The TeV spectrum of Mkn 501 as measured during the high state in 1997 by the HEGRA stereoscopic system of imaging air Čerenkov telescopes

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Abstract

The BL Lac object Mkn 501 has shown very high emission in TeV \( \gamma \)-rays from March to October, 1997. During this period the source was continuously monitored with the HEGRA stereoscopic system of 4 imaging air Čerenkov telescopes for a total exposure time of 110 hours. The unprecedented statistics of about 38,000 TeV photons, combined with the good energy resolution of \( \sim 20\% \) over the entire energy range and with detailed simulations of the detector response, allowed a determination of the average energy spectrum from 500 GeV to 24 TeV.

Although the \( \gamma \)-ray flux varied strongly with time, the daily energy spectra remained rather constant in their shape. Therefore it is justified to derive a time averaged spectrum and thus to extend, for the first time, the spectral measurement well beyond 10 TeV. This TeV spectrum of Mkn 501 shows a gradual steepening which could be caused by a number of physical processes, such as a limited energy range of the radiating particles, intrinsic \( \gamma \)-ray absorption inside the source, the Klein-Nishina effect (in the case of an inverse Compton origin of the radiation) and finally, an absorption of the TeV \( \gamma \)-rays propagating in the intergalactic medium.

1. Experiment

The VHE \( \gamma \)-ray observatory of the HEGRA collaboration consists of six imaging air Čerenkov telescopes (IACTs) located at the Roque de los Muchachos (2.2 km height) on the Canary Island of La Palma. The prototype telescope with a mirror area of 5 m\(^2\) effectively started its operation in 1992 (Mirzoyan et al., 1994) and since then has undergone several hardware upgrades (Lorenz et al., 1998). Nowadays this telescope is used as an independent instrument. The system of 4 IACTs has been taking data since 1996 (Daum et al., 1997; Aharonian et al., 1998a) and the complete system of 5 IACTs was put into operation in September, 1998. Five identical telescopes are set at the corners
and center of a quadrangular lot of 100x100 m² size. Four telescopes are separated by around 70 m from the central telescope. Observations of Mkn 501 have been performed by 4 IACTs in a system. Each of telescopes consists of a 8.5 m² reflector focusing the Čerenkov light onto a photomultiplier tube camera. The number of photomultipliers in the camera is 271, arranged in a hexagonal matrix covering a field of view with a radius of 2.3°. The angular size of one pixel is 0.25°. Any telescope camera is triggered when the signal in two next-neighbours of the 271 photomultiplier tubes exceeds a threshold of 10 (8, since June’97) photoelectrons, and the system readout starts when at least two telescopes were triggered by Čerenkov light from an air shower. Currently the array of 5 IACTs gives a cosmic ray detection rate of about 14 Hz, which is roughly 1.4 times higher than the rate for the 4 IACT system.

The IACT system detects at zenith the γ-ray air showers at impact distances as far as 250 m from the central telescope, yielding a collection area of 2·10⁹ cm². In the present analysis the collection area, as a function of energy and zenith angle, for γ-ray showers, has been inferred from detailed Monte Carlo simulations (Konopelko et al., 1998a). The energy threshold of the telescope system, defined as the energy at which the γ-ray detection rate reaches its maximum for the differential spectrum dNγ/dE ∼ E⁻².⁵, is ∼ 0.5 TeV at small zenith angles, and increases up to ∼ 2 TeV at 50° zenith angle. The sensitivity of the HEGRA IACT system was evaluated by simultaneous observations of the Crab Nebula which is a standard candle shining in TeV γ-rays at an almost constant flux level Jγ(> 1 TeV) ≃ 1.7 ± 0.5 · 10⁻¹¹ photons cm⁻² s⁻¹, as measured by the HEGRA IACT system (Konopelko et al., 1998b). The measured Crab flux is consistent within 20 % with other measurements performed by several groups using ground based imaging air Čerenkov telescopes (Weekes et al., 1997). At present, for both the online (the preanalysis routines are installed on the observation site in order to control the source activity) and the offline data analysis (the detailed analysis taking into account the complete a posteriori information about the system performance), there are two basic options: a search mode and the energy spectrum study mode. In the search mode the analysis technique reduces at most the cosmic ray events (κCR ≤ 10⁻³) using tight orientation and shape cuts still the loss of the γ-rays is of ∼ 50 %. For the second option we use a set of loose cuts in order to enrich the γ-ray statistics (κγ ≥ 90 %), even though the cosmic ray rejection is much lower (κCR ≃ 10⁻²).

