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Observations of Markarian 421 and Markarian 501 in 2000 and 2001 with the HEGRA Stereoscopic IACT System

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Abstract. The HEGRA system of five Imaging Atmospheric Cherenkov Telescopes (IACTs) has been used in 2000 and 2001 for a comprehensive study of the γ-ray emission from the BL Lac objects Mkn 421 and Mkn 501 in the energy range above 500 GeV. Here we summarize the TeV characteristics of Mkn 421 in 2000 and 2001 and of Mkn 501 in 2000. In particular, an unprecedented prolonged high-intensity state of Mkn 421 in Jan. /Feb. 2001 enabled detailed temporal and spectral studies.

1 Introduction

Blazars are a class of Active Galactic Nuclei (AGNs) whose emission is believed to arise predominantly from a relativistic jet with its axis closely aligned to the line-of-sight. More than 60 blazars have been discovered by the EGRET experiment on board the CGRO satellite (Hartman et al. 1999). A few BL Lac objects, a sub-class of blazars, have also been detected as TeV γ-ray emitters. The power emitted in γ-radiation frequently dominates the power radiated by the source (Fossati et al. 1998). Two classes of models explain the γ-ray emission from blazars either as Inverse Compton emission of relativistic electrons interacting with low energy photons or as resulting from protons interacting with magnetic and photon fields in the jet (Mücke and Protheroe 2001; Aharonian 2000).

The BL Lac Mkn 421 is the closest known BL Lac (z=0.031) and was the first extragalactic object to be discovered as a TeV emitter (Punch et al. 1992; Petry et al. 1996). The TeV emission from Mkn 421 was seen to be highly variable, showing flaring activity on time scales as short as 15 minutes (Gaidos et al. 1996) with low baseline emission. The spectrum of Mkn 421 was consistent with a power law and no evidence of spectral variability. Multiwavelength campaigns on Mkn 421 (Maraschi et al. 1999; Takahashi et al. 2000) have revealed correlated intensity fluctuations which can be well modelled with leptonic models, but the hadronic origin of the γ-ray emission cannot be ruled out.

The second established TeV blazar is Mkn 501 (z=0.034) (Quinn et al. 1996; Bradbury et al. 1997). After only moderate flux levels in the year following its discovery, Mkn 501 went into a state of surprisingly high activity and strong variability in 1997 with a 1 TeV integral flux up to 10 times that of the Crab Nebula (the strongest persistent TeV source) (Aharonian et al. 1999a; Aharonian et al. 1999b). During 1998-1999, the mean flux during HEGRA observations was an order of magnitude lower, substantially surpassing the Crab flux level only during two days (June 26/27 and June 27/28, 1998) (Aharonian et al. 2001). While the HEGRA data did not show a noticeable change in the spectral shape during the 1997 outburst, the low state spectrum of 1998-1999 was significantly softer:
$\frac{dN(1997)}{dE} / \frac{dN(1998-99)}{dE} \propto E^{\gamma}$ with $\gamma = 0.44 \pm 0.1$.

2 The HEGRA IACT System, Observational Data, Analysis Methods

The HEGRA system consists of five (until Fall 1998 four) IACTs on the Canary Island of La Palma, on the Roque de los Muchachos at 2200 m asl (Daum et al. 1997; Konopelko et al. 1999). The telescopes are arranged on a square with a side length of $\sim$100 m, with one telescope in the center of the square. Each telescope consists of a tesselated 8.5 m^2 mirror area and a high-resolution camera in the focal plane at 5 m distance. The camera contains 271 photomultiplier tubes, each viewing 0.25° of the sky, giving a total field-of-view of 4.3°. The PMT signals are digitized with 120 MHz FADCs. A telescope triggers if two neighboring signals are above an 8 mV threshold, and the system is read out if two telescopes trigger within a short coincidence window. Typical system trigger rates are $\sim$13 Hz.

