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LETTER

*Letter to the Editor*

# Measurement of the flux, spectrum, and variability of TeV $\gamma$-rays from Mkn 501 during a state of high activity

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**Abstract.** Between March 16, 1997 and April 14, 1997, a high flux level of TeV $\gamma$-rays was observed from Mkn 501, using the HEGRA stereoscopic system of four imaging Cherenkov telescopes. The flux level varied during this period from about one half up to six times the flux observed from the Crab Nebula. Changes of the detection rate by a factor of up to 4 within 1 day have been observed. The measured differential energy spectrum of the radiation follows a power law from 1 TeV to 10 TeV. The differential spectral index of 2.47 $\pm 0.07 \pm 0.25$ is close to that of the Crab Nebula of $2.66 \pm 0.12 \pm 0.25$.

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

## 1. Introduction

Among the TeV cosmic $\gamma$-ray sources observed by ground-based imaging atmospheric Cherenkov telescopes (IACTs) are two nearby active galactic nuclei (AGNs), Mkn 421 (Punch et al. 1992, Petry et al. 1996) and Mkn 501 (Quinn et al., 1996, Bradbury et al. 1997). In contrast to steady TeV $\gamma$-ray sources such as the Crab Nebula, the Whipple group (Kerrick et al. 1995a, Gaidos et al. 1996, Buckley et al. 1996) found a dramatic time variability in the radiation from Mkn 421, with characteristic scales as short as one hour. The study of TeV radiation from these and other AGNs is interesting for several reasons. The fast time dependence implies severe limitations on the size of the source, or on the combination of source size and Doppler factor in the case of emission from relativistic jets. TeV $\gamma$-radiation from such distant objects can furthermore be used to set limits on the diffuse extragalactic background radiation at optical and infrared wavelengths (Biller et al. 1995 and refs given there). TeV $\gamma$-rays interact with these background radiation fields through pair production, with the cross section peaking near threshold. The observation of a cutoff in the $\gamma$-ray spectrum at an energy $E_\gamma$ can be related to the background photon density at the conjugated energy $E_{BG} \approx 0.5$ eV(1 TeV$/E_\gamma$).

In early march 1997, the Whipple group communicated the observation of strong TeV $\gamma$-ray emission from Mkn 501 at a level well above the flux from the Crab Nebula. Earlier measurements had shown a flux at a level significantly below the Crab flux. Mkn 501 was then detected by the HEGRA IACTs CT1

*Send offprint requests to*: hermann@eu1.mpi-hd.mpg.de and CT2, operated independently from each other, and by CAT (Breslin et al., 1997), as well as by the HEGRA IACT system consisting of the four telescopes CT3,4,5,6, used in stereoscopic mode. In this Letter, we report the first results of the analysis of the data obtained with the CT system. Results obtained with CT1 and CT2 will be reported elsewhere.

## 2. The HEGRA IACT array

The HEGRA IACT system (Aharonian 1993) is located on the Canary Island of La Palma, at the Observatorio del Roque de los Muchachos of the Instituto Astrofisico de Canarias, at a height of about 2200 m asl. It consists of six IACTs, the first prototype CT1, the stereoscopic IACT system (CT3-CT6), and the prototype CT2, which will be included into the system after its refurbishment. The telescopes CT2,4,5,6 are arranged in the corners of a square with about 100 m side length, and the telescopes CT3 and CT1 are positioned in the center of the square. With the stereoscopic system, an air shower is viewed simultaneously from different directions, allowing to reconstruct the location of the shower axis in space, and in particular the direction of the primary and the core location. The four telescopes CT3-CT6 are essentially identical; they were installed during 1995 and 1996 and have been taking data as a 4-telescope system since Winter 1996/97. The telescopes have mirrors with 8.5 m$^2$ area and 5 m focal length and are equipped with 271-pixel photomultiplier (PMT) cameras with 0.25° pixel size and a 4.3° field of view (Hermann 1995). For the trigger of the system a coincidence of at least two out of four telescopes is required.

## 3. Data sample and analysis

The Mkn 501 data sample comprises data from 14 nights from March 15/16 to April 13/14, 1997 with a total observation time of 26.7 hours. Bad weather conditions and the rising moon prevented continuous observation. All observations were carried out in a mode where Mkn 501 was displaced in declination by ±0.5° from the optical axis of the telescopes, with the sign of the displacement changing every 20 min. A region displaced symmetrically by the same amount in the opposite direction was used to provide a control sample.

