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LETTER

Letter to the Editor

Detection of γ-rays above 1.5 TeV from Mkn 501

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Abstract. A detection of TeV γ-rays from Mkn 501 is reported, based on observations made between March and August 1996 with the first HEGRA Cherenkov telescope (CT1). From the image analysis, 351 excess candidate γ-ray events are obtained from the 147 h dataset. The statistical significance of the excess is 5.2 σ. The average excess rate is 2.4 ± 0.5 h^{-1} above the $\approx$ 1.5 TeV threshold of CT1. Under the assumption that the spectrum of Mkn 501 follows a power law we find a differential spectral index of 2.6$\pm$0.5 and obtain a time-averaged integral flux above 1.5 TeV of $2.3(\pm0.4)_{\rm Stat}(+1.5-0.6)_{\rm Syst} \times 10^{-12}$ cm^{-2}s^{-1}. Comparison with our near contemporary observations of the Crab Nebula, used as a standard candle to test CT1 after upgrading to a 127 pixel camera, indicates that Mkn 501 has a spectrum similar to that of the Crab Nebula above 1.5 TeV. The integral flux above 1.5 TeV from Mkn 501 is found to have been between 2.2 and 3.6 times smaller than that from the Crab Nebula. HEGRA is the second experiment to have detected Mkn 501 in the TeV range.

Key words: gamma rays: observations – BL Lacertae objects: individual: Mkn 501

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1. Introduction

Mkn 501, a relatively close BL Lac object (redshift z = 0.034), became a target for observation in the VHE waveband as a result of the unexpected emergence of AGN as a significant sub-class of the high energy γ-ray sources identified by EGRET onboard the Compton Gamma Ray Observatory (von Montigny et al. 1995). Using the atmospheric Cherenkov technique, the Whipple group observed γ radiation of between 0.5 and 1.5 TeV from the BL Lac object Mkn 421 (Punch et al. 1992) and a confirmatory detection by two independent telescopes of the HEGRA Collaboration helped to establish its status as a VHE source (Petry et al. 1996 = *Paper I*). The Whipple group has since surveyed more than 30 AGN with similar characteristics (Kerrick et al. 1995). Of these, one, Mkn 501, has been reported to emit above 300 GeV, at an average flux level of 8×10^{-12} cm^{-2}s^{-1} measured between March and July 1995. This was approximately 20% of the average Mkn 421 flux (Quinn et al. 1996). Mkn 421 has been detected by EGRET whereas Mkn 501 has not.

The HEGRA Collaboration's imaging air Cherenkov telescopes are part of its cosmic ray detector complex (e.g. Rhode et al. 1996) at the Observatorio del Roque de los Muchachos on the Canary Island of La Palma (28.75° N, 17.89° W, 2200 m a.s.l.). The first telescope, CT1, is described in detail in Mirzoyan et al. (1994) and Rauterberg et al. (1995). Its energy threshold is approx. 1.5 TeV. It has a 5 m^2 reflector as opposed to the 8.5 m^2 dishes of the 5 telescope system (CT2-6) now nearing completion (Hermann 1995). CT2 and CT3 were targeting other objects whilst CT1 was chosen to monitor Mkn 501.

2. Observations and data analysis

Between March and August 1996 Mkn 501 was observed in tracking mode (rather than taking interleaved ON- and OFF-source runs) to obtain maximum exposure time. 147 hours of good quality data were obtained at zenith angles θ between 11° and 25°. Atmospheric extinction measurements from the Carlsberg Automatic Meridian Circle near the HEGRA site were used as a guide to data quality. Analysis proceeded in three steps: (1) flat-fielding and calibration, (2) filtering to obtain a dataset of showers with well determined image parameters (for a definition see e.g. Reynolds et al. 1993), (3) selection of γ candidates using cuts on the image parameters. For a more detailed description of our image analysis methods see Paper I and references therein.