Note that the stand alone system telescope shows substantially lower sensitivity, compared with the system. Thus the test observations of the Crab Nebula in 1996 with the single system telescope provided ∼ 2.7σ/hr detection and a γ-ray rate of ∼ 27γ/hr. Assuming that all 4 IACTs are operating independently, one can achieve ∼ 5.4σ/hr whereas the stereoscopic observations yield 12σ/hr, at least, using several images from an individual air shower. In addition the stereoscopic observations reduce the energy threshold from ∼800 GeV for a single telescope down to ∼ 500 GeV. Interestingly, the stereoscopic observations give after the loose cuts a γ-ray detection rate which is
almost the same as in the case of independent operation of the telescopes $R_\gamma = 106 \approx 27 \times 4 = 108 \gamma/hr$. Thus a $\gamma$-ray source of 0.25 Crab flux can be detected (at the 3$\sigma$ level) within one hour of observations. Preliminary data analysis shows that the complete array of 5 IACTs allows to reach the $14\sigma$/per hour detection of the Crab Nebula with a $\gamma$-ray rate of $\geq 120\gamma/hr$.

Earlier we have developed the analysis cuts (Daum et al., 1997) which are very strong in the background rejection, reducing the cosmic ray rate down to $\sim 1\, hr^{-1}$, though the remaining $\gamma$-ray rate was 24 $\gamma$/hr in Crab Nebular observations. These cuts are of particular interest when searching for “burst like” $\gamma$-ray signals on very short time scales.

2. Observations

In the present analysis we used only the data runs with 4 operational IACTs. For the selected runs the event detection rate varies within about 15 % the average rate at the relevant zenith angle. The mean angular Width of the cosmic ray as well as the $\gamma$-ray images in each data run deviate from the Monte Carlo predicted value by less than 6 %. Note that the distribution of the image Width (e.g., see Reynolds et al., 1993) for the $\gamma$-ray air showers is very sensitive to the improper adjustment of the telescope mirrors, the camera bending etc. The measured cosmic ray detection rate has been reproduced by the Monte Carlo simulations with an accuracy better than 10 % utilizing an advanced detector simulation routine.

Mkn 501 was observed in a wobble mode; i.e., the telescopes were pointed in Declination $\pm 0.5$ aside from the nominal Mkn 501 position (the sign of angular shift was altered from one run of 20 min to the next). This is useful for continuous monitoring of the cosmic-ray background taking the OFF-source region to be symmetric about the camera center, offset 1° from the ON-source region. This simple approach gains a factor of 2 in observation time. Observations were made from March 16 to October 1, 1997, for a total of $\sim 110$ hr of data taken at zenith angles up to 60 degrees. Note that most of the data were taken at small zenith angles up to 30 degree (observation time of $\sim 80$ hr).

3. Analysis

The stereoscopic imaging analysis of the data is based on the geometrical reconstruction of the shower arrival direction and the shower core position in the observation plane, as well as on the joint parametrization of the shape of the Čerenkov light images. The first $\gamma$-ray selection criterion used here is $\Theta^2 \leq 0.05 \, \text{deg}^2$, where $\Theta^2$ is the squared angular distance of the reconstructed shower arrival direction to the source position. This orientational cut is very loose and gives 90% $\gamma$-ray acceptance whereas the number of cosmic ray showers is reduced by a factor of about 50. Further reduction of the cut on $\Theta^2$ was not made since it introduces a strong energy dependence of the
In addition to the γ-ray acceptance, we analyzed the data using the mean scaled width parameter, \( \langle \tilde{w} \rangle \). This parameter was introduced to provide an almost constant γ-ray acceptance over the dynamic energy range of the telescope system. Thus, the second γ-ray selection criterion was \( \langle \tilde{w} \rangle \leq 1.2 \), which accepts most of the γ-ray showers (\( \sim 96\% \)) while the corresponding acceptance of cosmic ray showers is 20%.

In stereoscopic observations, the impact distance of the shower axis to a system telescope can be measured with accuracy \( \leq 10 \text{ m} \). The energy of a γ-ray shower is defined by interpolation over the “size” parameter \( S \) (total number of photoelectrons in Čerenkov light image) at the fixed impact distance \( R \), as \( E = f_{MC}(S, R, \theta) \), where \( \theta \) is the zenith angle and \( f_{MC} \) is a function obtained from Monte Carlo simulations. The rms error of the energy determination is \( \Delta E/E \sim 0.18 \). The energy distribution for the ON- and OFF-source events, after the orientation and shape image cuts, was histogramed over the energy range from 500 GeV to 30 TeV with 10 bins per decade. The γ-ray energy spectrum was obtained by subtracting ON- and OFF-histograms and dividing the resulting energy distribution by the corresponding collection area and the γ-ray acceptance.

