VHE discovery and multi-band characterization of the blazar MAGIC J2001 +435

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Abstract: We present the first detection of very high energy (VHE; > 100 GeV) gamma-ray emission from MAGIC J2001+435 with the MAGIC stereoscopic system. MAGIC J2001+435 is a BL Lac object with a redshift $z > 0.11$. This source was identified as a promising candidate for VHE detection using *Fermi*-LAT photons above 10 GeV, which triggered observations with MAGIC in November 2009 and July – September 2010. The object was detected with MAGIC at a significance of 6.3 standard deviations during a 1.3-hour-long observation on July 16, and exhibited 15.8% of the flux of the Crab nebula in the energy range above 70 GeV. The source was not detected during the other days, which implies strong variability in the VHE range. Dedicated multi-instrument observations simultaneous to those of MAGIC show that this source is also very variable at optical, UV and X-ray energies. The broadband spectral energy distribution of this source during the VHE flare of July 16 can be described well within a one-zone synchrotron self-Compton scenario with typical parameter values for high-frequency-peaked BL Lac objects. The *Fermi*-LAT and MAGIC gamma-ray spectra can also be used to derive estimates for the redshift of this source under different assumptions.

Keywords: MAGIC, BL Lac objects, MAGIC J2001+435, VHE gamma rays, Multi-wavelength observation

1 Introduction

Blazars are radio-loud active galactic nuclei (AGN) with relativistic jets pointing towards the observer. They are the most common extragalactic sources detected in the very high energy (VHE; > 100 GeV) range. Blazars are classified into two categories by the equivalent widths of their optical emission lines: BL Lac objects and flat-spectrum radio quasars. Featureless spectra in optical bands characterize BL Lac objects, making it difficult to determine their redshift. Most of the spectral energy distributions (SEDs) of BL Lac objects are well reproduced by one-zone synchrotron self-Compton (SSC) models [1, 2].

MAGIC J2001+435 was initially one of the unidentified *Fermi*-LAT sources included in the *Fermi* bright source catalog (named 0FGL J2001.0+4352 [3]). This source was first detected only above 1 GeV in *Fermi*-LAT observations. The integral flux of $(7.8 \pm 1.2) \times 10^{-9}$ ph cm^{-2} s^{-1} between 1 and 100 GeV was reported in the 0FGL catalog [4]. A power-law function $dN/dE \propto E^{\Gamma}$ with $\Gamma = -1.90 \pm 0.03$ can well reproduce the observed hard-spectrum in the second *Fermi*-LAT source catalog, this source is denoted 2FGL J2001.1+4352 [5]. This source was selected by the *Fermi* collaboration as a good candidate source expected to exhibit VHE gamma-ray emission. Today, the location of this source is consistent with the radio source MG4 J200112+4352, and the source has recently been identified as a BL Lac object by Bassani et al. (2009) [6]. The redshift of this source is still uncertain. Bassani et al. estimated a redshift of $z \sim 0.2$. Recently, Shaw et al. (2013) [7] have derived a lower limit for the redshift of $z > 0.11$ based on the non-detection of the host galaxy, which is assumed to be a giant elliptical galaxy regarded as a standard candle with an absolute magnitude of $M_R = -22.5 \pm 0.5$.

2 MAGIC Observation and Analysis

The MAGIC telescope system consists of two Imaging Atmospheric Cherenkov Telescopes (IACTs) with a mirror dish diameter of 17 m, located on the Canary Islands of La Palma, Spain (28.8°N, 17.8°W at 2200 m a.s.l.). MAGIC has been operating in a stereoscopic mode since autumn 2009, leading to a low energy trigger threshold of ~ 50 GeV [8]. The stereoscopic observation mode provided a 5 standard deviation (σ) signal above 300 GeV from a source that exhibits 0.8% of the Crab nebula flux in a 50 hour observation time [8].

MAGIC J2001+435 was observed between November 7 and November 26, 2009, for a total of 9.0 hours. MAGIC observations were also performed in a multi-wavelength (MWL) campaign between July 6 and September 8, 2010, for a total of 14.4 hours. The data were taken at the zenith angle between 20° and 40° in November 2009 and at less than 30° in July – September 2010. The observations were carried out in the so-called wobble mode [9], in which the offset of the source position is 0.4° from the camera center. The pointing direction is alternated every 20 minutes to minimize systematic errors originating from possible exposure inhomogeneities.