The image analysis and the reconstruction of the shower axis from the images is described elsewhere (Daum et al., 1997). In the present analysis, improved corrections for the telescope pointing were applied, and an algorithm to estimate the shower energy was added. Monte-Carlo simulations were used to determine the relation between the light yield measured in a camera as the sum of pixel amplitudes, $Q = Q(r, E)$, the energy $E$ of the shower, and the distance $r$ to the shower core. In addition, the fluctuation of the light yield, $\Delta Q(r, E)$, was determined, taking into account the error in the measurement of $r$. The shower energy is then obtained as a weighted average over telescopes.

The system is expected to provide a $\gamma$-ray energy threshold of 500 GeV, an energy resolution of 20%, an angular resolution of about 0.1°, and a determination of the shower impact point of about 15 m in each coordinate. The angular resolution was verified by observations of $\gamma$-rays from the Crab Nebula (Daum et al. 1997).

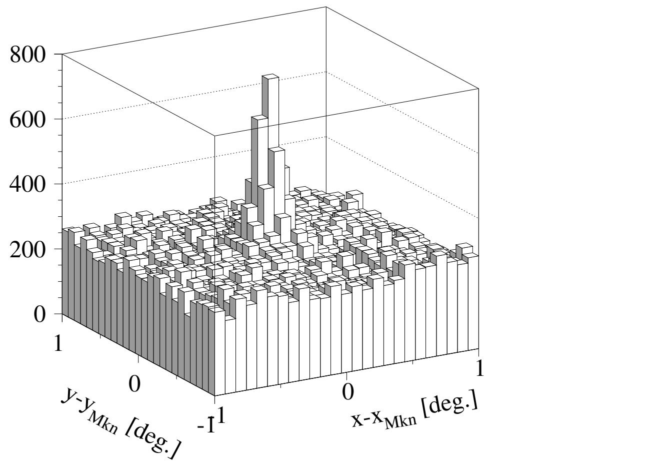


**Fig. 1.** Distribution of the reconstructed shower directions relative to the direction to Mkn 501, for events where at least two telescopes triggered, before shape cuts.

Already in the raw data, before selection cuts, a clear signal of Mkn 501 is visible. Fig. 1 shows the distribution of the reconstructed shower directions for all events which triggered at least two telescopes, and provided two images with 40 or more photoelectrons and at least two pixels with more than 10 photoelectrons. The position of Mkn 501, as reconstructed from such distributions (after cuts on the image shape, to reduce background), is consistent with its nominal position within the statistical error of 0.009°.

For a quantitative analysis, we plot the distribution in the angle $\theta$ between the shower axis and the source location; shown in Fig. 2(a) is $dN/d\theta^2$. For the uniform background from charged cosmic rays one expects a flat distribution in $\theta^2$. A $\gamma$-ray point source causes an excess around $\theta \approx 0°$. The observed distribution shows these features. An estimate for the background under the signal is obtained by plotting the distribution of shower axis relative to a virtual source displaced by the same amount from the telescope axis as the real source, but in the opposite direction. This backgound is shown as a shaded histogram; it is flat in $\theta^2$. In the region up to $\theta^2 = 0.05^{\circ 2}$ around the source, 3574 excess events are counted, corresponding to an average rate of 134 events/h.

The shapes of Cherenkov images can be used to suppress cosmic-ray background relative to $\gamma$-ray showers; $\gamma$-rays generate narrower and more compact images. Therefore the width of each image in a given event is scaled to the Monte-Carlo expected width of $\gamma$-ray images as a function of image amplitude and distance to the shower core. As selection parameter the mean scaled width is calculated for all telescopes participating in an event. To maintain high efficiency and to minimize corrections, a very loose cut is applied by selecting events with a mean scaled width below 1.3. Fig. 2(b) shows the angular distribution of events after this loose cut. The background is reduced by a factor of about 3, while the number of events in the peak is

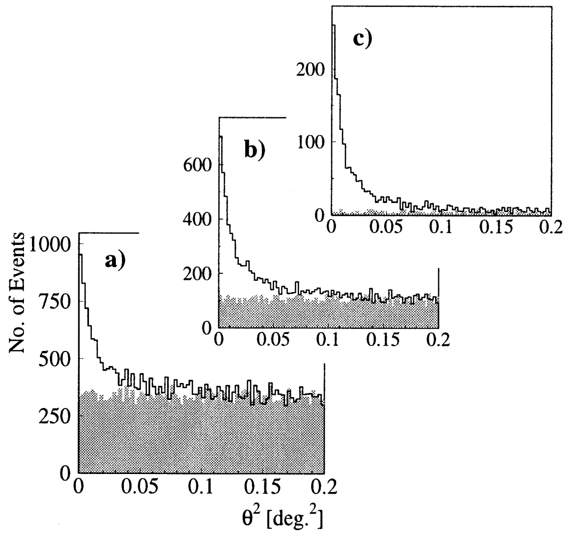


**Fig. 2.** Line: distribution $dN/d\theta^2$ of events in the square of the angle $\theta$ relative to the direction to the source. The shaded histogram shows the background, see text for details. (a) before cuts, (b) after loose shape cuts, and (c) after tight shape cuts.