The collection area for γ-rays rises very quickly in the energy range near the energy threshold of the telescope system, which is 500 GeV, whereas it is almost constant at the energy \( \geq 3 \text{ TeV} \). Even slight variations of the trigger threshold could lead to noticeable systematic changes in the predicted spectral behaviour in the energy range of \( \sim 0.5 - 1 \text{ TeV} \). In fact, the trigger threshold is washed away around the nominal value of 10 (8) ph.e. This effect leads to a noticeable probability for “sub-threshold” triggers. In addition, the trigger level for different camera pixels is slightly different even after very accurate adjustment of the high voltage using the calibration laser runs. Measurements of the trigger setting for a number of camera pixels revealed the variations in the trigger threshold of \( \sim 10\% \). These variations were implemented into simulations in order to estimate the corresponding systematic error of the energy spectrum at low energies, \( \leq 1 \text{ TeV} \).

The unique γ-ray statistics from the Mrk 501 allows the measurement of the energy spectrum up to a few tens of TeV. However, detection of Čerenkov light images with extremely large amplitudes - several thousands of ph.e. - is complicated by the nonlinearity in the PMT response as well as by saturation in the 8 bit Flash-ADC readout. Measurements of the photomultiplier response under the high light loading over the extended sample of the EMI 9073 PMTs provided us with a calibration function used to correct the image amplitudes. The readout of the HEGRA IACT is based on the sampling of Čerenkov light time impulse by the 16 FADC bins of \( \sim 8 \text{ ns} \) each (Hess et al., 1998). The time pulses from the air showers with a full width at half maximum of a few ns were widened using an electronic scheme in order to fit into several FADC bins for the accurate measurement of the time profile. The smoothing of the FADC signal was unfolded back to the impulse, which almost always fits 2 FADC bins. The calibrated amplitude, summed over two FADC bins, is used as a
measure of the pixel signal. For the high energy air showers the FADC signals run into saturation and the simple unfolding procedure fails. For such pulses the initial amplitude is reconstructed using the additional calibration function obtained by the simultaneous measurements of light flashes with FADCs and a 14 bit ADC. This procedure drastically extends the dynamic range of the FADC readout.

To avoid the saturation problem one might only use images detected from air showers at large impact distances from the telescope system (e.g. beyond 150 m). The size of these images is very small even for high energy events because of the low Čerenkov light density far off the shower axis. However these images are very often truncated by the camera edge and do not allow a proper reconstruction of the shower impact point and the shower energy. This effect becomes less important in observations at large zenith angles because of the high shower maximum height (the images shrink to the camera center). The increase of the impact distance limit from 200 m up to 250 m for a zenith angle of 30 degree gives an increase in the $\gamma$-rate of $\sim$20-30 % whereas it introduces large systematic errors due to the inferior energy reconstruction.

In the present analysis we applied a restriction on the shower impact distance from the central telescope of the system at 200 m. In addition we performed a large number of consistency and systematic checks. We analysed separately 2-fold and 3-fold coincidence events to reproduce the same spectral shape. The different orientation and shape cuts were used in order to check how robust the energy reconstruction procedure is. Finally the different approaches converged to the resulting energy spectrum shape.

4. Results

The Mkn 501 $\gamma$-ray flux, as averaged over the entire observation period, was about three times the Crab flux. The daily averaged $\gamma$-ray rate showed strong variations with a maximum of 10 Crab detected on 26/27 June 1997. As remarked in Aharonian et al., 1997 the hardness ratio of the steepening Mkn 501 spectrum appeared to be independent of the absolute flux. The high $\gamma$-ray detection rate provided event statistics of a few hundreds within 1 day’s observations ($\sim 3-5$ hours) which is enough for the energy spectrum evaluation in the energy range 1-10 TeV. The data analysis of the energy spectral shape on a daily basis did not reveal any substantial correlations between the $\gamma$-ray flux and the spectral behaviour (Aharonian et al., 1998b). This justified the measurement of a time-averaged energy spectrum of Mkn 501 in the high state of its activity.