The data were analyzed using the standard MAGIC analysis chain. Camera images were cleaned using a sum image-cleaning method [10, 11]. This algorithm originated from the concept of the sum trigger [12, 13]. In this procedure, the signals are clipped in amplitude and all possible combinations of 2, 3 and 4 neighboring pixels (2NN, 3NN, 4NN) in the camera are summed up. If the sum of the charges is above a certain threshold within a short time interval, these pixels are considered to belong to the shower image. The clipping ensures that afterpulses or strong night sky background fluctuations do not dominate the summed pixels. Generally, the sum image-cleaning method recovers more pixels than the standard method. This is important for reconstructing shower images of low-energy gamma rays. The sum image-cleaning method improves the sensitivity by 15% below 150 GeV [14].

3 MAGIC and Multi-wavelength Results

Figure 1 shows the distribution of the squared angular distance (θ^2) between the directions of reconstructed events and the real source position. We found an excess of events N_{ex} = 125.0 $\pm$ 20.2 in the energy range above 70 GeV in the observation on July 16, 2010, in which the effective observation time was 1.36 hours. This corresponds to a significance of 6.3 σ calculated using equation 17 in Li & Ma (1983) [15], which is the first detection of VHE gamma rays from MAGIC J2001+435. The integral flux above 70 GeV corresponds to 15.8% of the Crab nebula flux. The detected position of the excess (RA: 20.021 $\pm$ 0.001 h, Dec: 43.879 $\pm$ 0.010°) is consistent with the position of 2FGL J2001.1+4352. The difference between the detected position and pointing position is 0.011 $\pm$ 0.012°. The distribution of gamma-ray excess is consistent with a point like source. The source was not detected during the other days.

We obtained the differential flux from observation on July 16, 2010. This result is shown in Figure 2. The differential flux can be explained by a power law:

$$\frac{\mathrm{d}N}{\mathrm{d}E} = f_0 \times \left(\frac{E}{300\mathrm{GeV}}\right)^{\alpha}, \tag{1}$$

with flux normalization f_0 = $(6.2 \pm 1.8) \times 10^{-11}$ ph cm^{-2} s^{-1} TeV^{-1} and photon index α = (-2.8 ± 0.4). Then we applied the Tikhonov unfolding algorithm [16] to reconstruct the physical spectrum in terms of the true energy of the primary gamma rays.

The overall MWL light curves of MAGIC J2001+435 during the campaign in 2010 are shown in Figure 3. We present the MAGIC flux on July 16, 2010 in the energy range above 200 GeV. The *Fermi*-LAT light curve is plotted with a bin width of 3 days in the energy range from 1 to 300 GeV. The flux upper limit at a 95% confidence level was calculated for each time bin when the test statistic (TS, [17]) value was less than 4. The X-ray count rates and UV fluxes are plotted from the *Swift*/XRT and *Swift*/UVOT archival data, respectively. The optical R-band fluxes observed by several different optical instruments (GRT, KVA, Galaxy View observatory, a 70 cm AZT-8 telescope in Crimea and a 40 cm LX-200 telescope in St. Petersburg observatory) are shown in the same figure. MAGIC J2001+435 is most variable at optical and X-rays.

The top and bottom panels in Figure 4 show the *Swift*/XRT intranight light curve and the hardness ratio curve of MAGIC J2001+435 during July 16, 2010, respectively. The fit of a constant to the X-ray flux has a χ^2 of 12.3 for n_{dof} = 11 (P = 34.2%), which shows that the X-ray flux is consistent with a constant hypothesis within a 95% confidence level. The hardness ratio curve has a χ^2 of 2.9 for n_{dof} = 2 (P = 23.3%). There is no statistically significant intranight variability of the hardness ratio, although the data points might suggest the softening of the X-ray spectrum. The intranight VHE variability is currently being investigated, and the results will be presented elsewhere.

