MAGIC TeV Gamma-Ray Observations of Markarian 421 during Multiwavelength Campaigns in 2006

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ABSTRACT

Context. Wide-range spectral coverage of blazar-type active galactic nuclei is of paramount importance for understanding the particle acceleration mechanisms assumed to take place in their jets. The Major Atmospheric Gamma Imaging Cerenkov (MAGIC) telescope participated in three multiwavelength (MWL) campaigns, observing the blazar Markarian (Mkn) 421 during the nights of 2006 April 28, 29, and 2006 June 14.

Aims. We analyzed the corresponding MAGIC very-high energy observations during 9 nights from 2006 April 22 to 30 and on 2006 June 14. We inferred light curves with sub-day resolution and night-by-night energy spectra.

Methods. MAGIC detects γ-rays by observing extended air showers in the atmosphere. The obtained air-shower images were analyzed using the standard MAGIC analysis chain.

Results. A strong γ-ray signal was detected from Mkn 421 on all observation nights. The flux ($E > 250$ GeV) varied on night-by-night basis between $0.92 \pm 0.11 \times 10^{-14} \text{cm}^{-2} \text{s}^{-1} / (0.57$ Crab units) and $3.21 \pm 0.15 \times 10^{-15} \text{cm}^{-2} \text{s}^{-1} / (2.0$ Crab units) in 2006 April. There is a clear indication for intra-night variability with a duration of 36 ± 10 minutes on the night of 2006 April 29, establishing once more rapid flux variability for this object. For all individual nights γ-ray spectra could be inferred, with power-law indices ranging from 1.66 to 2.47. We did not find statistically significant correlations between the spectral index and the flux state for individual nights. During the June 2006 campaign, a flux substantially lower than the one measured by the Whipple 10-m telescope four days later was found. Using a log-parabolic power law fit we deduced for some data sets the location of the spectral peak in the very-high energy regime. Our results confirm the indications of rising peak energy with increasing flux, as expected in leptonic acceleration models.

Key words. Gamma rays: galaxies – BL Lacertae objects: individual (Mkn 421) – Radiation mechanisms: non-thermal

1. Introduction

The active galactic nucleus (AGN) Markarian (Mkn) 421 was the first extragalactic source detected in the TeV energy range, using imaging atmospheric Cerenkov telescopes (IACTs; Punch et al. 1992, Petry et al. 1996). With a redshift of $z = 0.030$ it is the closest known and, along with Mkn 501, the best-studied TeV γ-ray emitting blazar. So far, flux variations by more than one order of magnitude (e.g., Fossati et al. 2008, and occasional flux doubling times as short as 15 min (Gaidos et al. 1996, Aharonian et al. 2002, Schweizer, Wagner & Lorenz 2008) have been observed. Variations in the hardness of the TeV γ-ray spectrum during flares were reported by sev-
eral groups (e.g., Krennrich et al., 2002; Aharonian et al., 2003; Fossati et al., 2008). Simultaneous observations in the X-ray and very-high-energy (VHE; $E \gtrsim 100$ GeV) bands show strong evidence for correlated flux variability (Krawczynski et al., 2001; Blażejowski et al., 2005; Fossati et al., 2008). With a long history of observations, Mkn 421 is an ideal candidate for long-term and statistical studies of its emission (Tluczykont et al., 2007; Goebel et al., 2008; Hsu et al., 2009).

Mkn 421 has been detected and studied at basically all wavelengths of the electromagnetic spectrum from radio waves up to VHE $\gamma$-rays. Its wide-range spectral energy distribution (SED) shows the typical double-peak structure of AGN. Mkn 421 is a so-called blazar. These constitute a rare subclass of AGNs with beamed emission closely aligned to our line of sight. In blazars, the low-energy peak at keV energies is thought to arise dominantly from synchrotron emission of electrons, while the origin of the high-energy (GeV-TeV) bump is still debated. The SED is commonly interpreted as being due to the beamed, non-thermal emission of synchrotron and inverse-Compton radiation from ultrarelativistic electrons. These are assumed to be accelerated by shocks moving along the jets at relativistic bulk speed. For most of the observations, the SED can be reasonably well described by homogeneous one-zone synchrotron-self-Compton (SSC) models (e.g., Marscher & Gear, 1985; Maraschi et al., 1992; Costamante & Ghisellini, 2002). Hadronic models (Mannheim et al., 1996; Mücke et al., 2003), however, can also explain the observed features. A way to distinguish between the different emission models is to determine the positions, evolution and possible correlations (see, e.g., Wagner, 2008a, for a review) of both peaks in the SED, using simultaneous, time-resolved observations covering a broad energy range, e.g., as obtained in multichannel (MWL) observational campaigns.