Mkn 421 was extensively observed in 2000 and in 2001 with the HEGRA stereoscopic IACT system. The Mkn 421

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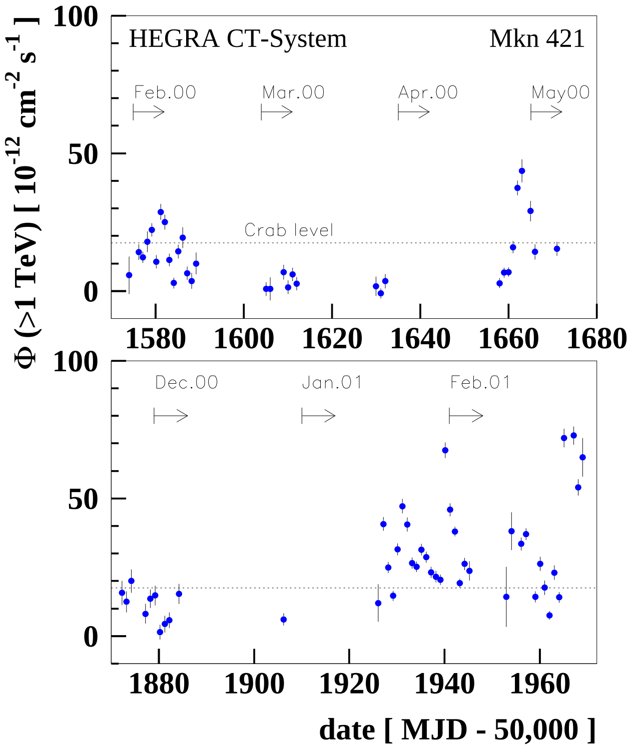

Fig. 1. The figure shows the average integral diurnal fluxes above 1 TeV for Mkn 421 from Feb. 2000 to Feb. 2001.

analysis is based on 100 h (76 h with zenith angles $< 30°$) taken from Jan. 31st 2000 to May 7th 2000, and 109 h (86 h with zenith angles $< 30°$) from Nov. 24th 2000 to Mar. 1st 2001. The Mkn 501 analysis is based on 54 h (46 h with zenith angles $< 30°$) taken from March 2nd 2000 to Sep. 25th 2000.

Only data taken during excellent weather conditions have been used for the analysis. Furthermore, data runs with a cosmic ray rate deviating more than 20% from the expected rate were rejected. All data were taken with a five-telescope configuration, excepting the days Feb.16-23 2000, where CT4 was excluded from the system due to a defective altitude motor. All observations were in the so-called standard wobble mode, with 20 minute run pairs taken with the source alternately displaced +0.5° and -0.5° in declination. This obviates the need for separate OFF-source runs.

Most of the analysis below uses only the data with zenith angles up to 30°. The analysis tools for the spectral and temporal analysis are described in detail in (Aharonian et al. 1999a; Aharonian et al. 1999b). The energy reconstruction requires two IACTs within 200 m of the shower impact point, each with at least 40 photoelectrons in the image, a "distance" cut of 1.7°, and a minimal stereo angle of 20°. Spectral studies are performed with "loose" selection cuts for γ-rays, with a cut on the angular distance θ of the reconstructed direction from the Mkn 421 direction $\theta^2 < (0.22°)^2$ and a cut on the parameter "mean scaled width" with a cut value of 1.2. The loose cuts minimize the effect of systematic errors due to energy-dependent cut efficiencies. The energy is reconstructed comparing the total amount of light in the camera to Monte Carlo expectations taking into account the zenith angle and shower core distance as parameters (Konopelko et al. 1999). The effective areas are determined from simulations separately for each data period to take into account the slowly changing mirror reflectivities and the loss in photomultiplier gain.

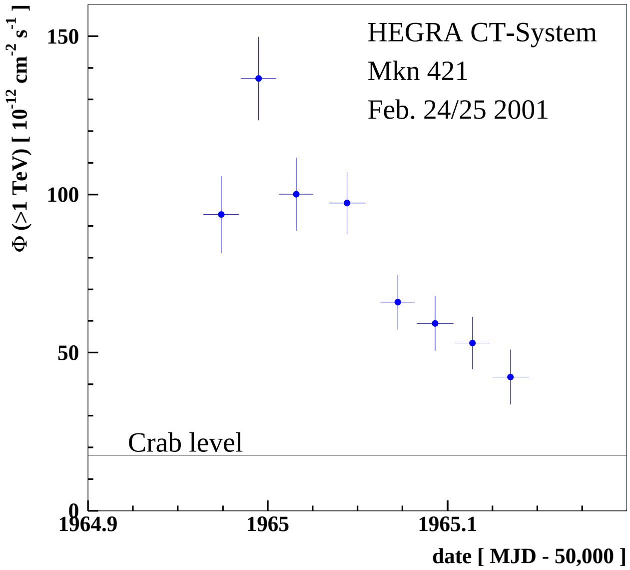

Fig. 2. The figure shows the integral flux above 1 TeV for Mkn 421 binned in 30-minute intervals for the night Feb. 24/25 2001.