1. Calibration and flat fielding are based on regular measurements of the pedestals and the relative photomultiplier gains.
2. CT1 carries a 127 photomultiplier camera faced with hollow hexagonal light guides of 0.25° diameter. In addition to a hardware trigger condition of any ≥ 2 out of 127 pixels fired, a software trigger condition of any ≥ 2 out of 91 pixels above 16 photoelectrons was applied to the calibrated signals to exclude camera-edge events with incomplete images. Events recorded under poor telescope positioning were rejected leaving a mean absolute pointing error of <0.1°.
3. A series of image parameter cuts was applied which reject events of probable hadronic origin leaving a sample of γ-shower candidates. For our detection of Mkn 421 (Paper I), neither observations of the Crab Nebula nor all parameters for the Monte Carlo optimization of the cuts were available for the new camera, therefore we used the set of cuts developed for a 91 pixel camera with similar resolution as described in Reynolds et al. (1993):

$$0.51^\circ < \mathrm{DIST} < 1.1^\circ$$
$$0.07^\circ < \mathrm{WIDTH} < 0.15^\circ$$
$$0.16^\circ < \mathrm{LENGTH} < 0.30^\circ$$
$$\mathrm{ALPHA} < 10^\circ$$

   In addition, a cut CONC > 0.4 was applied. We continued to use these previously successful cuts for our analysis of Mkn 501. Monte Carlo data now being available, we can calculate the flux from Mkn 501 by comparison with this simulated data which has not also been used in optimisation of the cuts (see Section 4).

The determination of the background follows an approach different to our earlier publications and will be described in more detail in Petry et al. (1997). In order to maximise our exposure time at small zenith angles the data were recorded in consecutive ON-source runs. OFF-source observations required for background determination were made when Mkn 501 was not observable. Observations of 9 different "empty-sky" regions made before, during and after the Mkn 501 observing season were available, forming a combined OFF-source dataset of 86.3 h at $5^\circ < \theta < 25^\circ$. From these data the background was determined, both for the Crab Nebula and for Mkn 501, as follows.

From Monte Carlo studies we expect less than 1% of source γ events in our camera to fulfill the condition $20^\circ <$ ALPHA $< 80^\circ$. The number of events which pass all other cuts and lie in this ALPHA region is therefore used to normalise the ALPHA-distribution of the OFF data to that of the ON data. Since the characteristics of the shower images are zenith angle (θ) dependent, we adjust the θ distribution of the OFF data to that of the ON data, by performing the normalization in n separate θ bins. The normalisation constants $\beta_1, ..., \beta_n$ are calculated using

$$\beta_i = \frac{M_{\mathrm{on},i}}{M_{\mathrm{off},i}}$$

where $M_{\mathrm{on},i}$ is the number of ON-source events with $20^\circ <$ ALPHA $< 80^\circ$ in θ bin i and $M_{\mathrm{off},i}$ is the corresponding number for the OFF data. The width of the θ bins was a compromise between the accuracy of a small bin width and sufficient events per bin for a low statistical error. For both Mkn 501 and the Crab Nebula n = 3 approximately equidistant bins between $\theta \approx 5^\circ$ and $\theta = 25^\circ$ were used.

The number of expected background events in the signal region of ALPHA $< 10^\circ$, B, is then obtained from

$$B = \sum_{i=1}^{n} \beta_i N_{\mathrm{off},i}$$

where $N_{\mathrm{off},i}$ is the number of OFF-source γ candidates (after all cuts including ALPHA $< 10^\circ$) in θ bin i. By standard error propagation, the statistical error on B is

$$\sigma(B) = \sqrt{\sum_{i=1}^{n} \beta_i^2 N_{\mathrm{off},i} + (\beta_i^2 + \beta_i^3) N_{\mathrm{off},i}^2 / M_{\mathrm{on},i}}$$

We calculate the significance S of the signal as the excess divided by the statistical error on the excess:

$$S = \frac{N_{\mathrm{on}} - B}{\sqrt{N_{\mathrm{on}} + (\sigma(B))^2}}$$

where N_{on} is the number of events in the ON-source dataset after all cuts including ALPHA $< 10^\circ$.

This conservative approach takes into account both the dependency of the image parameters on θ and the statistical error in our knowledge of this dependency.

