The Energy Spectrum of TeV Gamma-Rays from the Crab Nebula

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Abstract

The imaging atmospheric Čerenkov technique has been successfully used for observations of the Crab Nebula in the TeV energy range. However the Crab Nebula energy spectra, measured by several groups, still differ noticeably in power-law index as well as in absolute γ-ray flux. The HEGRA stereoscopic system of 5 imaging atmospheric Čerenkov telescopes has been used for long-term observations of the Crab Nebula in 97/98 and 98/99, for a total of about 200 hrs at small ($\leq 30^\circ$) zenith angles and 50 hrs at large ($\sim 60^\circ$) zenith angles. The good energy resolution of 18%, the wide dynamic range from 500 GeV to 20 TeV, and the ability for systematic studies using several images for an individual shower, resulted in a very accurate measurement of the spectrum. We present the results of the analysis, using an advanced technique of energy spectrum evaluation, recently developed by the HEGRA group.

1 Introduction

The Crab Nebula is the standard candle of TeV γ-ray emission. Since the time when it was detected by the Whipple group (Weekes et al., 1989) a number of observations of the Crab Nebula have been made at TeV energies (for review see Weekes et al., 1997). The significant improvements in the telescopes themselves as well as in the analysis of data recently provided measurements of the Crab Nebula energy spectrum over the range from 200 GeV up to 50 TeV using the ground based imaging air Čerenkov telescopes. The calibration of individual imaging air Čerenkov telescopes is difficult because there is no "test" beam of TeV γ-rays. Different methods of telescope calibration have been developed in order to reduce systematic errors which could influence the estimate of the absolute γ-ray flux and the slope of energy spectrum. The latest measurements of the Crab Nebula energy spectrum by the Whipple, CANGAROO, CAT, and HEGRA groups agree within 50% uncertainty on the absolute scale and within an uncertainty of 0.1 in the index of the energy spectrum. To improve the agreement, additional measurements are needed, particularly in the energy range within which there are a number of independent measurements. The HEGRA IACT system provides data in a very broad energy range, from 500 GeV up to 20 TeV.

The current understanding of the mechanisms of the TeV γ-ray emission is not complete, indeed. The SSC scenarios of the photon emission are widely believed as most appropriate for the Crab Nebula, even though one can not exclude the possible contribution of the γ-ray fluxes induced by π° decay. However, only the precise spectral measurements could constrain the choice of the model parameters.

2 Observational data

The Crab Nebula was extensively observed with the HEGRA IACT system in two observational seasons from 1997 September to 1998 March and from October 1998 to March 1999. The analysis of the data taken in the 1997/1998 period was summarized by Konopelko et al., 1998. In the 1998/1999 observational period, we carried out the observations at large zenith angles (LZA) ($\sim 60^\circ$) in order to study the performance of the telescope system at LZA and to extend the measurements of the Crab Nebula energy spectrum far beyond 10 TeV. Here we present mainly the results of the data analysis for the 1998/1999 observational season. Since September 1998, the HEGRA collaboration has operated a stereoscopic system of 5 IACTs. For technical reasons one telescope was not operational in October – November 1998, and the observations were made with a four telescope system. The observation schedule is summarized in Table 1.

Only data taken with good weather conditions was used in the analysis. We tested the data quality using several methods (for details see OG.2.1.38) to eliminate the data runs with hardware problems, inaccurate pointing,

Table 1: Summary of the exposure time (hrs) for the 1998/1999 Crab Nebula observation campaign.

	Zenith angle range			
Setup:	$0° \div 25°$	$25° \div 40°$	$40° \div 50°$	$50° \div 65°$
CT 2-6	17.0	2.70	6.46	9.01
CT 3-6	7.29	11.34	7.55	5.43
Total	24.3	14.04	14.0	14.4

low trigger rate etc. The relevant Monte Carlo simulations have been optimized for the two system configurations mentioned above. The energy spectra derived for the two configurations have been used in the overall spectrum.

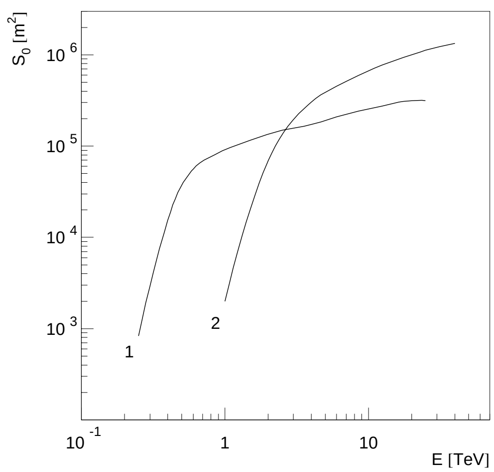

Figure 1: The effective collection area of γ-ray induced air showers for the HEGRA IACT system for observations at small (20°) (curve 1) and large zenith angles (60°) (curve 2).