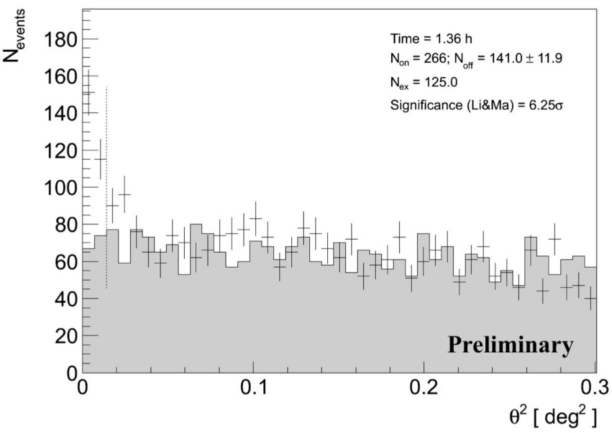

Fig. 1: Theta-squared distribution of MAGIC J2001+435 observed on July 16, 2010. Crosses are signal and the gray histogram is the estimated background. The region with smaller θ^2 than the value indicated by the dashed line is the signal region defined a priori.

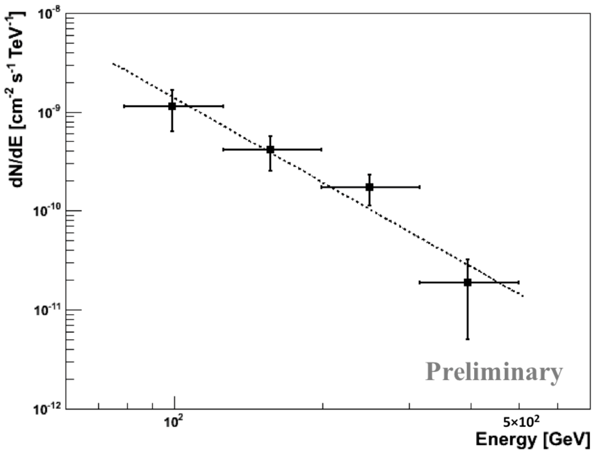

Fig. 2: Unfolded differential spectrum of MAGIC J2001+435 observed on July 16, 2010, by MAGIC. The spectrum is fitted by a power-law function between 78 and 500 GeV.

4 Discussion

We calculated the deabsorbed spectrum using the observed MAGIC spectrum on July 16, 2010, to estimate its redshift. In this work, we assume the extragalactic background light (EBL) density model presented by Franceschini et al. (2008) [18] and an intrinsic spectrum can be expressed by a simple power-law function. Assuming that the intrinsic photon