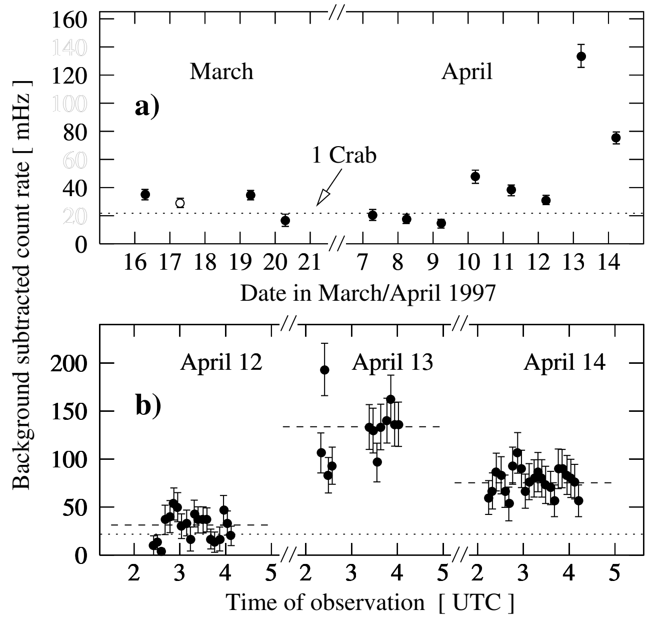


**Fig. 3.** Detection rate of Mkn 501 on a night by night basis (**a**) for the whole data set and in 5 min. intervals (**b**) for the last 3 nights. The dashed lines indicate the average per night, the dotted line shows the Crab detection rate. Only observations with a zenith angle below 30° are considered. On March 17 (open circle) the trigger rate was reduced by about 15 % due to slight overcast. Errors are statistical only.

nearly unchanged. We verified that the high selection efficiency is maintained for all shower energies. At the expense of signal statistics, the background can be reduced further. Fig. 2(c) illustrates the effect of tight cuts (Daum et al. 1997), which almost completely eliminate the background.

## 4. Time variability

To investigate time variability, data were grouped in different time bins, ranging from about 5 min. to entire nights. We required that at least two telescopes triggered, and applied a loose angular cut at $\theta = 0.22°$ ($\theta^2 = 0.05°^2$) as well as the loose selection based on the widths of the images. Only observations at zenith angles below 30° with good weather conditions are considered. Fig. 3 (a) shows the detection rate on a night by night basis for the whole data set. While the rate decreases by about 60 % during the first 9 nights, it increases by a factor of 3.3 during April 9 and again by a factor of 4.3 during April 12. Fig. 3 (b) gives a closer view on the period from April 12 to April 14 in 5 min. intervals. Data are statistically consistent with a constant flux within each of the 3 nights shown.

## 5. Flux and spectral index

The stereoscopic HEGRA IACT system with its energy resolution of about 20% allows detailed studies of the spectrum of $\gamma$-ray sources. To derive the flux $F(E)$, the rate at a given reconstructed energy $E$ is divided by the selection efficiency and the (energy-dependent) effective detection area. Only events where at least three telescopes triggered are used, to guarantee good stereoscopic reconstruction. Events are counted within a radius of 0.26° from the source, and the background determined from the average yield of events around a virtual source on the opposite side of the camera is subtracted. To avoid significant Monte-Carlo based corrections, the loose shape cuts were used, with a $\gamma$-ray efficiency above 90%. A similarly conservative approach is followed for the effective detection area. We impose an energy-dependent limit on the maximum distance $r_{max}(E)$ between the shower core and the central telescope, such that the trigger probability according to simulations is at least 80%, and also require at least one active telescope within 140 m from the core. Between 1 TeV and 4 TeV, $r_{max}$ rises from about 100 m to 200 m. After this selection, the effective area is determined by simple geometry, up to a small correction. Below about 0.8 TeV, trigger probabilities do not safely saturate and data are not used. In the determination of spectra, only runs with zenith angles below 30° were included, with a median zenith angle of 18°.