3 Analysis

For each individual shower *stereoscopic* observations permit the determination of the position of the shower axis in the observation plane, the arrival direction of the shower, and the angular size of the Čerenkov light image from the shower averaged over the triggered telescopes. At first, we selected only air showers within a certain impact distance R_0 from the center of the telescope system. We used the limiting upper radius of $\mathrm{R}_0 = 200\,\mathrm{m}$ for zenith angles less than 50 degrees and a significantly larger radius of 700 m for the large zenith angle observations. As discussed in Konopelko et al., 1999, the effective collection area in observations at LZA dramatically increases at high energies, far beyond the limiting radius of 200 m (see Figure 1). For the data taken at zenith angles up to $50°$ we applied an orientation cut $\theta^2 < 0.05\,[\mathrm{deg}^2]$ and an image shape cut $< \tilde{w} >< 1.2$ (θ^2 is the squared angular distance of the reconstructed source position from the true source position. $< \tilde{w} >$ is the so called *mean scaled Width* parameter). We found this set of the cuts to be optimal for the spectrum studies (e.g., see Aharonian et al., 1999). These loose analysis cuts mentioned above provide Crab Nebula γ-ray rate of 83 γs/hr at SMZ (less that $25°$) for the 5 IACT system. The corresponding energy threshold of the γ-rays is about 500 GeV. For the LZA data we used the looser orientation cut of $\theta^2 < 0.1\,[\mathrm{deg}^2]$ because of the low accuracy of the arrival direction reconstruction for the γ-ray showers. In order to improve the cosmic ray rejection in observations at LZA we introduced an additional parameter, *mean scaled Length*,

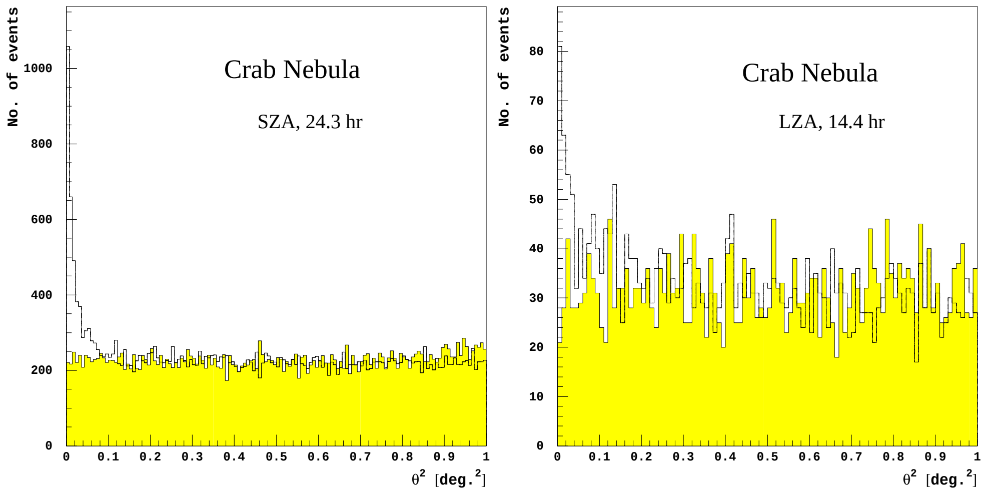

Figure 2: The event distribution as a function of θ^2 parameter for the ON and OFF (shaded histogram) regions for Crab Nebula observations at small and large zenith angles.

$<\tilde{l}>$, defined by analogy with $<\tilde{w}>$ (see Konopelko et al., 1999). The two parameters, $<\tilde{w}>$ and $<\tilde{l}>$, can be used for calculating a Mahalanobis distance, MD (see Mahalanobis, 1963), in two-dimensional space as

$$\mathrm{MD} = ((1-<\tilde{\mathrm{w}}>)^2/\sigma^2_{<\tilde{\mathrm{w}}>} + (1-<\tilde{\mathrm{l}}>)^2/\sigma^2_{<\tilde{\mathrm{l}}>})^{1/2} \quad (1)$$

where $\sigma_{<\tilde{w}>}$ and $\sigma_{<\tilde{l}>}$ are the standard deviations for the corresponding distributions of $<\tilde{w}>$ and $<\tilde{l}>$. We found that the optimum value of the MD cut for LZA is 1.5. Note that this analysis improves the enhancement factor by $\simeq 30\%$ (it gives $\sim 50\%$ acceptance of γ-rays) in observations at large zenith angles, whereas it gives only marginal improvement for the data taken at SZA. The Crab Nebula γ-ray rate in observations at LZA (60°) is about 16 γ's/hr with a corresponding energy threshold of $\sim$5 TeV. Note that SZA observations give a γ-ray rate at high energies (above 3 TeV) of $\sim 8\,\gamma$s/hr.