3 Results for Mkn 421

The average integral diurnal fluxes above 1 TeV for Mkn 421 from February 2000 to February 2001 are shown in Fig. 1. Mkn 421 can only be observed under small zenith angles from La Palma in the winter months - hence the gap in the lightcurve from May to November 2000. One can discern three periods of high activity: February 2000, April/May 2000 and January/February 2001. The mean flux of these periods related to the Crab flux are 0.9 Crab (Feb. 2000), 1.0 Crab (Apr./May 2000) and 2.2 Crab (Jan. /Feb. 2001), with maximal diurnal fluxes of 1.6 Crab (Feb. 6/7 2000), 2.5 Crab (Apr. 28/29 2000) and 4.2 Crab (Feb. 26/27 2001).

The lightcurve in Fig. 1 for Mkn 421 for 2000 and 2001 shows a strong contrast to former years (Aharonian et al. 1999c). The HEGRA data for 1997 to 1999 show an average flux level of $\sim$1/3 Crab, with short, $\sim$1-day bursts with a flux increase to $\sim$1 Crab. In 2000 and 2001, the average level of the source rises to 2.2 Crab, with sub-hour flares up to 8 Crab, and variability is seen on timescales ranging from sub-hour to months.

As one example of such short, sub-hour timescale variability, Fig. 2 shows the integral flux above 1 TeV binned in 30-minute intervals for the night Feb. 24/25 2001. The chance

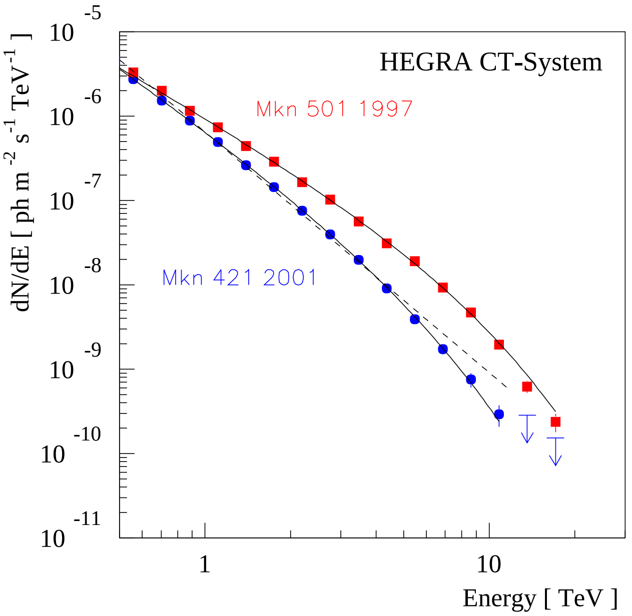

Fig. 3. The figure shows the Jan. /Feb. 2001 time-averaged Mkn 421 energy spectrum (lower curve) as well as the 1997 time-averaged Mkn 501 energy spectrum (upper curve). The solid lines show the fit of a power law with an exponential cutoff, the dashed line in the Mkn 421 spectrum shows a power law fit. Upper limits are 2σ confidence level.

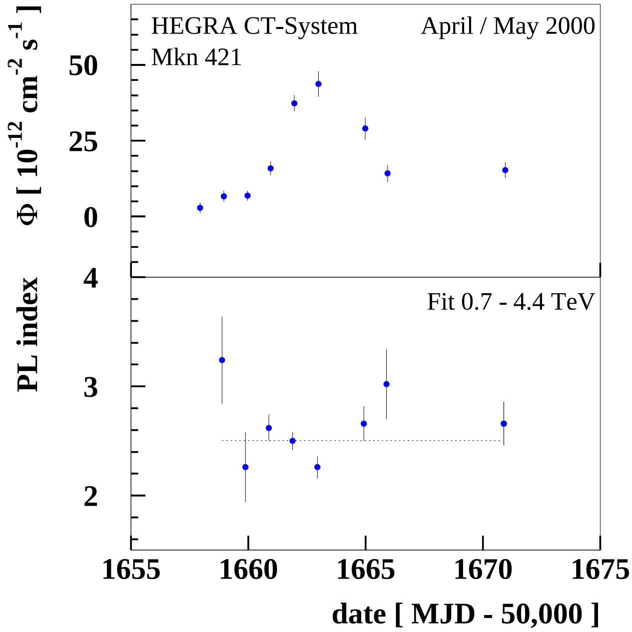

Fig. 4. The top figure shows the average diurnal flux above 1 TeV for Mkn 421 from April 24/25 to May 6/7 2000. The bottom figure shows the spectral index γ assuming a power law fit $dN/dE \propto E^{-\gamma}$ with the fit range 0.7 to 4.4 TeV for the same nights. The dashed line is the weighted mean of the spectral index.