The resulting differential energy spectrum of Mkn 501 is shown for energies up to 10 TeV in Fig. 4, together with the spectrum of the Crab Nebula analyzed in the identical fashion, based on 9.7 h of earlier observations at small zenith angles. The width of the energy bins corresponds roughly to the rms energy resolution of about 20%. Both spectra are compatible with pure power laws, with a differential spectral index of $2.66 \pm 0.12$ (stat. error only) in case of the Crab Nebula, and $2.47 \pm 0.07$ for Mkn 501; the integral fluxes above 1 TeV are $1.0 \pm 0.1 \cdot 10^{-11}/\mathrm{cm}^2\mathrm{s}$ (stat. error only) and $2.2 \pm 0.1 \cdot 10^{-11}/\mathrm{cm}^2\mathrm{s}$ , respectively. We note that this procedure has also been applied on a night by night basis and that the shape of the spectrum does not change within the statistical errors of about 0.2. Also it is found that

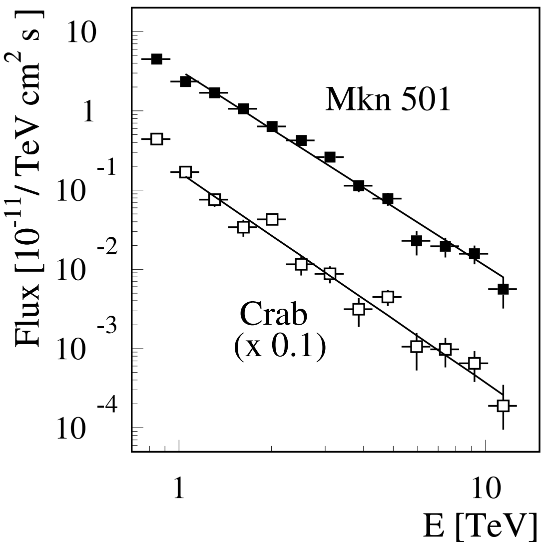


**Fig. 4.** Average differential spectrum of $\gamma$-rays from Mkn 501 and from the Crab Nebula. The Crab data points are scaled by a factor 0.1. The lines represent power-law fits, see text. Only statistical errors are shown. The energy scale has a 20% systematic error.

the spectrum of Mkn 501 shows no indication for a cutoff in the energy range from 1 TeV to 10 TeV.

To estimate the systematic errors on the flux and the spectral slopes, the cuts and reconstruction procedures were varied over a wide range. E.g., the width cut was omitted entirely, or the angular cut increased to 0.3°, or the maximum core radius was limited to 100 m. Different weights and radial dependencies were used in the energy determination. The fit range was varied. From these studies, we estimate a systematic error of $\pm 25\%$ in the flux and $\pm 0.25$ in the spectral slope. An additional error of 36% on the flux arises from the 20% uncertainty in the absolute energy calibration, increasing the total systematic error on the flux to 45%. It is likely that these errors can be reduced as our experience in the analysis of IACT system data increases. In the comparison of the characteristics of $\gamma$-ray emission from the Crab Nebula and from Mkn 501, the systematic errors should cancel to a large extent.

We note, that within the statistical and systematic errors, the measurements of the $\gamma$-ray flux from the Crab Nebula are consistent with earlier HEGRA measurements using the single telescopes CT1 and CT2 (Konopelko et al. 1996, Petry et al. 1996, Bradbury et al. 1997).

## 6. Conclusions

Observations of Mkn 501 with the stereoscopic HEGRA IACT system during 14 days in March and April 1997 showed a $\gamma$-ray flux at a level of about one half to six times the Crab flux. The energy spectrum is comparable to that of the Crab Nebula, and extends up to at least 10 TeV. The flux level was studied on time scales between as short as 5 min and days. On a day to day scale an increase of the flux by a factor of up to 4 could be observed. On sub-hour time scales the data are statistically consistent with a constant flux. The observations with all 6 HEGRA telescopes are still continued. The results will be published elsewhere.

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## References

Aharonian F.A., 1993 Proceedings of the Int. Workshop "Towards a Major Atmospheric Cherenkov Detector II", Calgary, R.C. Lamb (Ed.), p. 81
Biller, A.D., et al., 1995, ApJ 445, 227
Bradbury S.M., et al., 1997, A&A, in press.
Breslin A.C., et al., 1997, IAU Circular No. 6592
Buckley J.H., et al., 1996, ApJ 472, L9
Daum A., et al., 1997, submitted to Astrop. Phys., (Preprint MPI H - V 13)
Gaidos J.A., et al., 1996, Nature 383, 319
Hermann G., 1995, Proceedings of the Int. Workshop "Towards a Major Atmospheric Cherenkov Detector IV", Padua, M. Cresti (Ed.), p. 396
Kerrick A.D., et al., 1995, ApJ 438, L59
Quinn J., et al., 1996, ApJ 456, L83
Konopelko A., 1996, Astropart. Phys. 4, 199
Petry D., et al., 1996, A&A 311, L13
Punch M., et al., 1992, Nature 358, 477

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