4 Energy spectrum evaluation

We discussed the procedure for the evaluation of the energy spectrum using the *stereoscopic observations* in Aharonian et al., 1997; Hofmann, 1997 and recently in Aharonian et al., 1999. The reconstruction of the energy of γ-ray air showers is based on the image intensity (*Size*) at a given distance from the shower axis. This relationship is tabulated based on the Monte Carlo simulations, with the zenith angle of the shower as an additional parameter. In the present Crab Nebula analysis we have extended the energy spectrum measurements up to LZA. The data were processed independently for each of four zenith angle bins as defined in Table 1. The corresponding effective collection areas as well as the cut efficiencies were calculated as a function of the zenith angle. First, we derived the energy spectra for all bins independently. The spectra evaluated at different zenith angles are in a good agreement. The energy threshold of the detected γ-rays increases noticeably with increasing zenith angle (for details see Konopelko et al., 1999). For the final energy spectrum we joined the different zenith angle bins according to

$$dN^i_\gamma/dE = \sum_{j=1}^{4} w_j (dN^i_\gamma/dE)_j H(E^i - E^j_{th}),\ w_j = t_j/t_0,\ i = 1,n; H = (0, E^i < E^j_{th}; 1, E^i > E^j_{th}) \quad (2)$$

where dN^i_γ/dE, $(dN^i_\gamma)_j/dE$ are the differential energy spectra at energy E^i as measured over all zenith angle range and for the particular zenith angle bin (j), respectively. E_{th} is an estimated energy threshold for the zenith angle bin j. t_j is the observation time for j bin on the zenith angle, and t_0 is the total observation time.

5 Results

We have observed the Crab Nebula extensively in two observational seasons with the HEGRA IACT system. The differential energy spectrum of the Crab Nebula has been derived from the HEGRA data for both observational campaigns using recently developed advanced techniques for the measurements of the spectrum using *stereoscopic data*. The analysis for the different system configurations as well as, for different trigger threshold values give the resulting spectrum

$$\mathrm{dJ_\gamma/dE} = (2.7 \pm 0.2 \pm 0.8) \cdot 10^{-7} (\frac{\mathrm{E}}{1\,\mathrm{TeV}})^{-2.60 \pm 0.05 \pm 0.05} \mathrm{ph\, m^{-2}\, s^{-1}\, TeV^{-1}} \quad (3)$$

as measured at zenith angles up to 60°. The statistical and sytematic errors are also given. Based on the Monte

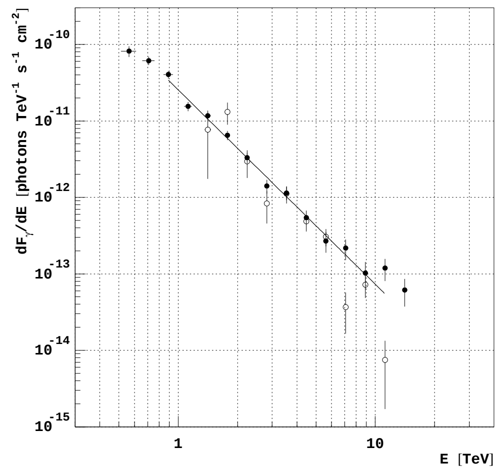

Figure 3: The Crab Nebula energy as measured by the HEGRA system (data are preliminary) during the observation period 1998 October – November. The filled circles are for the observations at zenith angles up to 50°, the open circles are for the LZA data (60°) (no normalization applied).

Carlo simulations for the γ-ray induced and cosmic ray induced air showers at large zenith angles (up to 60°), we have developed a specific analysis technique to be used for such data. The Crab Nebula differential energy spectrum derived from small zenith angle data matches quite well the spectrum derived at large zenith angles. The γ-ray rate measured at energies above 10 TeV in observations at large zenith angles exceeds the corresponding rate measured at small zenith angles. Our Crab Nebula spectrum is best fitted by a pure power law and shows no evidence for the curvature as expected from the SSC based modeling. To assess the contribution of π^0-produced γ-rays, measurements of the energy spectrum above 30 TeV are necessary based on large zenith angle observations.

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