Study of the Temporal and Spectral Characteristics of TeV Gamma Radiation from Mkn 501 During a State of High Activity by the HEGRA IACT Array

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Abstract. During the period March-April 1997, a high flux level of TeV γ-rays was observed from Mkn 501, using the HEGRA stereoscopic system of four imaging atmospheric Cherenkov telescopes (IACTs). The almost background-free detection of γ-rays with a rate exceeding in average $100\,\mathrm{h}^{-1}$, coupled with good energy resolution of the instrument $\leq 25\%$ allowed a study of the flux variation on time scales between 5 min and days, and measurements of the differential energy spectrum of the source for selected periods. Here we briefly discuss the results of observations with emphasis on the measurements of temporal and spectral characteristics of the source at 3 subsequent periods in April when the average flux of the source showed a remarkable increase of the flux from about one to eight times the flux observed from the Crab Nebula.

INTRODUCTION

Among the few TeV cosmic γ-ray sources are two BL Lac objects, Mkn 421 and Mkn 501 [1] – highly variable AGNs without strong emission lines, but showing a strong nonthermal (synchrotron) component of radiation from radio to hard X-ray wavelengths [2]. Interestingly, Mkn 501 has not yet been detected at MeV/GeV energies, and Mkn 421 is one of the weakest γ-ray emitting AGNs detected by the EGRET [3]. On the other hand, TeV γ-rays have not been detected from much more powerful radio loud AGNs and quasars which are strong GeV γ-ray emitters. Generally, this is in agreement with theoretical expectations that nearby BL Lac objects rather than quasars are most likely to be detected in TeV γ-rays (see e.g. [4,5]). The ASCA and Whipple discovery of correlated flares of Mkn 421 in keV and TeV energy bands supports the models which assume that both components originate in relativistic jets due to synchrotron and inverse Compton radiation of a single population of relativistic electrons [6]. In practice, this implies that the TeV radiation, combined with X-ray observations is likely to be a crucial channel for informing us about nonthermal processes in BL Lacs. TeV observations of distant extragalactic objects can address another important issue – to set meaningful limits on the diffuse extragalactic background at infrared and optical wavelengths (see [1] and references therein).

The first measurements of TeV radiation from Mkn 501 in 1995/1996 had shown a flux level significantly below the Crab flux [1]. However, in early March 1997, the Whipple group communicated the observation of strong TeV γ-ray emission from Mkn 501 which has increased by an order of magnitude, compared with the period of 1995/1996.

OBSERVATIONS

The HEGRA collaboration is continuously monitoring Mkn 501 with six imaging telescopes located on Canary Island La Palma since March'97. The results obtained by the $5\,\mathrm{m}^2$ telescope CT1, which operates in the 'stand alone' mode, will be published elsewhere [7].

The observations of Mkn 501 by the partially completed stereoscopic system of HEGRA IACTs consisting of 4 telescopes, CT3–CT6 [8], are described in [9]. The telescopes have mirrors with $8.5\,\mathrm{m}^2$ area and 5 m focal length and are equipped with 271-pixel photomultiplier cameras with 0.25° pixel size and $\approx 4.3^\circ$ effective field of view. The recent observations of TeV γ-rays from the Crab Nebula by the same CT3/4/5/6 telescope system [8], combined with Monte Carlo calculations, provide good understanding of the performance of the instrument in its current status, namely: energy threshold $\approx 500\,\mathrm{GeV}$, angular resolution as good as 0.1°, energy resolution $\leq 25\%$, minimum detectable flux of 0.3 Crab for 1 h observation of a point source.

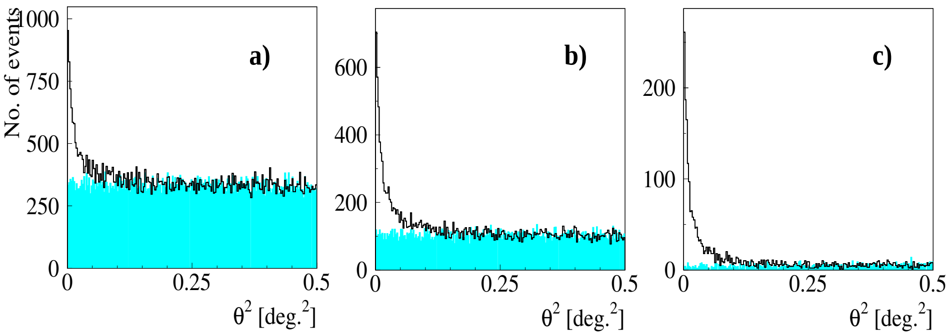

FIGURE 1. Distribution $dN/d\theta^2$ of events in the square of the angle θ relative to the direction to the source. The shaded histogram shows the background. (a) before shape cuts, (b) after loose shape cuts, and (c) after tight shape cuts.

