Observations of the Crab nebula with H.E.S.S.

C. Masterson*, W. Benbow*, S. Funk*, and S. Gillessen*
for the H.E.S.S. collaboration

*Max-Planck-Institut für Kernphysik, P.O. Box 103980, D 69029 Heidelberg, Germany

Abstract. The Crab nebula was observed with the H.E.S.S. stereoscopic Cherenkov telescope system in 2003, using three of the four telescopes. The data, taken at large zenith angles, show a clear signal with a significance close to 50 standard deviations and serve to verify the performance and calibration of the instrument. The energy spectrum of γ-ray emission from the Crab nebula is measured and is found to follow a straight power law, given by $dN/dE = 3.3E^{-2.57}cm^{-2}TeV^{-1}s^{-1}$, with a threshold energy of 350 GeV. A measurement of the exact position of the TeV emission is made.

INTRODUCTION

The Crab pulsar, with a rotational period of 33 ms and a spin-down luminosity $L = 5 \times 10^{38}$ erg/second, powers a surrounding synchrotron nebula which has been detected in radio and X-rays. The total energy available is of the order 10^{49} erg and thought to be the power source for production of very high energy (VHE) γ-rays. The rotational energy of the pulsar is believed to be mostly carried away by a relativistic wind of electrons and positrons. The interaction of this wind with the surrounding medium creates a relativistic shock wave, where the leptons are thought to be accelerated to high energies [2]. The lepton acceleration could be alternatively due to driven reconnection of the alternating magnetic field at the pulsar wind termination shock [7]. The interaction of accelerated leptons with ambient photon fields (e.g. the CMB, the local IR photons) can produce VHE γ-rays via the Inverse Compton process. The Crab nebula was discovered at TeV energies in 1989 [13] and is conventionally used as a standard reference source of TeV γ-rays, due to its relative stability and high flux.

The H.E.S.S. array of imaging air Cherenkov telescopes is situated in the Khomas highland of Namibia, at an elevation of 1800 metres above sea level. The four telescopes are placed in a square formation with a side length of 120 metres. The telescopes are of steel construction, with a reflective surface of diameter 13 metres, composed of 382 individual round mirrors, each of 60 cm in diameter. This gives an effective mirror surface area of 107m^2. The H.E.S.S. cameras each consist of a hexagonal array of 960 photo-multiplier tubes (PMTs), where each tube covers an area of 0.16° in diameter projected onto the sky [11]. The total field of view on the sky is 5°.

The experiment commenced operations on-site in Namibia in June, 2002, with the first of four Cherenkov telescopes, two more telescopes were installed in January and September of 2003 and the array was completed with the fourth telescope in January 2004.

Observations were made of the Crab nebula in October of 2003, during the construction phase of the experiment, with the three available H.E.S.S. telescopes. In total 3.4 hours of observation were selected for this analysis, corresponding to a livetime on source of 2.7 hours. The selection criteria reject data taken in bad weather conditions and during periods of unstable detector operation. The trigger rate for this data was 250 Hz with a system deadtime of 10%.

Calibration and analysis

In order to calibrate the H.E.S.S. telescopes, gain measurements are regularly made using independent light sources, including an LED system mounted on the dish of each telescope. An average gain for each channel is calculated for each observing period. The signal pedestal level is calculated periodically during a run using normal events, after rejection of pixels containing any Cherenkov signal. The equivalent flatfielded photoelectron intensity is then calculated using the high or low gain channel as appropriate. The full calibration chain for H.E.S.S. is described in [3].

In order to reject the overwhelming background of hadronic showers, two level image cleaning is used to remove pixels containing only background noise from each image and the image is then characterised using Hillas parameters. The source direction and shower impact point are calculated using standard geometric reconstruction. Mean reduced scaled width (MRSW) and length (MRSL) are calculated for each event by comparing the width and length of each telescope image with that expected for a given intensity and impact parameter. The average over the triggered telescopes is then used for cosmic ray background rejection. Analysis of H.E.S.S. data is covered in more detail in [6] and [4].

The ON signal for a given point in the sky is determined by integrating the raw sky map within a circle around that location with radius optimised to maximise the significance of the signal. The background level is determined using ring surrounding each position in sky map [10]. The ring radius is chosen to have a ratio of OFF/ON area of approximately 7. The normalisation for each bin is weighted by the radial γ-ray acceptance in the camera. Using this method gives a better determination of the background in the ON region that the simple method, and gives a significance level of 52.5σ or $30\sigma/\sqrt{hour}$ for this dataset. The corresponding rate is $6.4 \pm 0.1\,\gamma\mathrm{min}^{-1}$. The measured excess rate and the significance are in agreement with that expected from Monte Carlo simulations. The distribution of θ^2 (where θ is the angular distance of the reconstructed arrival directions of a γ-ray event relative to the position of the Crab nebula) is shown in figure 1. It shows a clear excess corresponding to the direction of the source.

Energy spectrum reconstruction

In order to reconstruct the energy spectrum of the incident γ-ray flux, the energy of each event is estimated using a lookup table as a function of image intensity and impact parameter, the average estimated energy over the triggered telescopes is then

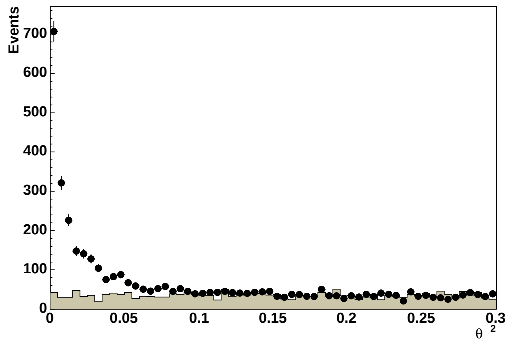

FIGURE 1. θ^2 plot of the distribution of the signal from the Crab nebula, where θ is the distance of the reconstructed γ-ray arrival direction for each selected event from the direction of the Crab nebula. The filled histogram corresponds to the estimated background level.