In this paper we present results from Major Atmospheric Gamma-ray Imaging Cerenkov (MAGIC) telescope VHE $\gamma$-ray observations of Mkn 421 during eight nights from 2006 April 22 to 30, and on 2006 June 14. For most of the days, optical $R$-band observations were conducted with the KVA telescope. Simultaneous observations were carried out by Suzaku (Mitsuda et al., 2007) and H.E.S.S., as well as by XMM-Newton (Jansen et al., 2001) on 2006 April 28 and 29, respectively. During both nights, we carried out particularly long, uninterrupted observations in the VHE energy band of $\approx 3$ h duration each. An onset of activity in the X-ray band triggered an INTEGRAL-led target-of-opportunity (ToO) campaign, which took place from 2006 June 14 -- 25 for a total of 829 ks (Lichti et al., 2008). Within this campaign, MAGIC observed Mkn 421 at rather high zenith angles from 43 to 52 degrees in parallel with INTEGRAL on 2006 June 14.

In the following sections, we describe the data sets and the analysis applied to the VHE $\gamma$-ray data, the determination of spectra for all observation nights, and put the results into perspective with other VHE $\gamma$-ray observations of Mkn 421. The interpretation of these data in a MWL context is carried out in Acciari et al. (2009) and subsequent papers.

VHE $\gamma$-ray observations in 2006 April and June have also been carried out by the Whipple telescope (Horan et al., 2009), by the VERITAS (Fegan, 2008), and TACTIC (Yadav et al., 2007) collaborations, although not simultaneously with our observations.

### 2. The MAGIC telescope

The VHE $\gamma$-ray observations were conducted with the MAGIC telescope located on the Canary island La Palma (2200 m above sea level, 28°45′N, 17°54′W). At the time of our observations in 2006, MAGIC was a single-dish 17-m $\varnothing$ instrument for the detection of atmospheric air showers induced by $\gamma$-rays. Its hexagonally-shaped camera with a field of view (FOV) of $\approx 3.5\,\text{mrad}$ diameter comprises 576 high-sensitivity photomultiplier tubes (PMTs): 180 pixels of 0.2° $\varnothing$ surround the inner section of the camera of 394 pixels of 0.1° $\varnothing$ ($\approx 2.2\,\text{mrad}$ FOV). The trigger is formed by a coincidence of $\geq 4$ neighboring pixels. Presently the accessible trigger energy range (using the MAGIC standard trigger; Meucci et al., 2007) spans from 50 -- 60 GeV (at small zenith angles) up to tens of TeV. Further details, telescope parameters, and performance information can be found in Baixeras et al. (2004; Cortina et al., 2005; Albert et al., 2008a).

### 3. Observations and data analysis

The observations were carried out during dark nights, employing the so-called wobble mode (Daum et al., 1997), in which two $\gamma$-ray telescopes, one on and the other off, are tracked alternatively for 20 minutes each. The on-source data are defined by calculating image parameters with respect to the source position, whereas background control (“off”) data are obtained from the same data set, but with image parameters calculated with respect to the position on the opposite side of the camera, the antisource position. The simultaneous measurement of signal and background makes additional background control data unnecessary. In order to avoid an unwanted contribution from $\gamma$-events in the off sample, and to guarantee the statistical independence between the on and the off samples in the signal region, events included in the signal region of the on sample were excluded from the off sample and vice versa.

The data were analyzed following the standard MAGIC analysis procedure (Bretz & Wagner, 2003; Bretz & Dornet, 2008). After calibration (Albert et al., 2008c) and extracting the signal at the pulse maximum using a spline method, the air-shower images were cleaned of noise from night-sky background light by applying a three-stage image cleaning. The first stage requires a minimum number of 6 photoelectrons in the core pixels and 3 photoelectrons in the boundary pixels of the images (see, e.g., Fegan, 1997). These tail cuts are scaled according to the larger size of the outer pixels of the MAGIC camera. Only pixels with at least two adjacent pixels with a signal arrival time difference lower than 1.75 ns survive the second cleaning stage. The third stage repeats the cleaning of the second stage, but requires only one adjacent pixel within the 1.75 ns time window.

### Table 1. Some characteristic parameters of the different data sets of the campaign.

| Night | Observation Window [MJD] | $t_{\text{eff}}$ [h] | ZA [$^\circ$] |
|-------|--------------------------|---------------------|--------------|
| 2006/04/22 | 53847.97649 -- 53848.01460 | 0.76 | 18 -- 28 |
| 2006/04/24 | 53849.96428 -- 53850.00669 | 0.99 | 16 -- 28 |
| 2006/04/25 | 53850.92813 -- 53850.99607 | 1.53 | 10 -- 26 |
| 2006/04/26 | 53851.92862 -- 53852.00383 | 1.64 | 10 -- 29 |
| 2006/04/27 | 53852.93474 -- 53853.00047 | 1.42 | 12 -- 28 |
| 2006/04/28 | 53853.88173 -- 53854.01394 | 2.23 | 10 -- 32 |
| 2006/04/29 | 53854.89514 -- 53854.04119 | 2.78 | 9 -- 41 |
| 2006/04/30 | 53855.97283 -- 53855.97906 | 0.16 | 23 -- 24 |
| 2006/06/14 | 53900.91979 -- 53900.95532 | 0.83 | 40 -- 52 |

$t_{\text{eff}}$ denotes the effective observation time. ZA gives the zenith angle range of the observations.
The data were filtered by rejecting trivial background events, such as accidental noise triggers, triggers from nearby muons, or data taken during adverse atmospheric conditions (e.g., low atmospheric transmission). 12.7 hours out of the total 15.0 hours' worth of data survived the latter quality selection and were used for further analysis.

