultaneous X-ray observation, while for the op-
tical we use the average (host galaxy subtracted) flux from nights
when MAGIC was also observing. This “low state SED” is pre-
sented for illustrative purposes only but was not modeled, since
both the synchrotron and IC peaks are poorly constrained.

The SED of 2011 shows two peaks, with the synchrotron peak
frequency slightly above the optical band, as found for many
other VHE γ-ray emitting BL Lac objects. The X-ray spec-
tral index is also typical for a BL Lac source. The second peak
seems to be located between the Fermi-LAT and MAGIC points
(∼1 GeV) as for many of the VHE γ-ray emitting BL Lacs.
The locations of the synchrotron and IC peaks agree with val-
ues derived in Abdo et al. (2010a) for this source, but the syn-
chrotron peak luminosity was slightly higher than in the previous
observation by Giommi et al. (2012).

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 (Bloom & Marscher 1996; Tavecchio et al. 1998).
The SED in 2011 is modeled with the one-zone leptonic model
fully described in Maraschi & Tavecchio (2003). The emission
region was assumed to be spherical, with radius R, filled with
a tangled magnetic field of intensity B and relativistic elec-
trons, emitting synchrotron and synchrotron self-Compton ra-
diation. The electrons follow a smoothed broken power law en-
ergy distribution with normalization K between γ_{min} and γ_{max},
with slopes n_1 and n_2 below and above the break at γ_0. The
relativistic boosting is fully accounted for by the Doppler factor δ.
We note, however, that one-zone models cannot reproduce the
spectrum at the lowest frequencies, since the emission is self-
absorbed below the millimeter band. It is generally assumed that
this part of the SED is due to outer regions of the jet that is not
important for the modeling of the high-energy emission.

The optical-UV and X-ray data define a narrow syn-
chrotron component peaking around 10^{15} Hz. At high ener-
gies, the SSC bump is well constrained by the Fermi-LAT and
MAGIC data to peak at about 10 GeV. This particular struc-
ture of the SED is not easy to reproduce. In particular, the rela-
tively wide separation between the two peaks inevitably implies
a large value of the Doppler factor if standard parameters are
used for the electron energy distribution (e.g. Georganopoulos & Kazanas 2003; Tavecchio & Ghisellini 2008). Our best attempt to reproduce the data in the standard framework provides the parameters given in Table 2 and is displayed as the dashed line of Fig. 8. As expected from the discussion above, we find a large Doppler factor, $\delta = 60$, well above the typical range of Doppler factors obtained from the modeling of the emission of similar sources (e.g. Tavecchio et al. 2010) and disagreeing with the lower values required by the FR I-BL Lac$^{6}$ unification scheme (Urry & Padovani 1995). However, there is an alternate, viable way to reproduce the observed SED using smaller Doppler factors; assume a relatively large minimum Lorentz factor of the emitting electrons, $\gamma_{\text{min}} = 8 \times 10^{3}$. This, along with a steep high energy electron energy distribution ($n_2 = 4.85$), allows us to properly reproduce the narrow synchrotron bump and to locate the SSC peak at high enough energies using a moderately large boosting, $\delta = 30$. This solution resembles one discussed for the case of BL Lacs showing hard spectra in the soft X-ray and TeV band (Katarzyński et al. 2005; Tavecchio et al. 2009; Kaufmann et al. 2011; Lefa et al. 2011). Interestingly, such parameters (large $\gamma_{\text{min}}$, steep slope) are consistent with the prediction of some simulations of particle acceleration by relativistic shocks (e.g. Virtanen & Vainio 2003; Sironi & Spitkovsky 2011). For example, for a proton-electron composition, it is expected that the electrons are heated when crossing the shock to a typical Lorentz factor of $\Gamma = \Gamma_{\text{rel}} m_p/m_e$, where $m_p/m_e = 1836$ is the proton to electron mass ratio and $\Gamma_{\text{rel}} = 2$–3 is the relative Lorentz factor between the upstream and the downstream flows. From this $\Gamma$ (that is equivalent to our parameter $\gamma_{\text{min}}$), electrons are subsequently accelerated, forming a non-thermal tail that is well approximated by a steep ($n = 3.5$) power law.

The goodness of the fit can be judged by eye or by $\chi^2$-minimization procedure. For the fits presented above the “eye estimate” was used, as for the latter the systematic errors of the data from different instruments are in the key role. However, we also tested the automatic $\chi^2$-minimization procedure of Mankuzhiyil et al. (2011) with estimated systematic errors of 2%, 10% and 40% for optical-X-ray, GeV $\gamma$-rays and VHE $\gamma$-rays respectively. The $\gamma_{\text{min}}$ is fixed to same value as in our high $\delta$ model (10$^3$) to allow easier comparison. The resulting parameters are shown in Table 2 and the fit with long-dashed (dark green) line in Fig. 8. The minimal $\chi^2$ fit results in lower $\delta$, but in a high $\gamma_{\text{max}}$ and rather large emission region radius $R$ compared to other fits, but still compatible with the day scale variability observed in X-rays and optical.