probability for the assumption of constant flux is $1.7 \cdot 10^{-9}$. The highest flux point in Fig. 2 is 7.8±0.7 Crab! Other nights with significant diurnal variability (with the chance probability assuming constant flux in parentheses) are Feb. 7/8 2000 ($3.0 \cdot 10^{-5}$), Jan. 30/31 2001 ($1.2 \cdot 10^{-5}$), Feb. 1/2 2001 ($2.4 \cdot 10^{-7}$), and Feb. 23/24 2001 ($6.9 \cdot 10^{-5}$). In contrast, a flare with a smooth risetime and falltime of several days was observed from Apr. 24 to May 2 2000 (see Fig. 4). The fast variability observed in Mkn 421 places severe constraints on the size of the emission region. Due to causality and light travel time arguments, one finds $R < \Delta t_{obs} \cdot c \cdot \delta \sim (3 \cdot 10^{14} \cdot \Delta t_{obs}[h] \cdot \delta)[cm]$, with R as the size of the emission region, t_{obs} as the observed variability timescale and δ as the Doppler factor of the jet. The Doppler factor thus must be more than a few to avoid internal absorption.

The Jan. /Feb. 2001 data with their unprecedented photon statistics allow for the first time in HEGRA CT-system data a precise determination of the spectrum of Mkn 421 up to 10 TeV. This allows to look for an energy-dependent attenuation of the spectrum as seen in the Mkn 501 1997 spectrum. Due to poor statistics at high energies, the Mkn 421 data were up to now well fit by a simple power law. The total Jan. /Feb. 2001 spectrum is shown in Fig. 3. The spectrum contains ∼13400 gammas, with high significance up to ∼10 TeV (the 8.6 TeV point with 83 ON and 28 OFF events has a significance of 5.2σ, the 10.8 TeV point with 43 ON and 16 OFF events has a 3.5σ significance). The January and February diurnal spectra show no significant change in spectral index, and fitting the January and February data separately gives identical fit results within errors. This legitimizes the procedure of taking the time-averaged spectrum to increase statistics. The spectrum is clearly seen to be curved, and cannot be fit by a simple power law ($\chi^2/dof = 8.8$ for the fit range 0.7 to 8.6 TeV). A power law with an exponential cutoff satisfactorily fits the data ($\chi^2/dof = 0.5$) : $dN/dE\ [ph/(m^2\ s\ TeV)] = 8.1{\pm}0.3{\cdot}10^{-7}(E/TeV)^{-2.33\pm0.08}\exp(-E/E_o)$ with $E_o = 4.2(^{+0.6}_{-0.4})$ TeV. The 1997 time-averaged Mkn 501 spectrum of the HEGRA CT-system is also shown in Fig. 3. The spectrum has a lower limit on the maximum TeV energy of 16 TeV and is well fit by $dN/dE\ [ph/(m^2\ s\ TeV)] = 10.8 \pm 0.2 \cdot 10^{-7}(E/TeV)^{-1.92\pm0.03}\exp(-E/E_o)$ with $E_o = 6.2 \pm 0.4$ TeV. Thus, the Mkn 421 2001 spectrum is steeper than the Mkn 501 1997 spectrum, and the comparison of the two cutoff energies merits discussion (see section 5). There is evidence that the average Mkn 421 high-state 2001 spectrum of Fig. 3 is harder than the 1997-1998 low-state Mkn 421 spectrum. Dividing both spectra over the range 500 GeV to 7 TeV yields $\frac{dN(2001)}{dE} / \frac{dN(1997-98)}{dE} \propto E^{\gamma}$ with $\gamma = 0.20 \pm 0.08$.