3. Results

Table 1 shows the event statistics. The number of expected events and the statistical significances are calculated according to the procedure described in Section 2. We obtain an excess of 351 events after all cuts with a significance of 5.2 σ. For comparison, 23 h of observations of the Crab Nebula taken between October 1995 and February 1996 at $\theta < 25^\circ$ were analysed. Using the same procedure as for Mkn 501, we find an excess of 186

Table 1. Statistics of the Mkn 501, Crab Nebula and OFF source datasets. The number of expected events after all cuts is found from the OFF source data ($B \pm \sigma(B)$ in Section 2).

target	Mkn 501	Crab Nebula	OFF source
observation time (h)	146.8	22.9	86.3
events after filter	359160	67045	209037
events after all cuts except ALPHA	8083	1971	4633
events after all cuts	1325	423	612
expected background events[1] after all cuts	974 ± 57	237 ± 13	-
excess	351	186	-
significance of excess	$5.2\ \sigma$	$7.6\ \sigma$	-

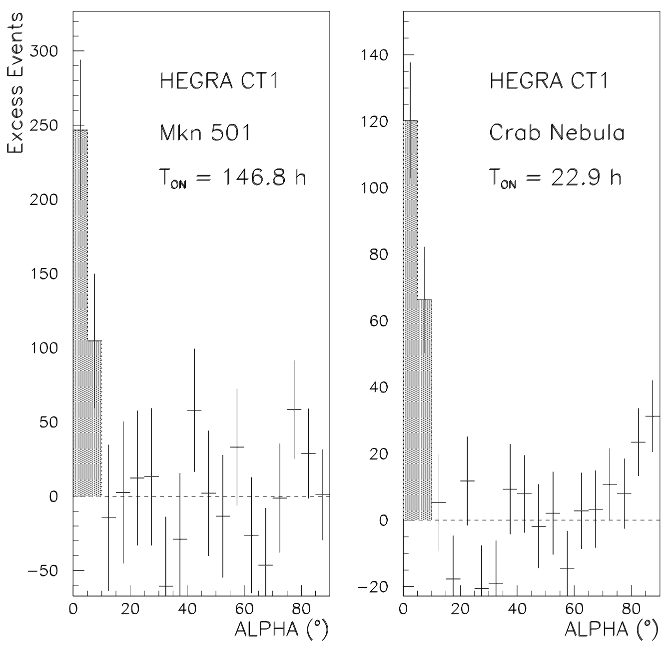

Fig. 1. The ON-source - OFF-source ALPHA distributions. ALPHA is a measure of the deviation of the shower axis from the source direction. For Mkn 501 there are 351 excess γ candidates after all cuts (shaded, rate 2.4 h^{-1} with a significance of 5.2 σ). For the Crab Nebula there are 186 excess γ candidates (8.1 h^{-1}) with a significance of 7.6 σ.

events with a significance of 7.6 σ. The ALPHA distributions for Mkn 501 and the Crab Nebula are shown in Figure 1.

4. Spectral Index and Flux calculations

The procedure to examine the spectral behaviour of the source and subsequently determine the integral photon flux follows largely the one described in Paper I. Again, Monte Carlo (MC) data was produced using the code described by Konopelko et al. (1996).

[1] Note that the errors are different from the normal $\sqrt{N}$ since they were obtained from the procedure described in Section 2.