We calculated image parameters \cite{Hillas1985} such as WIDTH, LENGTH, SIZE, CONC, M3LONG (the third moment of the light distribution along the major image axis), and LEAKAGE (the fraction of light contained in the outermost ring of camera pixels) for the surviving events. For the $\gamma$/hadron separation, a SIZE-dependent parabolic cut in AREA $\equiv$ WIDTH $\times$ LENGTH $\times$ $\pi$ was used \cite{Riegel2005}. The cut parameters for the assessment of the detection significance were optimized on Mkn 421 data from close-by days. For the data of the 2006 June 14 at rather large zenith angles, data of Mkn 501 from 2006 October were used to determine the optimal cuts. Any significance in this work was calculated using Eq. 17 of \cite{Li1985}.

The primary $\gamma$-ray energies were reconstructed from the image parameters using a Random Forest regression method \cite{Albert2008} (and references therein) trained with Monte-Carlo simulated events (MCs; \cite{Knapp2004,Majumdar2005}). The MC sample is characterized by a power-law spectrum between 10 GeV and 30 TeV with a differential spectral photon index of $\alpha = -2.6$, and a point-spread function resembling the experimental one. The events were selected to cover the same zenith distance range as the data. For the spectrum calculation, the area cut parameters were optimized to yield a constant MC cut efficiency of 99% over the whole energy range, increasing the $\gamma$-ray event statistics at the threshold.

The Mkn 421 observations presented here are among the first data taken by MAGIC after major hardware updates in April 2006 \cite{Goebel2008}, which required us to thoroughly examine the data. Despite the hardware changes, the MAGIC subsystems performed as expected with the exception of an unstable trigger behavior for some PMTs, leading to a significant decrease of the di $\gamma$-ray event rate through the six sectors of the camera. To mitigate the effect of the inhomogeneity, instead of an (already increased) energy threshold of 250 GeV, higher thresholds of 350 or 450 GeV were applied for some observation nights. In this way we made sure that the estimated systematic error remains within reasonable limits.

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For the calculation of the individual light curves as well as for the overall 2006 April lightcurve, the flux between 250 GeV and 350 GeV was extrapolated for the nights with higher threshold. We assumed a power-law behavior in this energy range, with the spectral index determined for the first three energy bins of the whole April dataset (i.e., $\alpha = -2.08$). The flux normalization for each night has been determined at 500 GeV by a fit to the first three differential spectral points, an energy range which is reliable for all affected nights.

Table I summarizes the analyzed data sets. The statistical significance of any detection is assessed by applying a cut in $\theta^2$, where $\theta$ is the angular distance between the expected source position and the reconstructed $\gamma$-ray arrival direction. The arrival directions of the showers in equatorial coordinates were calculated using the DISP method \cite{Fomin1994,Lessard2001}. We replaced the constant coefficient $\xi$ in the parameterization of DISP in the original approach by a term which is dependent on LEAKAGE, SIZE, and SLOPE.

\[ \xi = \xi_0 + \xi_1 \text{SLOPE} + \xi_2 \text{LEAKAGE} + k \xi_3 (\log_{10} \text{SIZE} - \xi_4)^2, \]

where $k = 0$ for $\log_{10} \text{SIZE} < \xi_4$ and $k = 1$ for $\log_{10} \text{SIZE} \geq \xi_4$. The coefficients were determined using simulated data. The parameter SLOPE is a measure for the longitudinal arrival time evolution of the shower in the camera plane similar to the time parameter GRADIENT in \cite{Aliu2009}. Instead of defining the parameter from a fit to the arrival time distribution, however, SLOPE is determined as an analytical solution of the fit. Note that this new parameterization makes DISP and therefore $\theta^2$ source dependent.

All stated errors are statistical errors only; we estimate our systematic errors to be 16% for the energy scale, 11% for absolute fluxes and flux normalizations, and 0.2 for the spectral slopes \cite{Albert2008}, not including the additional systematic flux errors mentioned above.

A second, independent analysis of the data yielded compatible results to those presented here.

4. Results

4.1. Results for 2006 April 22 – 30

MAGIC observed Mkn 421 from MJD 53847 to MJD 53855. During the observations, two MWL campaigns were carried out.
Table 2. Analysis results.

