Discovery of Very High Energy γ-rays from the famous blazar S5 0716+714

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***Abstract*. The MAGIC collaboration reports the detection of the blazar S50716+714 (redshift uncertain) in very high energy gamma-rays. The observations were performed in November 2007 and in April 2008, and were triggered by the KVA telescope due to the high optical state of the object. The blazar S50716+714 is the third low frequency BL Lac detected at energies above 100 GeV until today. Here, we present the results of the MAGIC observations.**

***Keywords*: gamma-rays:Observations, MAGIC, BL Lacs:individual:S5 0716+714**

I. Introduction

Blazars, a common term used for flat spectrum radio quasars (FSRQ) and BL Lacertae objects, are the most extreme types of Active Galactic Nuclei (AGN). In these objects the dominant radiation component originates in a relativistic jet pointed nearly towards the observer. The double-peaked spectral energy distribution (SED) of blazars is attributed to a population of relativistic electrons spiraling in the magnetic field of the jet. The low energy peak is due to synchrotron emission and the second, high energy peak is attributed to inverse Compton scattering of low energy photons in leptonic acceleration models. Models based on the acceleration of hadrons can also sufficiently describe the observed SEDs and lightcurves [Mannheim (1993)], [Mucke et al.(2003)]. For most FSRQs and a large fraction of BL Lacertae objects (namely LBLs[1]) the low energy peak is located in the energy range between submillimeter to optical. On the other hand, for most of the sources detected to emit VHE γ-rays (high frequency peaking BL Lacs, HBLs) the low energy peak is located at UV to X-rays energies [Padovani (2007)].

Blazars show variable flux in all wavebands from radio to very high energy (VHE defined as $>$ 100 GeV) γ-rays. The relationship between the variability at different wavebands appears rather complicated. The MAGIC Collaboration is performing Target of Opportunity observations of sources in a high flux state in the optical and/or X-ray band. The optically triggered observations have resulted in the discovery of VHE γ-rays from Mrk 180 [Albert et al.(2006)] and 1ES 1011+496 [Albert et al.(2007)]. In this paper we report the results of observations of the BL Lac object S5 0716+714 in November 2007 and April 2008, the latter resulting in the discovery of VHE γ-rays from the source as announced in [Teshima et al. (2008)].

S5 0716+714 has been studied intensively at all frequency bands. It is highly variable with rapid variations observed from the radio to X-ray bands (Wagner et al. 1996). It has therefore been target to several multiwavelength campaigns, the most recent one organized by the GLAST-AGILE Support Program in July-November 2007 [Villata et al.(2008)], [Giommi et al.(2008)]. Due to the very bright nucleus, which outshines the host galaxy, the redshift of S5 0716+714 is still uncertain. The recent detection of the host galaxy [Nilsson et al. (2008)] suggests a redshift of $z = 0.31 \pm 0.08$ which is consistent with the redshift $z = 0.26$ determined by spectroscopy for 3 galaxies close to the location of S5 0716+714 [Stickel et al. (1993)], [Bychova et al.(2006)]. In the SED of S5 0716+714 the synchrotron peak in located in the optical band and is, therefore, classified either as LBL [Nieppola et al. (2006)] or as IBL[2] [Padovani et al. (1995)]

S5 0716+714 was detected several times at different flux levels by the EGRET detector on board the Compton Gamma-ray Observatory [Hartman et al.(1999)]. Also AGILE reported detection of a variable γ-ray flux with peak flux density above the maximum reported from EGRET [Chen et al.(2008)]. Observations at VHE γ-ray energies by HEGRA resulted in an upper limit of $\mathrm{F}(> 1.6\,\mathrm{TeV}) = 3.13$ photons/cm^2/s [Aharonian et al.(2004)]. In this paper we present the first detection of VHE γ-rays from S5 0716+714. It is the third optically triggered discovery of a new VHE γ-ray emitting blazar by MAGIC. We also present MAGIC observations of the source in a low optical state, at which

[1]LBL = low peak frequency BL Lacertae

[2]IBL = intermidiate peak frequency BL Lacertae

the observations resulted in a flux upper limit that is clearly lower than the observed VHE γ-ray flux during the optical high state.

II. Observations

The MAGIC telescope is a stand alone imaging atmospheric Cherenkov telescope located on the Canary Island of La Palma. MAGIC has a standard trigger threshold of 60 GeV, an angular resolution of $\sim 0.^\circ 1$ and an energy resolution above 150 GeV of $\sim 25\%$ (see [Albert et al.(2008b)] for details).

Tuorla blazar monitoring program [Takalo et al. (2007)] (http://users.utu.fi/kani/1m) monitors S5 0716+714 on a nightly basis using the KVA 35 cm Telescope at La Palma and the Tuorla 1 meter telescopes. At the end of October 2007 (22th) the optical flux had more than doubled (from 19 mJy to 42 mJy) in less than a month and MAGIC was alerted. Due to moon and weather constraints, the MAGIC observations started 11 days later, when the optical flux had already decreased significantly (see Fig. 2). MAGIC observed the source for 14 nights for a total of 16.8 hours. During some nights the observing conditions were rather poor and the affected data was rejected from the analysis. The observation time of the remaining good quality data amounts to 10.3 hours. The zenith angle range of these observations was 42 to 46 degrees.