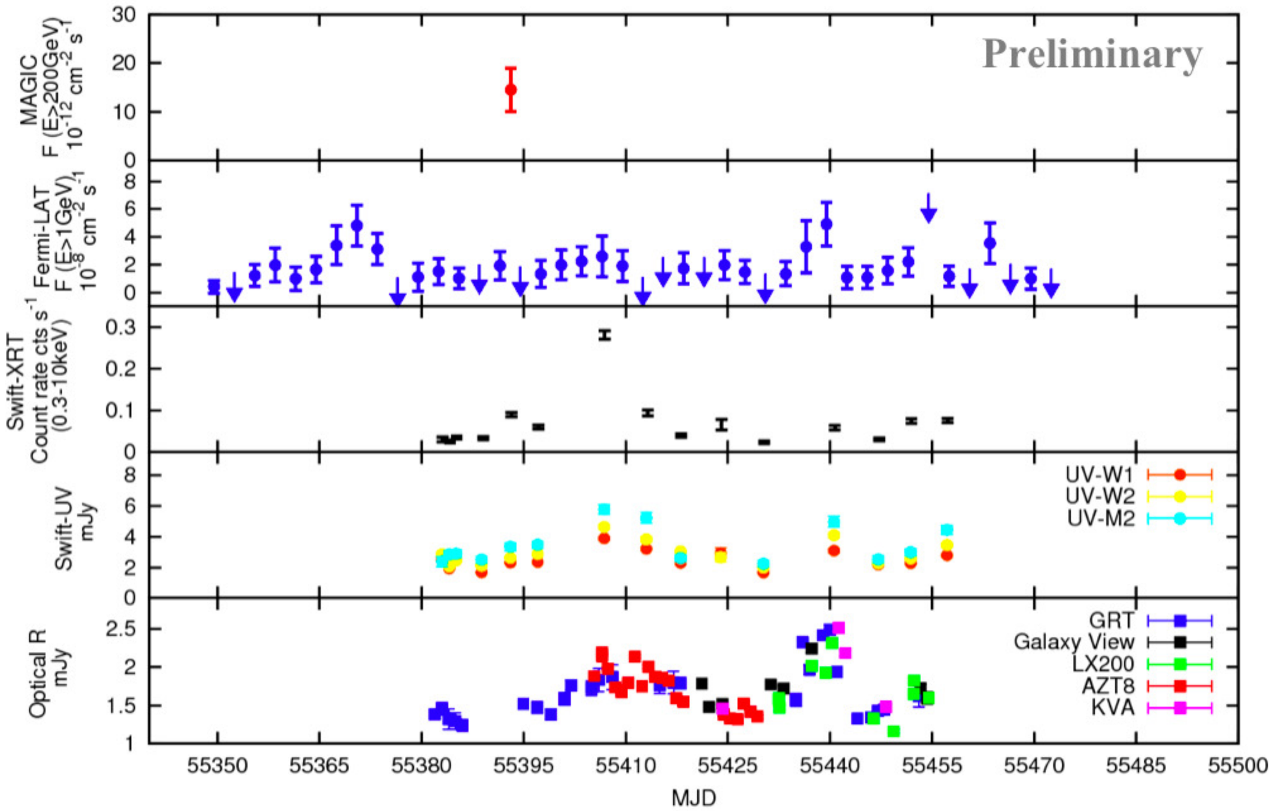

Fig. 3: Simultaneous MWL light curves of MAGIC J2001+435 during the campaign in July – September 2010. The MAGIC flux on July 16, 2010, is plotted in the energy range above 200 GeV. The *Fermi*-LAT light curve between 1 and 300 GeV is presented in the second panel, where the time bin size is 3 days from June 1, 2010 (MJD; 55348 – 55474). The arrows correspond to 95% confidence level upper limits (TS value < 4). The third panel shows the X-ray (0.3 – 10 keV) count rate from *Swift*/XRT. The UV fluxes taken with *Swift*/UVOT with UVW1, UVM2 and UVW2 filters are shown in the fourth panel. The bottom panel includes optical R-band fluxes.

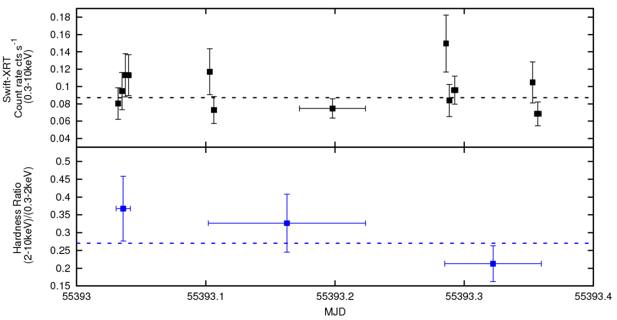

Fig. 4: Intranight X-ray light curves for MAGIC J2001+435 observations on July 16, 2010. The constant fluxes are shown as dashed lines.

index can not be harder than $\Gamma_{\rm int} = 1.5$ [19], we obtain a redshift limit of $z < 0.637$ with a confidence of 95%.

We analyzed *Fermi*-LAT data of MAGIC J2001+435 between July 1 and August 1, 2010, and obtained a one-month-averaged *Fermi*-LAT spectrum. This spectrum has a quite hard spectral index of $\Gamma_{\rm LAT} = -1.83 \pm 0.18$ assuming a power-law function in the energy range between 300 MeV and 30 GeV. The integral flux is $(9.8 \pm 2.6) \times 10^{-8}$ ph cm^{-2} s^{-1} between 100 MeV and 300 GeV. We calculated the redshift z^* by assuming that the power-law slope fitting to the deabsorbed VHE spectrum is equal to the slope measured by *Fermi*-LAT. We obtained the redshift of the source to be $z^* = 0.30 \pm 0.16$, where Franceschini's EBL model is assumed. Here, to reconstruct the distance to MAGIC J2001+435, we applied the method from Prandini et al. (2011) [20]. As a result, we found the reconstructed distance to be $z_{\rm rec} = 0.165 \pm 0.101$ for MAGIC J2001+435. This value is compatible with the lower limit ($z > 0.11$) reported by Shaw et al. [7].