| Observation Night | $N_{\text{excess}}$ | $N_{\text{back}}$ | $S$ | $F_{\text{cut}}$ [GeV] | $F(E > E_{\text{min}})$ | $\alpha$ | $\chi^2_{\text{red}}$ |
|-------------------|---------------------|------------------|----|---------------------|---------------------|------|------------------|
| 2006/04/22        | 100                 | 29               | 10.9r | 350              | 0.92 ± 0.11       | 1.3/2 | 0.98 ± 0.15       | 2.05 ± 0.21 | 2.1/2      |
| 2006/04/24        | 419                 | 69               | 25.0r | 250              | 2.32 ± 0.13       | 2.7/2 | 2.45 ± 0.14       | 2.25 ± 0.09 | 2.0/3      |
| 2006/04/25        | 342                 | 83               | 20.8r | 250              | 1.34 ± 0.09       | 1.7/2 | 1.43 ± 0.09       | 2.26 ± 0.12 | 0.24/3    |
| 2006/04/26        | 225                 | 62               | 16.4r | 350              | 1.08 ± 0.09       | 1.3/4 | 1.21 ± 0.11       | 2.35 ± 0.17 | 0.41/2    |
| 2006/04/27        | 615                 | 56               | 33.5r | 350              | 3.21 ± 0.15       | 1.9/4 | 3.37 ± 0.18       | 2.07 ± 0.07 | 4.8/4      |
| 2006/04/28        | 311                 | 75               | 19.9r | 350              | 1.14 ± 0.08       | 4.3/8 | 1.32 ± 0.10       | 2.47 ± 0.14 | 0.65/2    |
| 2006/04/29        | 514                 | 169              | 23.7r | 350              | 1.04 ± 0.06       | 41/7  | 1.14 ± 0.06       | 2.28 ± 0.09 | 2.0/4      |
| 2006/04/30        | 69                  | 11               | 10.3r | 250              | 2.39 ± 0.33       | —    | 2.16 ± 0.34       | 1.66 ± 0.20 | 1.4/1      |
| 2006/06/14        | 95                  | 87               | 7.5r  | 450              | 0.34 ± 0.06       | 2.4/1 | 0.168 ± 0.032     | 2.38 ± 0.44 | 1.5/2      |

Number of excess ($N_{\text{excess}}$) and background ($N_{\text{back}}$) events, resulting significances $S$, lower cuts in event energy, integral fluxes $F$ above $E_{\text{min}} = 250$ GeV for the 2006 April data and $E_{\text{min}} = 450$ GeV for the 2006 June 14 data (in units of $10^{-10}$ cm$^{-2}$ s$^{-1}$), fit quality of a constant-flux fit to the individual observation nights (see Fig. 2), and power-law fit results for the differential energy spectra of $dF/dE = f_0 \cdot (E/E_0)^\alpha$ with $E_0 = 0.5$ TeV for the 2006 April data and $E_0 = 1.0$ TeV for the 2006 June 14 data, respectively; $f_0$ in units of $10^{-16}$ TeV$^{-1}$ cm$^{-2}$ s$^{-1}$.

Fig. 2, VHE ($E > 250$ GeV) light curve for Mkn 421 observations in April 2006. The dotted line represents the Crab nebula flux (Albert et al. 2008), whereas the individual dashed lines show the result of a fit to the time bins (average nightly flux) of the corresponding nights.

simultaneously with Suzaku and with XMM-Newton on MJD 53854 and MJD 53855, respectively. Mkn 421 was also observed as part of the monitoring program of the Whipple 10-m telescope (see Horan et al. 2009), albeit about 3.5 hours after the MAGIC observations stopped, due to the different longitudes of the two instruments.

A strong $\gamma$-ray signal from the source was detected in all eight observation nights. In total, 3165 excess events were recorded over a background of 693 events, yielding an overall significance of 64.8$\sigma$. Mkn 421 exhibited an average flux of $F_{250\text{GeV}} = (1.48 \pm 0.03) \cdot 10^{-10}$ cm$^{-2}$ s$^{-1}$. When compared to earlier observations (see e.g. Albert et al. 2007, Tluczykont et al. 2007, Goebel et al. 2008a, Steele et al. 2008), our observations indicate an elevated flux state of Mkn 421. We found high flux states in the nights of MJD 53580, $F_{250\text{GeV}} = (2.32 \pm 0.13) \cdot 10^{-10}$ cm$^{-2}$ s$^{-1}$; MJD 53583, $F_{250\text{GeV}} = (3.21 \pm 0.15) \cdot 10^{-10}$ cm$^{-2}$ s$^{-1}$; and MJD 53856, $F_{250\text{GeV}} = (2.39 \pm 0.33) \cdot 10^{-10}$ cm$^{-2}$ s$^{-1}$ (Fig. 1). In the remaining nights (we assumed nights with fluxes below $1.6 \cdot 10^{-10}$ cm$^{-2}$ s$^{-1}$ as non-flare nights), Mkn 421 exhibited a low-flux average of $F_{250\text{GeV}} = (1.09 \pm 0.03) \cdot 10^{-10}$ cm$^{-2}$ s$^{-1}$. The analysis results on a night-by-night basis are summarized in Tab. 2, and include the nightly numbers for excess and background events, significances, and average integral fluxes above 250 GeV (where the nights with an energy cut of 350 GeV where extrapolated down to 250 GeV, see Sect. 3 for details). The results of a spectral fit based on a simple power law (PL) of the form

$$\frac{dF}{dE} = f_0 \cdot 10^{-10} \text{TeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \left(\frac{E}{E_0}\right)^\alpha$$

are also shown.

