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The TeV spectrum of Mkn 501 in 1997 as determined from the dark night and moon observations of the HEGRA Cherenkov telescope CT1

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Abstract. During the 1997 outburst of Mkn 501 extended observations in the presence of moonlight have been carried out with the HEGRA Cherenkov telescope CT1. Here we present the Mkn 501 energy spectrum derived from this moon data as well as the combined moon and no-moon spectrum extending well above 10 TeV.

1 Introduction

The AGN Mkn 501 ($z = 0.034$) is one of the few known TeV γ-ray sources. It has been discovered in 1995 by the Whipple collaboration (Quinn et al. 1996) at a flux level equivalent to a few % of the Crab nebula flux. An independent confirmation was given by the HEGRA collaboration in 1996 (Bradbury et al. 1997). From February until October 1997 Mkn 501 showed an unexpected strong emission of TeV γ-ray photons which was observed by several groups (Protheroe et al. 1997) and reference therein). The emission was characterized by dramatic, short term variations in intensity ($\Delta t_{obs} \sim 0.5$ d), peak flux values of up to 10 times the Crab Nebula flux (the brightest known steady γ-ray source) and a mean flux of about 3 times the Crab flux.

2 Observations and data analysis

CT1 (Mirzoyan et al. 1994) is the first of 6 Cherenkov telescopes of the HEGRA experiment, located on the canary island La Palma. The 1997 setup of CT1 consisted of an equatorial mount, a $5\,\mathrm{m}^2$ segmented mirror and a high resolution 127 pixel camera ($\sim 3°$ FOV). CT1 is operated as a standalone telescope at an energy threshold of ~ 1.2 TeV (1997).

The 1997 CT1 data from Mkn 501 consist of several different data samples, taken with different PMT HV settings and/or different night sky background light (NSB) contribution (e.g. due to the presence of moonlight). Some statistics of the different data samples are summarized in tab. 1. The label $NOMxx$ denotes no-moon, while $HVxx$ denotes moon observation data; the value of xx refers to the HV reduction of the PMTs.

Each individual data sample was separately analyzed using dynamical, i.e. zenith angle, impact parameter and energy dependent cuts (Kranich 2001). Appropriate MC simulations which also take the corresponding NSB condition and the PMT HV setting into account were used to determine the individual energy spectra. Data runs, which were taken under poor atmospheric conditions or runs, where detector problems showed up, were ignored. Data, which was taken in the presence of moonlight is analyzed in the same way as dark night data (Kranich et al. 1999). In the following the algorithm for the calculation of energy spectra is described in more detail.

An important part of the energy spectrum calculation is an accurate method for the determination of shower energies. In the case of CT1, the energy of an idividual air shower is determined by means of the shower image parameters SIZE, WIDTH, LENGTH and DIST (changes of the image parameters due to the zenith angle were taken into account). The image parameter SIZE denotes the observed light yield and is in first order proportional to the shower energy. The other parameters are used to take care of some 2nd order corrections due to the different shower impact parameters and the fluctuations in the height of the shower maxima.

From MC generated γ-ray showers we determined an energy reconstruction function by minimizing the mean squared error of the energy resolution:

$$MSE\,(\Delta E) := \sigma^2\,(\Delta E) + bias^2\,(\Delta E) \qquad (1)$$

($\Delta E = \frac{(E^{MC} - E^r)}{E^{MC}}$, E^{MC} denotes the MC Energy and E^r the reconstructed energy; see Kranich 2001 for details). The obtained energy resolution (RMS) is about 25%-30%, depending on the used γ-hadron selection cuts. Note, that the RMS value is about 25% larger than the corresponding standard deviation from a Gaussian fit to the ΔE distribution. A comparison of the reconstructed energy for coincident events between CT1 and CT-system is shown in fig. 1. As can

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	NOM00	NOM06	HV00	HV06
threshold (TeV)	1.2	1.8	1.2	1.8
Time (h)	196.9	61.0	20.2	77.3
zenith angle (deg.)	$11.0° - 58.7°$	$11.0° - 58.2°$	$11.0° - 48.4°$	$11.0° - 58.9°$
background	2074 ± 31	331 ± 13	243 ± 11	866 ± 20
excess	6335 ± 96	1040 ± 39	688 ± 32	1307 ± 50
$Flux\,(E > 1.5$ TeV)	1.86 ± 0.04	1.71 ± 0.08	1.87 ± 0.13	2.33 ± 0.11
significance	64.1	26.1	20.7	24.1