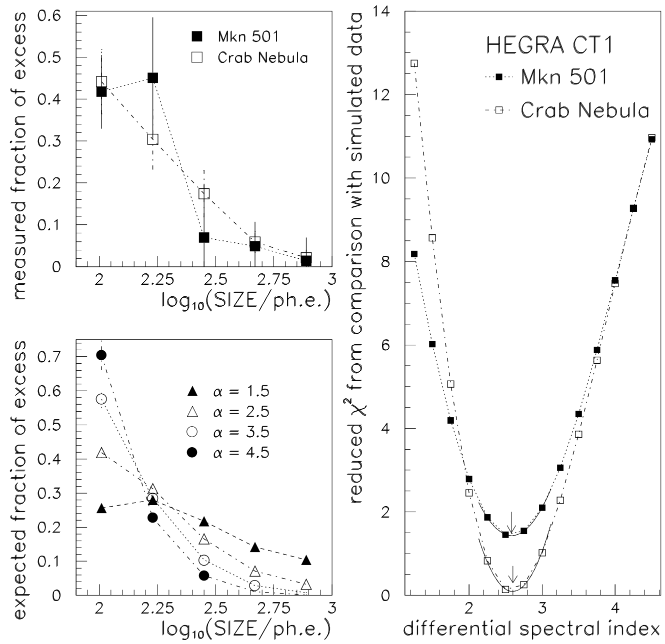

Fig. 2. a (upper left) the measured differential SIZE distribution for Mkn 501 and the Crab Nebula. The integrals of all distributions are normalized to 1. The SIZE parameter is measured in units of photoelectrons (ph.e.). The errorbars are the combined statistical and systematic error. **b** (lower left) four examples of simulated SIZE spectra for different shapes of the primary energy spectrum. α is the differential spectral index of the power law. **c** (right) the reduced χ^2 from the comparison of the measured with the simulated SIZE spectra as a function of α.

The effective collection area of CT1 for our given set of cuts was calculated taking into account the dependence of the cut efficiencies on primary energy and impact parameter. The main sources of systematic errors in the flux calculation are the energy calibration, i.e. the conversion from Cherenkov photons to ADC counts which our measurements suggest is uncertain by $\pm$ 20 %, and the determination of the shape of the primary photon energy spectrum.

Spectral shape is estimated from analysis of the differential distribution of the parameter SIZE which is defined as the total light content of the shower image in the camera. Our MC simulations show that here SIZE is in first order proportional to the energy of the primary γ-ray, but fluctuates for individual showers by up to 50 % (2σ).

The measured distributions for Mkn 501 and the Crab Nebula are shown in Figure 2a. The signal in each SIZE bin was derived in the same way as the total signal (see Section 2). From MC simulations of γ-showers and the detector, the shape of the SIZE distribution can be predicted for a given night sky background noise, average zenith angle and shape of the primary energy spectrum. Figure 2b shows examples for power law spectra with differential spectral index α = 1.5, 2.5, 3.5 and 4.5.

By varying α between 1.25 and 4.5 in steps of 0.25 and calculating the reduced χ^2 of the comparison of the simulated with the measured SIZE distribution, we find that the spectrum of the Crab Nebula is compatible with an index

$$\alpha(\text{Crab Nebula}) = 2.60(\pm 0.41)_{\text{Stat}}$$

The minimum reduced χ^2 reached is 0.1 independent of whether only the first three, four or all five points are used. In order to test the robustness of the procedure we varied the photon to ADC count conversion factor by $\pm$ 20 %. The most probable index changed by less than 0.1.

Assuming a spectral index of 2.6 $\pm$ 0.4, we determine the integral flux of the Crab Nebula above 1.5 TeV from the 1995/96 CT1 data to be

$$7.7(\pm 1.0)_{\text{Stat}}(+4.6 - 0.9)_{\text{Syst}} \times 10^{-12}\ \text{cm}^{-2}\text{s}^{-1}$$

where the systematic error combines the uncertainties in the spectral index and the energy calibration.

The same method applied to Mkn 501 results in a similar spectral index:

$$\alpha(\text{Mkn 501}) = 2.58(\pm 0.51)_{\text{Stat}}$$

The minimum χ^2 reached is 1.4.

Given this uncertainty in the spectral shape, we cannot make strong statements about modifications to the power law spectrum such as cutoffs. We find that the impact of a possible cutoff on our calculated integral flux would be negligible if it was at energies $>$ 6 TeV. We assume for the calculation of the flux a spectral index of 2.6$\pm$0.5. Based on the total Mkn 501 dataset at $\theta < 25°$ we thus find an integral flux above 1.5 TeV of

$$2.3(\pm 0.4)_{\text{Stat}}(+1.5 - 0.6)_{\text{Syst}} \times 10^{-12}\ \text{cm}^{-2}\text{s}^{-1}$$