There was another strong optical flare from S5 0716+714 in April 2008. The optical flux almost doubled within three nights (14th of April: 29 mJy, 17th April: 52 mJy), and at 17th of April reached its historical maximum value. MAGIC started the observations 5 nights later, when the moon conditions allowed. The source was observed during 9 nights with zenith angles from 47 to 55 degrees for a total of 7.1 hours. Unfortunately, during the last 6 nights of the observations there was strong calima (sand from Sahara desert) in the atmosphere and this data was, therefore, rejected from the analysis. The observation time of the remaining data of this period amounts to 2.8 hours only. The total life time of S5 0716+714 MAGIC observations in 2007 and 2008 after data quality cuts was 13.1 hours.

In addition to R-band photometry we also made polarimetric observation of S5 0716+714 using the KVA 60 cm telescope on 2008, April 29. The polarization was $3.95\% \pm 0.2\%$ and the polarization angle 102 ± 2. [Larinov et al.(2008)] reported that between 2008, April 19 and April 25 the positional angle of polarization rotated with an approximate rate 60 degrees per day and that after 2008, April 26 it returned to the pre-outburst level. Since we measured the polarization only during one night, we cannot confirm this behaviour of the positional angle of polarization.

III. Data Analysis and Results

The MAGIC data was analyzed using the standard analysis chain as described in [Albert et al.(2008d)], [Albert et al.(2008b)], [Aliu et al.(2009)]. Background rejection is achieved by a cut in Hadronness, which was optimized using Crab Nebula data taken under comparable conditions (NSB noise, zenith distance, etc.). The cut in |Alpha| that defines the signal region was also optimized in the same way. An additional cut removed the events with a total charge of less than 200 photoelectrons (phe) in order to assure a better background rejection. For the given cuts and zenith angle range of the observations the analysis threshold corresponds to 400 GeV. The resulting |Alpha| distribution after all cuts for the overall S5 0716+714 data sample in 2007 – 2008 is shown in Fig. 1. An overall excess of 252 γ-like events over 1548 background events corresponding to a significance of $S = 5.8\,\sigma$ was found. Most of the signal comes from the 2008 data sample: the analysis of the 2008 data only results in 176 excess events over 422 background events corresponding to $S = 6.9\,\sigma$. From the 2007 data alone an excess corresponding to $S = 2.2\,\sigma$ was found.

The day-by-day light curve as measured by MAGIC data is shown in Fig. 2 (upper panel) together with the optical KVA light curve (lower panel). In November

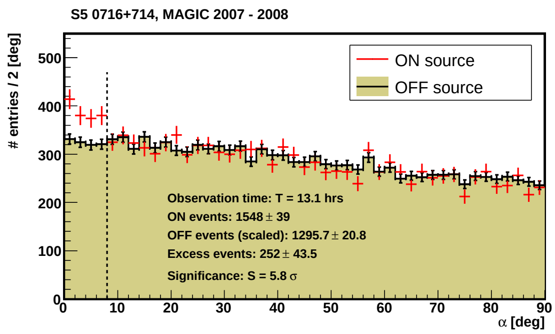

Fig. 1. |Alpha| distribution after all cuts for the total MAGIC data sample in 2007 – 2008. A γ-ray excess with a significance of $5.8\,\sigma$ is found.

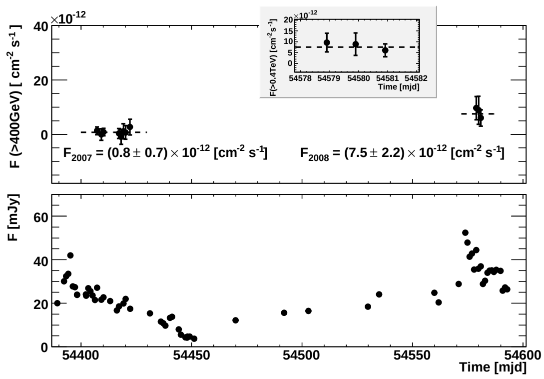

Fig. 2. The light curve of S5 0716+714 as measured from November 2007 until April 2008. The day-by-day γ-ray light curve from MAGIC is shown in the upper panel whereas the optical KVA data is shown in the lower panel. A zoom into the MAGIC 2008 data is shown in the inset of the upper panel to illustrate that there is no significant variability.