Table 1. Statistical data and results for the different data samples for Mkn 501 taken with CT1. The flux is given in units of $10^{-11}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

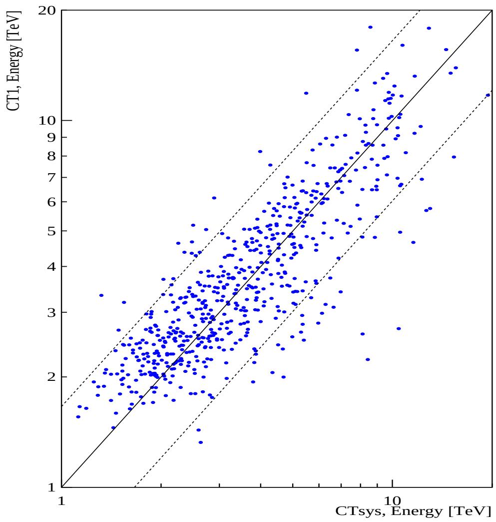

Fig. 1. A comparison of the reconstructed energy for coincident events from CT1 and CT-system. The dashed lines mark the 1σ confidence band for an energy resolution of 29% (CT1) and 20% (CT-system).

be seen, the agreement is very good over the whole energy range, even at the CT1 threshold energy. The 1σ confidence band is too wide when compared with the reconstructed energies in CT1 and the CT-system ($\sim 93\%$ of the data points lie within the dashed lines). The reason is that both detectors observe the same shower and are therefore subject to the same fluctuations in the shower development and atmospheric conditions. From fig. 1 it is seen that the method sometimes significantly underestimates the shower energy, while all the overestimated energies are within the $2\,\sigma$ limit. This method does therefore not fake high-energy data (beyond statistical effects) in spectra with low energy physical cutoffs.

Once a method to estimate shower energies is available, the differential flux $\mathrm{d}F/\mathrm{d}E$ can be determined according to:

$$\frac{\mathrm{d}F\,(E_i)}{\mathrm{d}E_i} = \frac{\frac{\mathrm{d}R(E_i,\vartheta)}{\mathrm{d}E_i}}{A_{\mathrm{eff}}\,(E_i,\vartheta)} = \frac{\kappa_i}{A_{\mathrm{eff}}\,(E_i,\vartheta)}\,\frac{\mathrm{d}R\,(E_i^r,\vartheta)}{\mathrm{d}E_i^r} \qquad (2)$$

Here, E_i denotes a MC energy bin and E_i^r the corresponding reconstructed energy bin; $A_{\mathrm{eff}}\,(E_i,\vartheta)$ is the effective collection area, ϑ the zenith angle and $\frac{\mathrm{d}R(E_i^r,\vartheta)}{\mathrm{d}E_i^r} = \frac{1}{\kappa_i}\cdot\frac{\mathrm{d}R(E_i,\vartheta)}{\mathrm{d}E_i^r}$ the reconstructed differential excess rate. The proportionality constants κ_i slightly depend on the shape of the energy spectrum (for a power law spectrum with spectral index$\alpha = 2.0$ and $\alpha = 2.7$ the difference of the κ_i-values is about 5-15%) and are therefore recursively calculated when deriving the energy spectra (see below).

The next step in deriving the energy spectrum is the calculation of the mean energy value $\overline{E_i}$ assigned to each bin. For a known differential flux $f\,(E)$, $\overline{E_i}$ is calculated according to:

$$\overline{E_i} = \frac{\int_{E_{i,lo}}^{E_{i,up}} E\cdot f\,(E)\,\mathrm{d}E}{\int_{E_{i,lo}}^{E_{i,up}} f\,(E)\,\mathrm{d}E} \qquad (3)$$

Again, the values $\overline{E_i}$ have to be calculated recursively, since $f\,(E)$ is not known in advance. The main algorithm to estimate the spectrum is then as follows:
A power law spectrum with spectral index $\alpha = 2.7$ is used to get a first estimate of the mean energy values $\overline{E_i}$ and the proportionality constants κ_i[1]. The energy spectrum itself is then derived from a χ^2-fit of a model function (e.g. power law: $f\,(E) = f_0\cdot E^{-\alpha}$ or a power law modified by a cutoff parameter: $f\,(E) = f_0\cdot E^{-\alpha}\cdot e^{-E/E_0}$) to the data pairs $(\frac{\mathrm{d}F(E_i)}{\mathrm{d}E_i}, \overline{E_i})$. Once the spectral shape is determined, $\overline{E_i}$ and κ_i are recalculated and the energy spectrum estimated. This continues until the relative difference of the fit parameters is below 1%.