The energy thresholds of the individual observations are also given in Tab. 2. As the analysis threshold is always lower than the applied energy cut, the latter one defines the energy threshold value.

The strong $\gamma$-ray signal allowed to infer light curves with a resolution below one hour for all of the observation nights, which are shown in Fig. 3 (see Tab. 4 for the light curve data). Most light curves are compatible with a constant flux during the nightly observation time (see Tab. 2 for all constant-fit $\chi^2_{\text{red}}$ values), while on MJD 53855 a clear intra-night variability is apparent. A fit with a constant function yields an unacceptable $\chi^2_{\text{red}} = 41/7$ ($P = 8 \cdot 10^{-5}$) for this night, and the data suggest a flux halving time of 36 $\pm 10_{\text{stat}}$ minutes. Note that this interesting observation window has also been covered by XMM-Newton observations in the X-ray band (Acciari et al. 2009).

3 Table 4 is available only in the electronic edition of the journal, www.aanda.org
Fig. 3. Differential photon spectrum for Mkn 421 for the observation night of 2006 June 14 (black data points). A power-law fit to the spectrum results in a spectral slope of $\alpha = -2.38 \pm 0.44$ (see Tab. 2 for the fit results). Also shown are spectral points measured with the Whipple 10-m telescope during 2006 June 18–21.

4.2. Results for 2006 June 14

An onset of activity to $\approx 2$ times the average quiescent-flux level of Mkn 421 was measured in April 2006 by the RXTE all-sky monitor (ASM) instrument. It triggered an INTEGRAL ToO campaign from 2006 June 14 to 25 for a total of 829 ks (Lichti et al., 2008). This > 30 mCrab flux remained until September 2006. During the 9-day campaign, Mkn 421 was targeted by various instruments in the radio, optical, X-ray and VHE wavebands. Results are reported in Lichti et al. (2008). On 2006 June 14, MAGIC observed Mkn 421 at rather high zenith angles in parallel with the OMC, JEM-X, and IBIS measurements aboard INTEGRAL. Further VHE coverage was provided by the Whipple 10-m telescope on 2006 June 18, 19, and 21 (Lichti et al., 2008).

The MAGIC observations on 2006 June 14 lasted for $\approx 50$ minutes. The high zenith angles of 43 to 52 degrees of this observations and the previously mentioned inhomogeneities result in an energy threshold of $E_{\text{thresh.}} = 450$ GeV. In spite of the overall rather difficult observational circumstances caused by the high zenith angle observations (Tonello, 2006; Albert et al., 2006), a firm detection on the 7.5-$\sigma$ significance level was achieved.

The corresponding differential energy spectrum is shown in Fig. 3. Between 450 GeV and 2.2 TeV, it can be described by a simple power-law of the form

$$\frac{dF}{dE} = (1.68 \pm 0.32) \cdot 10^{-11} \text{TeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \left( \frac{E}{1.0 \text{ TeV}} \right)^{-2.38\pm0.44}. \quad (3)$$

For comparison we also show the spectral points reported by the Whipple 10-m telescope averaged over the nights of 2006 June 18, 19, and 21. Generally, there might be systematic differences between the Whipple and MAGIC measurements. It could, however, be shown that such inter-instrument systematic effects are rather small and under control, e.g. those between MAGIC and H.E.S.S. (Mazin et al., 2005). Particularly the Crab nebula spectra measured by Whipple and MAGIC agree quite well (Albert et al., 2008). The Mkn 421 flux measured by the Whipple 10-m telescope four days after the MAGIC observation is substantially higher than our measurements (Fig. 3), pointing to a clear evolution of the source emission level within the INTEGRAL campaign.

5. Discussion

In leptonic acceleration models, e.g., SSC models, a shift of the high-energy peak (attributed to Inverse Compton radiation) in the spectral energy distribution towards higher energies with an increasing flux level is expected. In the VHE domain, such a shift can be traced by spectral hardening. Variations in the hardness of the TeV $\gamma$-ray spectrum during flares were reported by several groups (e.g., Krennrich et al., 2002; Aharonian et al., 2005; Fossati et al., 2008). We tested for a correlation of the spectral hardness with the flux level of the de-absorbed spectrum (i.e., after removing any attenuation effects caused by the Extragalactic Background Light [EBL], cf. Nikishov 1962; Gould & Schrédér 1966; Hauser & Dwek 2001) in our data (Fig. 4), but found that the correlation neither can be described by a constant fit ($\chi_{\text{red}}^2 = 17/8$, $P \approx 3\%$) nor by a linear dependence of spectral hardness and flux level ($\chi_{\text{red}}^2 = 11/7$, $P \approx 12\%$), giving no clear preference for either. Although clear flux variations are present in the data set, the overall dynamical range of 3.9 in flux might be too small to see a significant spectral hardening with increasing flux.