5. Variability

With this Mkn 501 dataset collected over an exceptionally long period (approx. 6 months) during which no significant change was made to the telescope and data processing stream, an investigation of the stability of our signal over time is of interest. In fact, flux variability is a common characteristic of EGRET blazar measurements (von Montigny et al. 1995). The Whipple group finds the VHE flux of Mkn 501's sister object Mkn 421 to be highly variable on timescales of months to days (Macomb et al. 1995) even observing a flare event in which the flux rose to $>$ 50 times its quiescent level (Gaidos et al. 1996). During the 1995 Whipple Mkn 501 observations the flux from this source appeared approximately constant (Quinn et al. 1996) except on one day (of 58) when the measured rate lay 5 standard deviations above the mean. Figure 3 shows the rate of excess γ-ray candidate events recorded by CT1 on nights when Mkn 501 was observed for more than 20 minutes at $\theta < 25°$. Above our threshold of 1.5 TeV we have seen no significant "burst behaviour".

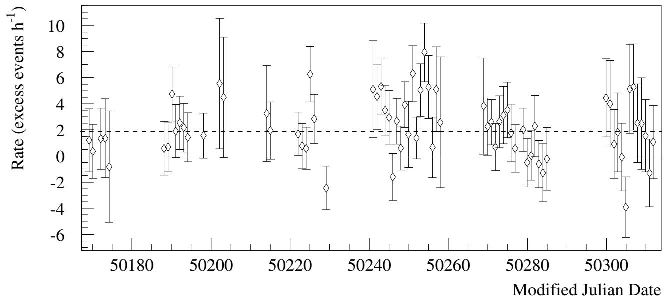

Fig. 3. Daily excess γ-ray event rates from Mkn 501. A constant fit (dashed line) to 70 nights of CT1 data (the 70 nights on which Mkn 501 was observed at $\theta < 25°$ for at least 20 minutes) leads to a rate of 1.88 $\pm$ 0.26 h^{-1}, consistent within our errors with the mean rate obtained from the total $\theta < 25°$ dataset of 2.39 $\pm$ 0.46 h^{-1}. The peak rate of 7.9 $\pm$ 2.2 h^{-1}, recorded during a 3.5 h observation centred on MJD 50253.97, lies 2.5 standard deviations from the mean.

6. Conclusion

We have detected γ-radiation above 1.5 TeV from Mkn 501 using the first imaging air Cherenkov telescope of the HEGRA Collaboration. An integral flux above 1.5 TeV of approx. 2.3×10^{-12} cm^{-2}s^{-1} was found from the March - August 1996 data. Mkn 501 shows a spectrum compatible with a differential spectral index of 2.6$\pm$0.5, where the large error is mainly statistical.

Our near contemporary Crab Nebula data show an excess rate 3.4 times larger than that for Mkn 501 and a spectral index of 2.6$\pm$0.4, from which a flux above 1.5 TeV of approx. 7.7×10^{-12} cm^{-2}s^{-1} is calculated. This is in very good agreement with our earlier measurement using CT2 at a threshold of 1 TeV (Petry et al. 1996). Within the statistical errors, the integral flux above 1.5 TeV from Mkn 501 is less than that from the Crab Nebula by a factor of 2.9$\pm$0.7.

In 70 nights of data no significant deviation of the Mkn 501 event rate from a mean of 2.4 events h^{-1} was observed.

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References

Gaidos J.A., et al., 1996, Nature 383, 319
Hermann G., 1995, in M. Cresti (ed.) Towards a Major Atmospheric Cherenkov Detector IV, Padua, 396
Kerrick A.D., et al., 1995, ApJ 452, 588K
Konopelko A., et al., 1996, Astropart. Phys. 4, 199
Macomb D.J., et al., 1995, ApJ 449, L99
Mirzoyan R., et al., 1994, Nucl. Instr. and Meth. A351, 513
von Montigny C., et al., 1995, ApJ 440, 525
Petry D., et al., 1996, A&A 311, L13
Petry D., et al., 1997, to be submitted to Astropart. Phys.
Punch M., et al., 1992, Nature 358, 477
Quinn J., et al., 1996, ApJ 456, L83
Rauterberg G. et al., 1995, in Proc. 24th ICRC, Rome, 3, 460
Reynolds P. T., et al., 1993, ApJ 404, 206
Rhode, W., et al., 1996, Nucl. Phys. B (Proc. Suppl.) 48, 491

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