The time averaged spectrum of Mkn 501 over the entire energy range from 500 GeV to 24 TeV is shown in Figure 1. The vertical error bars correspond to the statistical errors. Note that the systematic errors at energies below 1 TeV appear to be quite large, and reach $\sim$50 % at 500 GeV.

The Mkn 501 energy spectrum shows a gradual steepening over the entire energy range. The energy bin of 19-24 TeV contains an excess of $3.3\sigma$ signifi-
The energy spectrum of Mkn 501 (preliminary) as measured by the HEGRA IACT array (filled circles). The combined power law plus exponent fit of the HEGRA data is shown by dotted-dashed curve. The Mkn 501 spectrum measured by the Whipple group (open circles) is taken from Samuelson et al, 1998.

The steep energy spectrum plus 20 \% energy resolution still allow these 23 \( \gamma \)-rays to be spilled out from lower energy bins. Therefore the energy spectrum is consistent with the hypothesis of a maximum energy for the detected \( \gamma \)-rays of 18.5 TeV at the 2\( \sigma \) confidence level. The shape of the energy spectrum is well determined by a power law fit with an exponential cutoff. A fit of the data over the energy region where the systematic errors are small, i.e. from 1.25 TeV to 24 TeV, gives

\[
dN/dE = 9.7 \pm 0.3 \text{ (stat)} \pm 2.0 \text{ (syst)} \cdot 10^{-11} E^{-1.9 \pm 0.05 \text{(stat)} \pm 0.05 \text{(syst)}} \nonumber \exp \left[ -E/(5.7 \pm 1.1 \text{(stat)} \pm 0.6 \text{(syst)} \text{TeV}) \right] \text{[cm}^{-2}\text{s}^{-1}\text{TeV}^{-1}] . \quad (1)
\]

The logarithmic slope of the energy spectrum (“power law index”) is 1.8 $$\pm$$ 0.14$$\pm$$0.82 in the energy range 1.25-5.0 TeV, and 3.7$$\pm$$0.33$$\pm$$0.6 above 5 TeV.

5. Discussion

Detection of TeV \( \gamma \)-rays from Mkn 501 leads to the conclusion that they are produced within the relativistic jet. If not, the \( \gamma \)-rays will be absorbed inside the source due to the \( \gamma \)-\( \gamma \) interactions with the soft radiation field. This constrains the Doppler factor of the jet \( \delta \geq 10 \). Assuming that the observed spectrum of Mkn 501 is a power law modified by the source internal \( \gamma \)-\( \gamma \) ab-
sorption, one can get more accurate determination of the Doppler factor of the jet $\delta \simeq 8.5$. However, since there is a number of reasons for the steepening of the TeV spectrum, this estimate can only be considered as a lower limit on the Doppler factor of the relativistic jet.

The curvature of Mkn 501 energy spectrum could occur due to a several physics processes related to the blazar mechanism of the VHE $\gamma$-ray emission, e.g., the exponential cutoff in the spectrum of accelerated particles, as well as the energy spectrum modifications caused by $\gamma$-ray propagation in the intergalactic medium. Thus the extragalactic background light attenuate the intrinsic blazar $\gamma$-ray energy spectrum substantially at the high energy end via the pair-production interactions of the $\gamma$-rays with the diffuse background photons. The extension of Mkn 501 spectrum beyond 10 TeV gives a strong upper limit on the intergalactic IR field in a region between 2 and $\sim 40 \mu$m as $\nu F(\nu) \sim 4$ nWm$^{-2}$sr$^{-1}$ and corresponding optical depth at 18 TeV, $\tau \leq 3$. Since this upper limit is rather close to the current theoretical as well as phenomenological estimates of the intergalactic radiation field, it would be even possible to derive the absolute fluxes based on the TeV energy spectrum. However the current uncertainties in the spectral energy distribution of the intergalactic radiation does not allow us to reconstruct definitely the intrinsic energy spectrum of Mkn 501.

We believe that the real progress in understanding of the TeV $\gamma$-ray emission can be achieved by the correlated spectral and temporal studies of the BL Lac objects in the X-ray and TeV $\gamma$-rays obtained during the multiwavelength campaigns as well as by the future detections of the blazars at the different states of activity, and at the different distances up to several hundreds Mpc.

Acknowledgements

The support of the German Ministery for Research and Technology BMBF and of the Spanish Research Council CICYT is gratefully acknowledged. We thank the Instituto de Astrofísica de Canarias for the use of the site and providing excellent working conditions. We gratefully acknowledge the technical support staff of Heidelberg, Kiel, Munich, and Yerevan.

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