The individual night-by-night spectra during the campaign in April 2006 are shown in Fig. 4. All spectral data points are summarized in Tab. 5. For the nights of 2006 April 22, 26, and 29, there seems to be evidence for a resolved peak, but a likelihood ratio test (e.g., Mazin & Goebel, 2007) yields significant curvature only for 2006 April 27.

$$\frac{dF}{dE} = \left( f_0 \cdot 10^{-11} \text{TeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \left( \frac{E}{E_0} \right)^{(-\alpha) \log_{10}(E/E_0)} \right). \quad (4)$$

and

$$\frac{dF}{dE} = \left( f_0 \cdot 10^{-11} \text{TeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \left( \frac{E}{E_0} \right)^{-\alpha} \exp \left( -\frac{E}{\beta} \right) \right). \quad (5)$$

4. Table 6 is available only in the electronic edition of the journal, www.aanda.org
5. the respective log-P values are 83%, 48%, 73%, and 96%.
respectively. The likelihood ratio test results in a clear preference towards a log-P or a PL+P compared to a simple power-law with a probability of ≈ 96% for both of them. The $\chi^2_{\text{red}}$ values for PL, log-P, and PL+C fits on the individual night-by-night spectra in Fig. 7 are given in Tab. 5. The high statistics data sets defined by combining all data from April, all data from the low-state nights, and all data from the three high-state nights, clearly showed evidence for a parabolic or cutoff shape of the spectra. The results of the fits and the probability of a likelihood ratio test are given in Tab. 3. For all these nights our data did not allow to prefer one model over the other. The fact that all of the high statistics data sets show a curved spectral shape is an indication of this feature being always visible for Mkn 421 and hence source intrinsic.

The curved power laws enable to locate a peak in the de-absorbed spectrum at $E_{\text{peak}} = E_0 10^{-2-\alpha(\log f_0)}$ for the log-P and at $E_{\text{peak}} = (2-\alpha)\beta$ if $\alpha < 2$ for the PL+C fit. For simplicity we determined $E_{\text{peak}}$ of the log-P by using the apex form of the parabola in a logarithmic representation:

$$\log_{10} \frac{dF}{dE} = \log_{10} (f_0) + \log_{10} (\alpha) \left( \log_{10} \left( \frac{E}{0.5 \text{TeV}} \right)^{\beta} \right)^2$$

which naturally yields both $E_{\text{peak}}$ and the flux at the peak as $\beta$ and $f_0$, respectively. Additionally, the spectral cutoff is naturally obtained from the PL+C fit as the fit parameter $\beta$. The results are shown in Tab. 3. The values of $E_{\text{peak}}$ as determined using the log-P and the PL+C were compatible with each other for the data sets averaging several nights and showed indications for an increase of the peak energy with rising flux level, as predicted if the VHE radiation were due to SSC mechanisms. We compare our results with historical values taken from Albert et al. (2007a) in Fig. 5. Our data confirm the previously suggested correlation.

The observation of a relation between flux (and thus, fluence) and the position of the VHE peak in the SED could be signalling a relation similar to the one suggested by Amati et al. (2002) and the position of the VHE peak in the SED could be signalling a relation similar to the one suggested by Amati et al. (2002) and the fading of this behavior, showing, with the exception of 2006 April 27, an increase with rising flux and indicating a source-intrinsic rather than a cosmological reason for the cutoff feature. This is in

Table 3. Special fit results.

| Data Set          | Used Fit | $E_0$ [TeV] | $f_0$ | $\alpha$ | $\beta$ [TeV] | $\chi^2_{\text{red}}$ | Likelihood | $E_{\text{peak}}$ [TeV] |
|-------------------|----------|-------------|-------|----------|---------------|------------------------|------------|--------------------------|
| 2006/04/27        | PL       | 0.5         | 9.54 ± 0.52 | 1.92 ± 0.07 | 5.34         | 94%                    | 1.4 ± 0    |
|                   | log-P    | 0.5         | 11.5 ± 0.9 | 0.26 ± 0.17 | 1.2 ± 0.2    | 0.48/3                 | 96%        |
|                   | PL+C     | 0.5         | 11.3 ± 1.2 | 1.44 ± 0.24 | 2.6 ± 1.3    | 0.34/3                 | 96%        |
| All April Data    | PL       | 0.5         | 4.35 ± 0.07 | 2.07 ± 0.04 | 10.15       | 94%                    | 0.80 ± 0.42|
|                   | log-P    | 0.5         | 8.48 ± 0.16 | 0.41 ± 0.11 | 0.69 ± 0.06 | 7.2/4                  | 99%        |
|                   | PL+C     | 0.5         | 5.36 ± 0.31 | 1.77 ± 0.09 | 3.6 ± 1.1    | 1.8/4                  | 99%        |
| High-State Nights | PL       | 0.5         | 8.19 ± 0.28 | 1.93 ± 0.05 | 6.0/4       | 94%                    | 1.5 ± 1    |
|                   | log-P    | 0.5         | 9.21 ± 0.47 | 0.52 ± 0.17 | 1.1 ± 0.3    | 2.0/3                  | 97%        |
|                   | PL+C     | 0.5         | 9.02 ± 0.64 | 1.75 ± 0.12 | 6.1 ± 4.0    | 3.1/3                  | 91%        |
| Low-State Nights  | PL       | 0.5         | 3.39 ± 0.10 | 2.17 ± 0.05 | 6.6/4       | 97%                    | 0.45 ± 0.47|
|                   | log-P    | 0.5         | 3.55 ± 0.13 | 0.41 ± 0.16 | 0.48 ± 0.12 | 1.1/3                  | 97%        |
|                   | PL+C     | 0.5         | 4.15 ± 0.40 | 1.85 ± 0.15 | 2.9 ± 1.3    | 0.75/3                 | 97%        |