The presented Mkn 501 data sample comprises observations from March 15/16 to April 13/14 with a total exposure time of 26.7 hours. The image analysis, reconstruction of the shower axis, and determination of the shower energy are described elsewhere [8,9]. Fig. 1 shows the $\mathrm{d}N/\mathrm{d}\theta^2$ distributions of the reconstructed shower directions for all events which triggered at least two telescopes. Remarkably, due to the good angular resolution as well as the strong suppression of hadronic showers at the trigger level, a clear γ-ray signal is visible already in the raw data (Fig.1a). Application of the image shape cuts (γ-rays generate narrower and more regular images compared with the images of hadronic showers) provides further suppression of the background caused by cosmic rays. To maintain the high efficiency of acceptance for γ-ray events, below we use very loose cuts (Fig.1b) which reduce the background by a factor of 3, while the number of events in the peak remains almost unchanged. Finally, at the $\approx$ 50% expense of signal statistics, the background can be almost eliminated by applying tight shape cuts [8] (Fig.1c). The reconstructed position of the source is consistent with position of Mkn 501 within 0.01°.

TIME VARIABILITY AND ENERGY SPECTRA

To investigate time variability, data are grouped in different time bins. Fig.2a shows the detection rate on a night by night basis for the whole data set. While the rate decreases by $\approx$ 60% during the first 9 nights, it increases by a factor of 3.5 during April 9/10 and again by a factor 4 during April 12/13. Fig.2b gives a closer view on the period from April 12 to April 14 in 5 min intervals. While one could interpret a sub-hour structure into these data, they are not inconsistent with a constant flux within each of these 3 nights.

The stereoscopic HEGRA IACT system with its energy resolution of about 25% enables detailed study of the differential energy spectrum of γ-rays, if the photon statistics exceeds several hundreds. This allows us to measure not

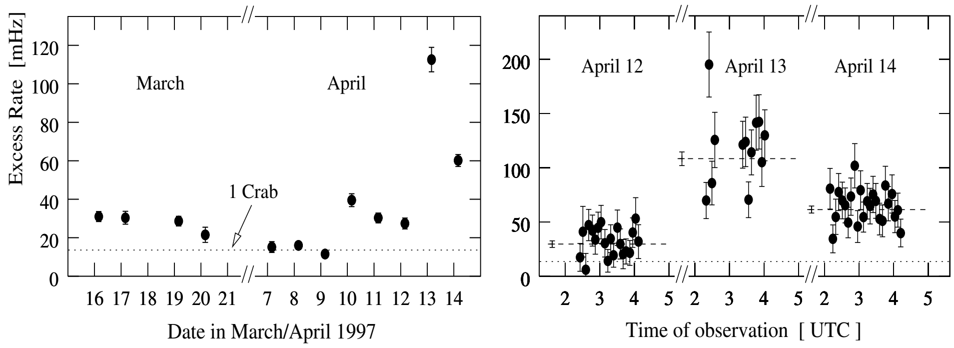

FIGURE 2. Detection rate of Mkn 501 on a night by night basis at zenith angles $\leq 30°$ (a) for the whole data set and in 5 min. intervals (b) for the last 3 nights. The dashed lines indicate the average per night, the dotted line shows the Crab detection rate.

only the spectrum on average for the whole March-April period (approximately 2500 γ-ray events detected at zenith angles up to 45°), but also for shorter periods, from 1 to 3 nights of observations depending on the flux level. Fig.3 shows the energy spectra of Mkn 501 measured during 3 periods of source activity in April : (i) Apr 7-10, (ii) Apr 11-12; (iii) Apr 13. The combination of ≥ 1 subsequent (similar) days in one period provides reasonable statistics for an evaluation of the differential spectra of the source at 3 different average flux levels (see Fig.2). Remarkably, in the case of a strong flare of the source on Apr 13 the spectrum can be derived even in a few hours of continuous observations. In Fig.3 we show the measured fluxes between 1 and 10 TeV. In fact, the statistics of γ-rays detected at both lower and higher energies formally is sufficient for flux estimates also below 1 TeV and above 10 TeV. However, due to a strong energy dependence of γ-ray detection efficiencies at lower energies and possible saturation effects at very high energies, the quantitative evaluation of the spectra in these energy bands is still in progress. In Fig.3 only statistical errors are shown. The systematic errors on the flux caused by different reasons, like the accuracy of calculations of the collection area and determination of the energy of γ-rays, as well as an uncertainty in the absolute energy calibration, currently are estimated as large as 45%. Within such uncertainties, the fluxes shown in Fig.3 can be fitted by a 'conventional' power-law spectrum, although we may notice a tendency of a gradual steepening of the observed spectra, especially for the statistically rich ones corresponding to the whole March-April dataset and to the flare in Apr 13.