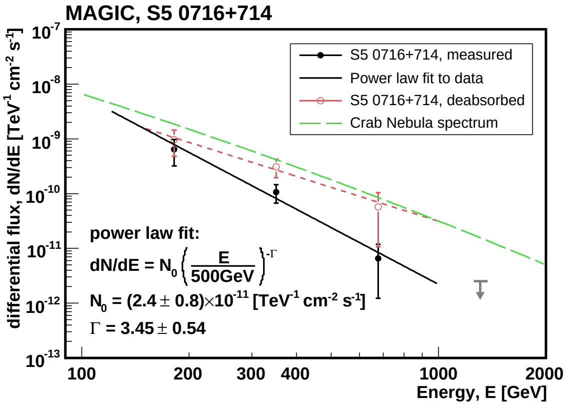

Fig. 3. The differential energy spectrum of S5 0716+714. Data from April 2008 are used only. The measured (full black points) as well as deabsorbed (using the an EBL model of [Primack et al. (2005)] and assuming z=0.31, hollow points) spectra are shown. The highest energy point at 1.3 TeV corresponds to a 95% upper limit. The results from a power law fit to the measured spectrum are shown in the plot. The fitted power law to the deabsorbed spectrum has a photon index of 2.06 ± 0.56 (short–dashed line). The Crab Nebula spectrum is shown for comparison (long–dashed line).

2007 the MAGIC flux above 400 GeV is at $F_{2007}(>0.4\text{TeV}) = (0.8 \pm 0.7)[\text{cm}^{-2}\text{s}^{-1}]$, whereas the flux is about 9 times higher in 2008: $F_{2008}(>0.4\text{TeV}) = (7.5 \pm 2.2)[\text{cm}^{-2}\text{s}^{-1}]$. No significant variability is seen on time scales shorter than 6 months. However, we note that due to the observation windows and available data, we are not sensitive to week or months variability time scales. No intranight variability was detected either but given the low significance of the individual MAGIC points, an intranight variability by a factor of at least ten would have been required to detect it. In the optical band, instead, a clear variability on time scales from days to months is visible with two distinct flares: the first in October 2007, and the second in April 2008.

The differential energy specrum is calculated only for the April 2008 data set. The measured (and unfolded for detector effects) spectrum is shown in Fig. 3. The last energy point (at an energy of $E = 1.3\,\text{TeV}$) has a significance lower than $1\,\sigma$ and was, therefore, converted into an upper limit corresponding to a 95% confidence level. The measured spectrum can be well fitted by a simple power law (with the differential flux fiven in units of TeV^{-1} cm^{-2} s^{-1}):

$$\frac{\mathrm{d}N}{\mathrm{d}E\,\mathrm{d}A\,\mathrm{d}t} = (2.4 \pm 0.8) \times 10^{-11} (E/500\,\text{GeV})^{-3.5 \pm 0.5} \quad (1)$$

Due to the energy-dependent attenuation of VHE γ-rays with low-energy photons of the extragalactic background (EBL, [Gould & Schréder(1967)]), the VHE γ-ray flux of distant sources is significantly suppressed. We calculated the deabsorbed, i.e. intrinsic, spectrum of S5 0716+714 using an EBL model of [Primack et al. (2005)] and assuming a redshift of $z = 0.31$. The resulting intrinsic spectrum (shown in Fig. 3, hollow points) has a fitted photon index of $\Gamma = 2.1 \pm 0.6$, which is well within the range of other extragalactic sources measured so far.

IV. Discussion

MAGIC observed the blazar S5 0716+714 in November 2007 and April 2008, the observations resulting in the discovery of a very high energy γ-ray excess with a significance of 5.8σ. During the November 2007 MAGIC observations the average optical flux was $\sim$ 20mJy, while during the optical flux was ~ 45mJy in April 2008. The same trend is also visible in the MAGIC data: the flux in April 2008 is significantly higher than in November 2007. This seems to support the indication seen in previous MAGIC observations for other BL Lac objects [Albert et al.(2006)], [Albert et al.(2007)], [Albert et al.(2007b)], that there is a connection between optical high states and VHE γ-ray high states.

In April 2008 S5 0716+714 was also in a historical high state in X-rays [Giommi et al.(2008)] and the optical polarization angle started to rotate immediately after the optical maximum has been reached [Larinov et al.(2008)]. However, the radio flux at 37 GHz did remain at a quiescent level. This multiwavelength behavior is very similar to the one in BL Lac 2005 [Marscher et al.(2008)] indicating that the flaring events might have a similar origin.

The SED modeling of the available data is not straight forward as there are various simultaneous data suggesting a rather broad Inverse Compton peak extending from high X-rays (measured by *Swift*) to VHE γ-rays (MAGIC). A detailed modeling of the source spectrum and an overall SED discussion will be published elsewhere.

As the source redshift is still uncertain, we used the MAGIC spectra to calculate upper limits to the redshift. We assumed two different maximum possible hardness of the intrinsic spectrum: 1.5, being a canonical value for a γ-ray spectrum emitted by electrons with a spectral index of 2.0; and 0.666, being the limiting case for a γ-ray spectrum emitted by a monoenergetic electron distribution. We get following upper limits for the redshift: $z < 0.57$ (assuming the hardest intrinsic index of 1.5) and $z < 0.72$ (assuming the hardest intrinsic index of 2/3). Both limits agree with the redshift determined from the host galaxy detection ($z = 0.31 \pm 0.08$) and from the spectroscopy of 3 nearby galaxies ($z = 0.26$).

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