Results of a log-parabolic power-law fit in apex form (Eq. 6) and a power-law fit with an exponential cutoff (Eq. 5) in $E^2 dF/dE$ after EBL de-absorption for special data sets. $f_0$ is given in units of $10^{-11} \text{TeV}^{-1} \text{cm}^{-2} \text{s}^{-1}$. $\alpha$ and $\beta$ are the fit parameters as stated in the text, and Likelihood denotes the probability of a likelihood ratio test.
In summary, we followed the evolution of a sequence of mild flares of the blazar Mkn 421 during one week from 2006 April 22 to 30, peaking at $F(E > 250 \text{ GeV}) = (3.21 \pm 0.15) \times 10^{-10} \text{ cm}^{-2} \text{s}^{-1}$ ($\approx 2.0$ Crab units). The nocturnal observations lasted at least for about one hour and allowed for the reconstruction of night-by-night spectra. During three observation nights high fluxes were recorded, in which, however, no variability could be measured. In two of these nights, rather hard spectral indices were found, but this was also the case for the night with the lowest flux. During the night of 2006 April 29 with a not particularly high flux of $F(E > 250 \text{ GeV}) = (1.04 \pm 0.06) \times 10^{-10} \text{ cm}^{-2} \text{s}^{-1}$ ($\approx 0.65$ Crab units), clear intra-night variability with a flux-doubling time of $36 \pm 10_{\text{stat}}$ minutes was observed.

According to a likelihood ratio test, the spectra of some data sets were better described by curved power laws than simple power laws, enabling us to calculate peak and cutoff energies in the VHE regime. The derived peak values are consistent with an evolution of the peak energy with the flux, as suggested by historical data. Indications of an intrinsic cutoff in the spectra of Mkn 421, as found in former observations, are confirmed by our results.

During the INTEGRAL-triggered MWL campaign in 2006 June we observed Mkn 421 in one night at high zenith angles. Our measurements complement the three-night observations conducted by the Whipple 10-m telescope four days later. Taking the MAGIC and Whipple results together, a variability of Mkn 421 also during the INTEGRAL observations is evident. The energy coverage of the Whipple telescope spectrum ($\Delta E \approx 600 \text{ GeV}$) was not sufficient to assess any spectral evolution by comparing it to the MAGIC spectrum ($\Delta E \approx 2 \text{ TeV}$).

The determined fluxes and spectra will be further used for studies of the SED taking into account data taken at other photon energies in detailed MWL analyses (publications in preparation).

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Fig. 6. EBL de-absorbed historical spectra of Mkn 421 (see Albert et al., 2007a, for references) along with selected spectra from the 2006 April campaign and the flare spectrum of Donnarumma et al. (2009). The solid line is the result of a fit using Eq. 4. Note that the historical data were deabsorbed using the model of Primack et al. (2005), our data and those from Donnarumma et al. (2009) with the model of Kneiske & Dole (2008).
Fig. 7. Differential energy spectra for Mkn 421 for April 2006 before (gray points) and after (black points) correcting for EBL absorption. For the apparently hard spectra on 2006 April 22, 26, 27, and 29, log-P (Eq. 4) and PL+C (Eq. 5) fits were performed (red solid and blue dashed curves, respectively).
Table 4. Light curve data.

| Observation [MJD] | $F_{\gamma,250\text{GeV}}$ [$10^{-15}\text{cm}^{-2}\text{s}^{-1}$] |
|-------------------|--------------------------|
| 53847.983407      | 1.00 ± 0.21              |
| 53847.99775       | 0.70 ± 0.23              |
| 53848.00867       | 0.99 ± 0.17              |
| 53849.971155      | 2.56 ± 0.23              |
| 53849.98618       | 2.04 ± 0.21              |
| 53850.00033       | 2.37 ± 0.22              |
| 53850.93996       | 1.24 ± 0.13              |
| 53850.96431       | 1.49 ± 0.15              |
| 53850.98652       | 1.26 ± 0.15              |
| 53851.93677       | 0.97 ± 0.20              |
| 53851.95255       | 1.04 ± 0.21              |
| 53851.96726       | 1.23 ± 0.20              |
| 53851.98190       | 1.00 ± 0.18              |
| 53851.99680       | 1.13 ± 0.18              |
| 53852.94098       | 3.01 ± 0.33              |
| 53852.95502       | 3.19 ± 0.38              |
| 53852.96823       | 3.05 ± 0.31              |
| 53852.98159       | 3.57 ± 0.32              |
| 53852.99406       | 3.17 ± 0.28              |
| 53853.88734       | 1.38 ± 0.25              |
| 53853.89880       | 0.80 ± 0.27              |
| 53853.92893       | 1.22 ± 0.24              |
| 53853.93984       | 1.09 ± 0.25              |
| 53853.95457       | 1.18 ± 0.24              |
| 53853.96887       | 1.22 ± 0.27              |
| 53853.98040       | 0.95 ± 0.19              |
| 53853.99316       | 1.32 ± 0.21              |
| 53854.00687       | 1.12 ± 0.18              |
| 53854.99739       | 2.37 ± 0.42              |
| 53854.91620       | 1.42 ± 0.19              |
| 53854.95206       | 0.86 ± 0.16              |
| 53854.96625       | 1.11 ± 0.17              |
| 53854.97974       | 1.27 ± 0.18              |
| 53854.99354       | 0.83 ± 0.15              |
| 53855.00847       | 0.80 ± 0.14              |
| 53855.02879       | 0.69 ± 0.11              |
| 53855.97595       | 2.39 ± 0.33              |
| 53900.92327       | 0.45 ± 0.10              |
| 53900.94585       | 0.26 ± 0.08              |