In Figure 5, we show the MWL SED of MAGIC J2001+435. The simultaneous MWL SED has previously been modeled with a one-zone SSC scenario [21]. In this model, the emission region is assumed to be spherical with radius R and to be filled by a tangled magnetic field of intensity B in a comoving frame. The emission region is in motion with a Lorentz factor of Γ and a viewing angle of θ in the observer frame. The injected energy distribution of the relativistic emitting electrons is described as a broken power law with the normalization of electron density K, extending from $\gamma_{\rm min}$ to $\gamma_{\rm max}$ with indices n_1 and n_2 below and above the break Lorentz factor $\gamma_{\rm bk}$, respectively. Relativistic effects are taken into account by the Doppler factor $\delta = [\Gamma(1-\beta\cos\theta)]^{-1}$. We obtained the following one-zone SSC scenario parameters: $\gamma_{\rm min} = 1.0$, $\gamma_{\rm bk} = 3.3 \times 10^4$, $\gamma_{\rm max} = 6.0 \times 10^5$, $n_1 = 2.0$, $n_2 = 5.0$, $K = 2.1 \times 10^4$ cm^{-3}, $B = 100$ mG, $\log_{10}(R[\rm cm]) = 15.9$ and $\delta = 27$, where we assumed a redshift of $z = 0.165$. The estimated synchrotron

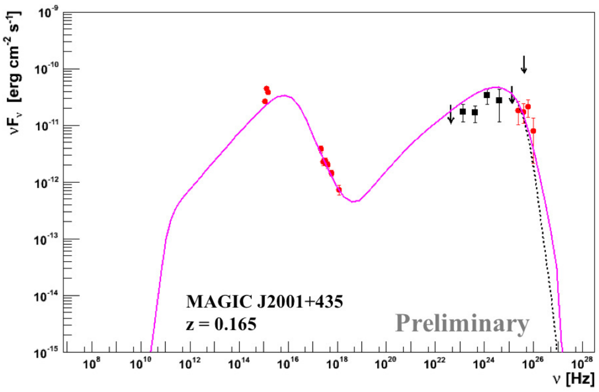

Fig. 5: Simultaneous MWL SED of July 16, 2010 (red circles: MAGIC, *Swift*/XRT and *Swift*/UVOT) for MAGIC J2001+435, modeled with a one-zone SSC scenario. MAGIC points show the deabsorbed spectrum with a redshift of $z = 0.165$. The black squares represent the one-month-averaged *Fermi*-LAT spectrum (MJD; 55378 – 55409). The arrows of the *Fermi* spectrum show 2 σ confidence level upper limits. The result of one-zone SSC modeling is shown by the dashed black curve. Taking into account EBL absorption, the magenta solid curve represents the resulting intrinsic spectrum.

emission peak of MAGIC J2001+435 is located at a high frequency ($\sim 10^{16}$ Hz), which indicates that this object is a typical high-frequency-peaked BL Lac object (HBL). The simultaneous MWL SED of MAGIC J2001+435 on July 16, 2010, can be described well by a one-zone SSC scenario, yielding typical parameters for HBLs.

5 Conclusions

We observed MAGIC J2001+435 for a total of 23.4 hours in November 2009 and July – September 2010, detected a significant gamma-ray signal on July 16, 2010. The detection indicates that this source is variable in the VHE range, as implied by longer-time light curves at other wavelengths. Assuming a distance of $z_{rec} = 0.165$, the simultaneous MWL SED is reproduced by a one-zone SSC scenario with parameters similar to those of other HBLs.

Acknowledgment: 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.

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