The method was tested on MC simulated power-law and cutoff spectra and worked fairly well. It was possible to distinguish between power-law and cutoff spectra, small spillover effects (i.e. effects caused by the overestimation of low energy showers) are therefore correctly handled.

3 Results

The time averaged energy spectrum for the different Mkn 501 data samples are shown in fig. 2. Even without normalization, the individual data samples show a very good agreement. The variability of Mkn 501 is not a problem, since all data samples cover a large time range and possible variations in the spectral shape should therefore level out. The results of a cutoff fit to the individual energy spectra are shown in tab. 2. As can be seen, the obtained fit parameters are also in

[1]The κ_i-values for $\alpha = 2.0$, $\alpha = 2.7$ and $\alpha = 3.4$ were calculated from MC data. All other κ_i-values are obtained through linear interpolation.

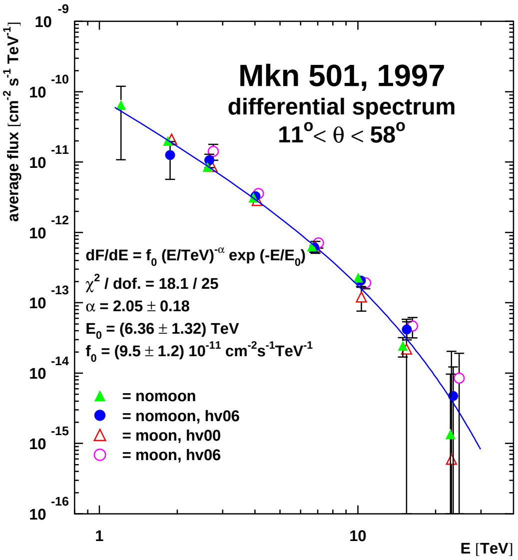

Fig. 2. Differential energy spectra as derived for the different CT1 data samples The spectra for the different observation conditions were not normalized onto each other (see text).

good agreement. In the case of the HV06 data, a pure power law was favored by the data (E_0 well above the maximum observed energies), however, keeping α fixed shows that the data is still in good agreement with the other CT1 data samples.

The energy spectrum of the combined CT1 data is shown in fig. 3 and tab. 3. Here, the data points were derived as weighted mean from the different data samples of fig. 2. A power-law spectrum is ruled out by the combined CT1 spectrum on the 3.8σ level, whereas a cutoff spectrum is in good agreement with the data (only data points with a signal to noise ratio > 1.5 have been used for the fit). The time averaged energy spectrum of Mkn 501 in 1997 is thus given as (only statistical errors):

$$\frac{\mathrm{d}F}{\mathrm{d}E} = (9.8 \pm 1.2) \cdot \left(\frac{E}{\mathrm{TeV}}\right)^{-2.1\pm0.2} \cdot e^{-E/(6.5\pm1.5)\ \mathrm{TeV}} \quad (4)$$

(in units of $10^{-11}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{TeV}^{-1}$). This result is in good agreement with the results from the CT-system (Aharonian et al. 1999) and other experiments.

The highest observed γ-ray energies are of special interest in deriving limits on the DEBRA density and/or acceleration models. It is therefore essential to properly investigate the main source of errors for the high-energy region of the spectrum, i.e. the misinterpretation of low-energy showers as high-energy events (so called spillover events). This analysis is described in the remaining section.

data sample	cutoff fit f_0	α	E_0 (TeV)
NOM00	8.1 ± 1.3	1.74 ± 0.26	4.95 ± 1.18
NOM06	10.6 ± 3.7	2.22 ± 0.42	9.13 ± 7.06
HV00	11.0 ± 2.6	1.93 ± 0.52	4.44 ± 3.08
HV06	24.3 ± 7.2	2.97 ± 0.15	56.91 ± 133.66
HV06 (fixed α)	11.3 ± 2.1	2.09	7.31 ± 1.48

Table 2. Parameters describing the differential energy spectra as derived for the different CT1 data samples (all zenith angles included). The results from a power law fit with exponential cutoff are shown (f_0 is in units of $10^{-11}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{TeV}^{-1}$).