The observations of Mkn 501 by the HEGRA IACT system allow a study of the time variation of the energy spectrum of the source based on the temporal behavior of the hardness ratios in counting rates, which are rather insensitive to the uncertainties in the collection areas. The hardness ratios $r_1 = \mathrm{R}(\leq 1\,\mathrm{TeV})/\mathrm{R}(1-2.5\,\mathrm{TeV}) = 0.310; 0.266; 0.274$, $r_2 = \mathrm{R}(1-2.5\,\mathrm{TeV})/\mathrm{R}(2.5-5\,\mathrm{TeV}) = 1.70; 1.71; 2.21$, and $r_3 = \mathrm{R}(2.5-5\,\mathrm{TeV})/\mathrm{R}(5-10\,\mathrm{TeV}) = 2.26; 2.80; 2.32$ respectively for the Apr10-12, Apr 13, and to-

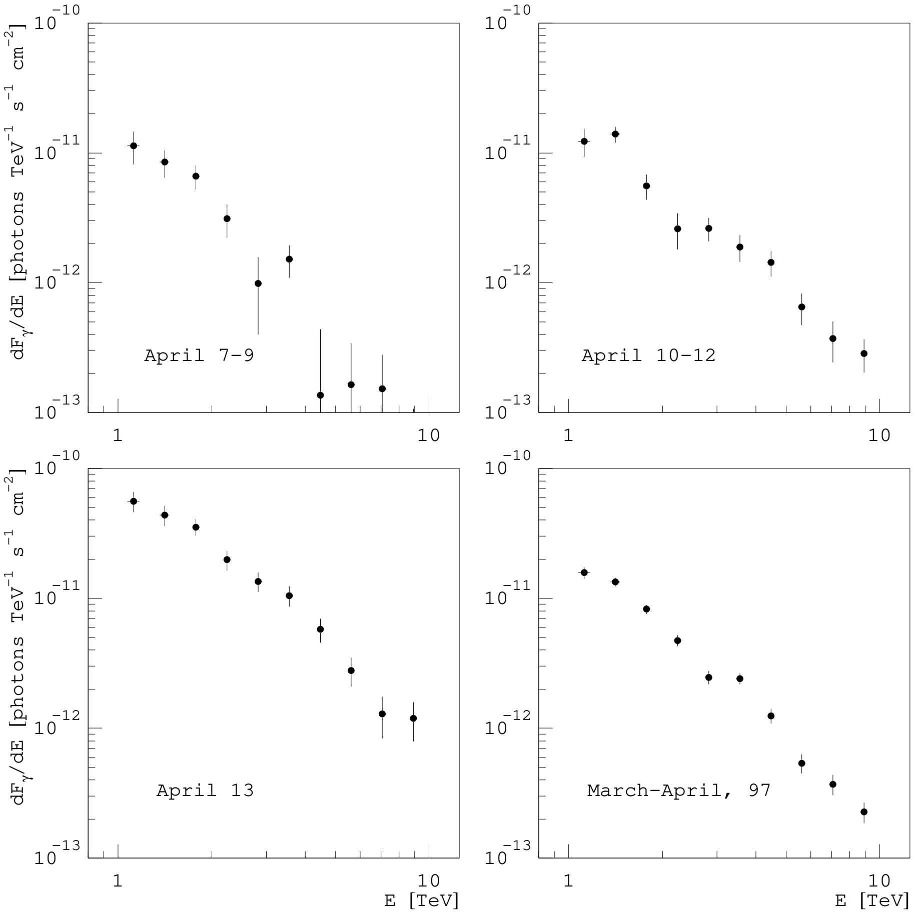

FIGURE 3. Differential energy spectra of Mkn 501 for different observational periods measured by the HEGRA IACT system. Only statistical errors are shown.

tal March-April datasets do not show, within the statistical uncertainties of about ±20%, significant variation of the spectral shape of Mkn 501 during the whole period of observations, whereas the amplitude of the absolute flux does vary during these periods by almost 1 order of magnitude.

REFERENCES

1. Weekes, T.C. et al., Review Paper; these Proceedings (1997).
2. Urry, C.M., Padovani, P., *PASP* **107**, 803 (1995).
3. von Montigny C. et al., *Ap.J* **440**, 525 (1995).
4. Dermer, C., Schlickeiser, R., *Ap.J. Suppl.* **90**, 945 (1994).
5. Ghisellini, G, Maraschi, L., *ASP Conf. Ser.*, in press (1997).
6. Takahashi, T. et al., *Ap.J* **470**, L89 (1996).
7. Lorenz, E. et al., these Proceedings (1997).
8. Daum, A. et al., *Astroparticle Physics*, submitted (1997).
9. Aharonian, F.A. et al., *A & A Letters*, submitted (1997).