5. Summary and conclusions

In this paper the first detection of VHE $\gamma$-rays from 1ES 1215+303, resulting from MAGIC observations triggered by an optical outburst of the source in 2011 January, has been reported. In those data, the source is clearly detected at a 9.4$\sigma$ significance level. Also simultaneous multi-wavelength data are presented from radio to HE $\gamma$-rays respectively. The $\gamma_{\text{min}}$ is fixed to same value as in our high $\delta$ model (10$^3$) to allow easier comparison. The resulting parameters are shown in Table 2 and the fit with long-dashed (dark green) line in Fig. 8. The minimal $\chi^2$ fit results in lower $\delta$, but in a high $\gamma_{\text{max}}$ and rather large emission region radius $R$ compared to other fits, but still compatible with the day scale variability observed in X-rays and optical.

Our collected multi-wavelength data set is the most extensive energy coverage for 1ES 1215+303 to date. The optical-VHE $\gamma$-ray outburst seems to have been accompanied by an X-ray outburst, while in the Fermi-LAT band the flux increased only marginally. The optical photo-polarimetric data suggests that the high state could be caused by a shock traveling down the jet that collides with a standing shock with a differently oriented

Table 2. Input model parameters for the three models shown in Fig. 8.

<table>
<thead>
<tr>
<th>Model</th>
<th>$\gamma_{\text{min}}$</th>
<th>$\gamma_0$</th>
<th>$\gamma_{\text{max}}$</th>
<th>$n_1$</th>
<th>$n_2$</th>
<th>$B$</th>
<th>$K$</th>
<th>$R$</th>
<th>$\delta$</th>
<th>$\chi^2$/d.o.f.</th>
</tr>
</thead>
<tbody>
<tr>
<td>high $\delta$ (dashed)</td>
<td>1</td>
<td>3</td>
<td>1.0</td>
<td>2.0</td>
<td>4.2</td>
<td>0.02</td>
<td>8</td>
<td>10$^3$</td>
<td>0.8</td>
<td>60</td>
</tr>
<tr>
<td>high $\gamma_{\text{min}}$ (solid)</td>
<td>8</td>
<td>9.2</td>
<td>2.5</td>
<td>3.0</td>
<td>4.85</td>
<td>0.055</td>
<td>1.3</td>
<td>10$^6$</td>
<td>1.0</td>
<td>30</td>
</tr>
<tr>
<td>min $\chi^2$ (long dashed)</td>
<td>1</td>
<td>1.6</td>
<td>16.1</td>
<td>1.8</td>
<td>3.7</td>
<td>0.01</td>
<td>3.22</td>
<td>10$^6$</td>
<td>3.75</td>
<td>36</td>
</tr>
</tbody>
</table>

Notes. The following quantities are reported: the minimum, break, and maximum Lorentz factors and the low and high energy slope of the electron energy distribution, the magnetic field intensity, the electron density, the radius of the emitting region and its Doppler factor. In addition in the last column we report the $\chi^2$/d.o.f. assuming 2%, 10% and 40% systematical errors for optical-X-ray, GeV $\gamma$-rays and VHE $\gamma$-rays respectively.

Fig. 8. Spectral energy distribution of 2011 January–February data (dark red) symbols modeled with the one-zone SSC model of Maraschi & Tavecchio (2003). From high to low energies: the deabsorbed MAGIC spectra (asterisk, see text), the Fermi-LAT data (filled squares), Swift/XRT and Swift/UVOT data (triangles: upper (red) for MJD 55 569, lower (blue) for MJD 55 565) and simultaneous KVA data (filled circle, host galaxy subtracted, see text). The light (cyan) symbols report the January–June data of Fermi-LAT (data points and arrows) and MAGIC (the thick oblique line). The (green) open squares are archival data. The dashed line is the model fit using the extreme Doppler factor $\delta = 60$, while the solid line is the model fit with high $\gamma_{\text{min}}$ and the long dashed line reports the model parameters that produces with smallest $\chi^2$ (see text and Table 2).
magnetic field. The X-ray and VHE γ-ray high states could then also originate from this collision. The SED of 1ES 1215+303 in 2011 January was modelled using a one-zone SSC model since it provides a good description of the SED of many VHE γ-ray emitting BL Lac objects. However, for 1ES 1215+303 the synchrotron and IC peaks are narrow, the separation between the two peaks is wide, and a simple one-zone SSC model with typical parameters failed to reproduce the observed SED. To fit the SED, a high Doppler factor or a narrow electron energy distribution is required. While high Doppler factors are disfavored by the unified models, the high γmax value could be a viable solution in the light of simulations of the particle acceleration in a relativistic shock in a proton-electron jet. This should be further investigated, e.g. using the fully self-consistent SSC model with particle acceleration due to shock and stochastic acceleration by Weidinger & Spanier (2010).

Given the rather extreme conditions needed for the one-zone model, the presence of a velocity structure in the jet (Georganopoulos & Kazanas 2003; Ghisellini et al. 2005) is also possible and should be tested for modeling the SED. The narrow synchrotron and IC peaks should well constrain the model. Additionally, the more complex emission scenario suggested by the photo-polarimetric behavior of 1ES 1215+303 should be tested using, for instance, a model of Marscher (2011), who investigated the emission from a turbulent ambient jet plasma that passes through either the standing or moving shocks in the jet. Further observations of this exceptional VHE γ-ray emitting BL Lac are strongly encouraged.

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