The highest energy bin with a significant flux value in the Mkn 501 energy spectrum corresponds to the $E = 15.5$ TeV data point (see tab. 3). In order to test, whether such a flux can be faked by wrongly reconstructed low-energy events, MC simulated energy spectra with a sharp cutoff (no events with energies above E_c) have been used. For a given value of E_c (varied in steps of 0.1 TeV between 12.0 TeV and 15.9 TeV) a set of 200 individual energy spectra with a power law shape ($\alpha = 2.7$) or a power law with a cutoff ($\alpha = 2.0$ and $E_0 = 6.0$) were generated. In case one of the MC simulated energy spectra resulted in a flux ratio $fr := \frac{f_7}{f_2} > 1.5 \cdot 10^{-3}$ (f_2 and f_7 denote the differential flux in the 2nd and 7th energy bin, $1.5 \cdot 10^{-3}$ denotes the observed flux ratio from tab. 3) it was considered a fake high energy spectrum. The maximum energy with a significant γ-ray emission was then defined as the maximum energy E_c with less than 5% (corresponding to 2σ) fake high energy spectra. Note, that the MC statistics in the $E = 15.5$ TeV bin was about a factor 10 smaller compared to the real data sample. The error on the 15.5 TeV MC flux value is therefore larger compared to real data and the probability for fake high energy spectra is overestimated. The maximum energy with a significant γ-ray emission was derived as $E_c = 12.6$ TeV (pure power law) and $E_c = 13.8$ TeV (power law with cutoff at 6.0 TeV).

energy [TeV]	$\mathrm{d}F/\mathrm{d}E$ $[\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{TeV}^{-1}]$	$\sigma_{stat}\,(\mathrm{d}F/\mathrm{d}E)$ $[\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{TeV}^{-1}]$
1.21	$6.49 \cdot 10^{-11}$	$5.41 \cdot 10^{-11}$
1.84	$2.02 \cdot 10^{-11}$	$1.93 \cdot 10^{-12}$
2.61	$9.10 \cdot 10^{-12}$	$6.44 \cdot 10^{-13}$
3.92	$3.15 \cdot 10^{-12}$	$1.63 \cdot 10^{-13}$
6.63	$6.36 \cdot 10^{-13}$	$4.75 \cdot 10^{-14}$
10.03	$1.92 \cdot 10^{-13}$	$1.72 \cdot 10^{-14}$
15.08	$3.13 \cdot 10^{-14}$	$5.67 \cdot 10^{-15}$

Table 3. The time averaged differential spectrum of Mkn 501.

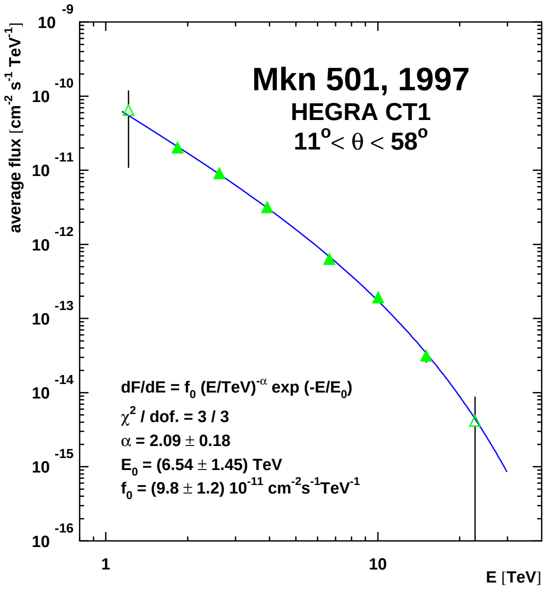

Fig. 3. Averaged Mkn 501 energy spectrum from the complete CT1 data. The results from a power law fit with exponential cutoff are shown. The first and last data point is insignificant and has not been used in the fit.

4 Conclusions

In summary, the CT1 data moon observations have proven to yield reliable energy spectra. Due to the easy applicability (no hardware modifications and only slight changes in the analysis procedure necessary, Kranich et al. 1999) this observation technique is very valuable in extending the time coverage of TeV sources. The increased time coverage is of main importance in the case of variable sources, like Mkn 501.

Excellent agreement between the spectra derived from dark night and moonshine data has been found. The combination of the data allows the rejection of the pure power law spectrum and increases the precision at energies above, say, 5 TeV. The derived energy spectrum is in good agreement with the results from other experiments. A significant γ-ray flux up to ~ 14 TeV could be detected, which is consistent with, and a confirmation of the corresponding results from the CT-system (γ-ray flux up to ~ 16 TeV, Aharonian et al. 1999). This is an important result with respect to the discussion on the DEBRA density.

It should be noted, that this is the first time, that TeV energy spectra have been derived from moon observational data.

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