The stability of the spectral reconstruction could be verified with contemporaneous Crab data taken in Jan. /Feb. 2001. The dataset consists of 23 h with zenith angles $< 30°$ for the spectral analysis. The spectrum from 0.7 to 8.6 TeV is well fit by a power law with normalization $2.96 \pm 0.13 \cdot 10^{-7}\ ph/(m^2\ s\ TeV)$ and spectral index 2.69 ± 0.06 ($\chi^2/dof = 1.1$). These values agree well with the previous values obtained with the HEGRA CT system

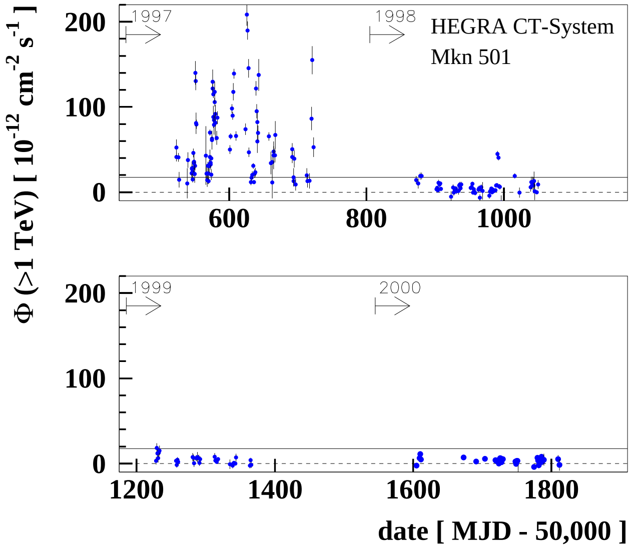

Fig. 5. The figure shows the average integral diurnal fluxes above 1 TeV for Mkn 501 from 1997 to 2000.

(Aharonian et al. 2000). Fitting a power law with an exponential cutoff leads to $E_o = 14 \pm 12.4$ TeV ($\chi^2/dof = 1.1$), i.e., outside of the fit range. Thus, there is no evidence for curvature in the Crab spectrum, confirming that the curvature in the Mkn 421 spectrum is real.

There are indications for a correlation of the spectral index and the integral flux in the April/May 2000 outburst of Mkn 421. Fig. 4 shows the average integral diurnal flux above 1 TeV and the spectral index for a power law fit with the fit region 0.7 to 4.4 TeV as a function of MJD. There is evidence that the spectrum hardens with the onset of the flare and softens afterwards. However, the chance probability for a constant spectral index is 3%, not making this result conclusive.

4 Results for Mkn 501

Fig. 5 shows the lightcurve for Mkn 501 from 1997 to 2000. There is no high activity in 2000, and the Crab flux level is not reached for any day of the dataset. The mean flux is 0.26 Crab, comparable to $\sim 1/3$ Crab in 1998 and 1999. The mean flux in 1997 was ~3 Crab.

The spectrum contains ~700 gammas with a total significance of 11.4σ. The spectrum is well fit by a power law with a spectral index of 2.90 ± 0.15, compatible with the low-state spectrum determined in 1998-1999 (spectral index 2.76 ± 0.08).

5 Conclusions and Discussion

The high intensity of Mkn 421 in the periods Feb. 2000, April/May 2000 and Jan. /Feb. 2001 have allowed both temporal and spectral measurements of unprecedented precision with the HEGRA CT-system.

For both the Feb. 2000 as well as the Jan/Feb 2001 measurements, variability on timescales of ~30 minutes could be determined. This confirms the fast variability of Mkn 421 seen previously (Gaidos et al. 1996).

There are indications for a correlation of the spectral index with TeV flux. This behaviour would be expected in numerous flare models. The data however do not allow definate conclusions.

For the first time, a cutoff in the Mkn 421 spectrum could be determined. The cutoff energy is particularly interesting in view of the diffuse extragalactic background radiation (DEBRA). Considering the very similar redshift of Mkn 421 and Mkn 501, one would expect the same attenuation of both spectra if the absorption is indeed wholely an effect of the DEBRA. Our results seem to suggest a difference in the cutoff energies of both sources. However, preliminary investigations have shown that cutoff energies resulting from a fit for different spectral indices are sensitive to the energy resolution and other parameters. Furthermore, the Mkn 421 2001 spectrum, when fit with the cutoff energy found for Mkn 501, still gives an acceptable fit ($\chi^2/dof = 1.3$). Thus, the cutoff energies of Mkn 421 and Mkn 501 seem to be compatible, but further investigation is clearly needed.

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