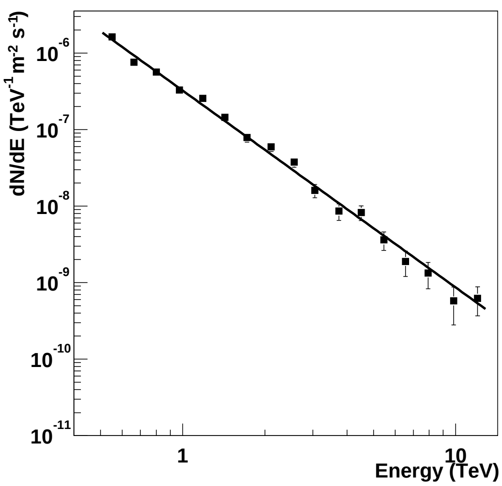

FIGURE 2. Reconstructed energy spectrum of γ-ray photons from the direction of the Crab nebula, with statistical error bars.

taken. The average energy resolution in the range used for spectral studies is 15%. The energy spectrum is reconstructed using events passing standard cuts, the effective areas are estimated from Monte Carlo simulations as a function of energy, zenith angle and source position in the field of view. The reconstructed energy spectrum for these observations is well fitted by a straight power law from 500 GeV to 15 TeV, given by $dN/dE = 3.3 \pm 0.11 \times 10^{-11} E^{-2.57 \pm 0.05} cm^{-2} s^{-1} TeV^{-1}$. The statistical errors are only given here, the systematic erors are discussed further in [4]. A plot of the energy spectral distribution is shown in figure 2. The flux and spectral slope agree well with previous measurements, e.g. [5, 8, 9].

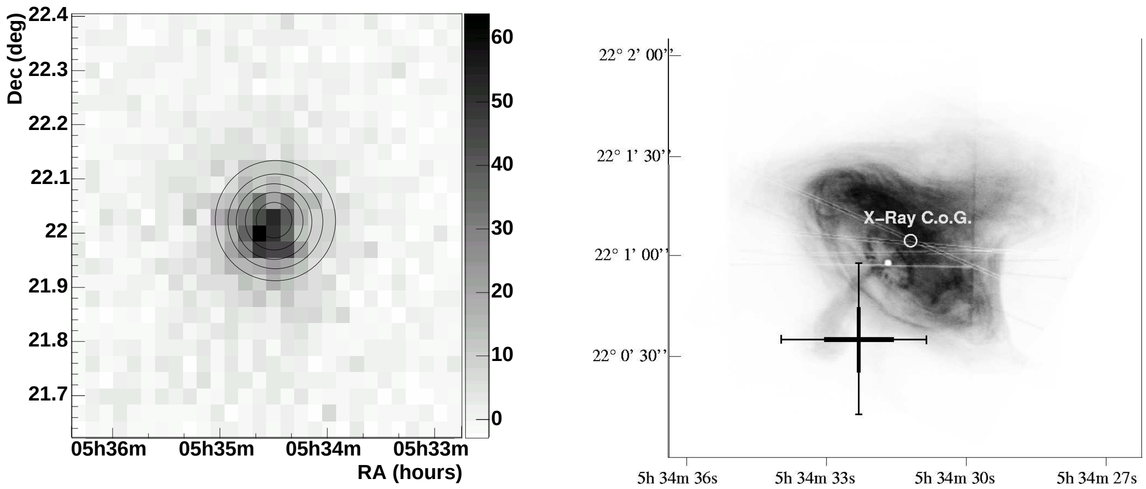

FIGURE 3. *Left* Fit of a two-dimensional Gaussian distribution to the excess from the Crab nebula. *Right* Position of the centre of gravity of the TeV emission. The statistical errors are indicated by the thick cross and the systematic errors by the thin cross.

Position reconstruction

In order to study the precise position and extent of the TeV emission from the nebula surrounding the Crab pulsar, we constructed an uncorrelated map of the γ-ray excess from the sky in the region of the Crab. A two dimensional Gaussian distribution was then fit to the image, and the mean position of the excess was measured to be coincident with the Crab nebula. The two dimensional sky-map is shown in figure 3 (left) and the fitted position is RA 5h34m32.3s, Dec. 22d0'35" (J2000). The statistical error on this fit is 10 arcseconds.

This position is compared to the X-ray observations of the nebula from the Chandra satellite in figure 3 (right), and the extent of the statistical and systematic errors are shown. It can be seen that the position is consistent with the centre of the observed X-ray emission [12].

CONCLUSIONS

A strong signal has been detected from the Crab nebula during the construction phase H.E.S.S. Instrument, with a significance of 52.5σ and an excess of over 1000 events in under 3 hours of observation time, the excess seen is compatible with that expected from Monte Carlo simulations. A preliminary spectrum has been measured, with a differential slope of -2.60. The flux normalisation and spectral slope are consistent with measurements from other instruments. The position of the source can be reconstructed to a precision of 20 arcminutes, and is consistent with a point source. This position may be improved with further observations, using the complete H.E.S.S. array.

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