Table 6. Energy spectra for all observation nights under study after EBL de-absorption.

| $E$ bounds [GeV] | Flux [TeV cm$^{-2}$ s$^{-1}$] |
|------------------|-------------------------------|
| 350              | 554 (2.39 ± 0.56) · 10$^{-7}$ |
| 554              | 877 (3.67 ± 0.75) · 10$^{-7}$ |
| 877              | 1389 (3.29 ± 0.79) · 10$^{-7}$ |
| 1389             | 2200 (2.51 ± 0.93) · 10$^{-7}$ |
| 250              | 435 (7.00 ± 0.64) · 10$^{-7}$ |
| 435              | 758 (7.69 ± 0.76) · 10$^{-7}$ |
| 758              | 1320 (6.12 ± 0.86) · 10$^{-7}$ |
| 1320             | 2297 (6.54 ± 1.33) · 10$^{-7}$ |
| 2297             | 4000 (4.80 ± 1.74) · 10$^{-7}$ |
| 250              | 416 (4.36 ± 0.43) · 10$^{-7}$ |
| 416              | 693 (3.95 ± 0.48) · 10$^{-7}$ |
| 693              | 1154 (3.86 ± 0.62) · 10$^{-7}$ |
| 1154             | 1922 (3.47 ± 0.87) · 10$^{-7}$ |
| 1922             | 3200 (3.85 ± 1.31) · 10$^{-7}$ |
| 350              | 572 (3.41 ± 0.41) · 10$^{-7}$ |
| 572              | 935 (3.46 ± 0.49) · 10$^{-7}$ |
| 935              | 1529 (2.90 ± 0.65) · 10$^{-7}$ |
| 1529             | 2500 (2.38 ± 0.75) · 10$^{-7}$ |
| 350              | 635 (3.92 ± 0.34) · 10$^{-7}$ |
| 635              | 1153 (3.01 ± 0.39) · 10$^{-7}$ |
| 1153             | 2093 (2.96 ± 0.57) · 10$^{-7}$ |
| 2093             | 3800 (2.06 ± 0.79) · 10$^{-7}$ |
| 250              | 387 (3.37 ± 0.32) · 10$^{-7}$ |
| 387              | 600 (3.24 ± 0.32) · 10$^{-7}$ |
| 600              | 929 (3.29 ± 0.39) · 10$^{-7}$ |
| 929              | 1438 (3.33 ± 0.45) · 10$^{-7}$ |
| 1438             | 2228 (2.31 ± 0.53) · 10$^{-7}$ |
| 2228             | 3450 (2.08 ± 0.81) · 10$^{-7}$ |
| 250              | 572 (4.87 ± 1.09) · 10$^{-7}$ |
| 572              | 1310 (1.01 ± 0.21) · 10$^{-6}$ |
| 1310             | 3000 (1.01 ± 0.33) · 10$^{-6}$ |
| 450              | 609 (2.76 ± 0.74) · 10$^{-7}$ |
| 609              | 995 (1.61 ± 0.67) · 10$^{-7}$ |
| 995              | 1480 (2.54 ± 0.79) · 10$^{-7}$ |
| 1480             | 2200 (1.80 ± 0.85) · 10$^{-7}$ |

The two energy bounds specify the range in which the corresponding flux was measured.
Table 5. $\chi^2_{\text{red}}$ values for the PL, log-P, and PL+C fits performed in Fig. 7

|       | 22   | 24   | 25   | 26   | 27   | 28   | 29   | 30   |
|-------|------|------|------|------|------|------|------|------|
| PL    | 2.2/2| 1.9/3| 0.21/3| 0.47/2| 5.3/4| 0.59/2| 2.3/4| 1.5/1|
| log-P | 0.14/1| 0.041/1| 0.48/3| 1.1/3 |
| PL+C  | 0.27/1| 0.076/1| 0.34/3| 0.87/3 |

The columns represent days in 2006 April.