THE HEGRA IMAGING ATMOSPHERIC CHERENKOV TELESCOPES: STATUS AND OBSERVATIONS

GERMAN HERMANN
Max–Planck–Institut für Kernphysik Heidelberg
Postfach 103980, 69029 Heidelberg, Germany

The HEGRA–Collaboration is installing a system of five Imaging Atmospheric Cherenkov Telescopes, dedicated to the search of sources of γ–rays at energies above 500 GeV. The system has been specially designed for coincident operation of the telescopes to fully exploit the advantages of stereoscopic observations. Since December 1996 four of the five system telescopes are operational. From first observations on the Crab–Nebula, conclusions on the power of the telescope system can be deduced: an angular resolution of better than 0.1^o and improved hadron suppression result in a flux sensitivity of better than $0.8{\cdot}10^{-13}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for pointlike sources at energies above 1 TeV. Besides the system telescopes two prototype telescopes are in operation in the single telescope mode since several years. With these telescopes TeV–γ–rays from the two nearby BL Lac objects Markarian 421 (z=0.03) and Markarian 501 (z=0.034) could be detected.

1 Overview

The HEGRA–Experiment is located on the Canary Island La Palma (28.8^o N, 17.9^oW) at a height of about 2200 m asl. The experiment consists of an array of szintillator counters and Geiger towers for the direct measurement of particles in air showers and of an array of integrating cherenkov counters. With these three arrays the search for γ–ray emission above 20 TeV and measurements on the composition of the cosmic radiation are continued.
In addition an array of 6 Imaging Atmospheric Cherenkov Telescopes (IACTs) has been built, dedicated to the search for sources of TeV–γ–rays. In this energy range two classes of sources are at present of special interest:

- Supernova remnants (SNR) are assumed to be responsible for the acceleration of the bulk of galactic cosmic rays. If this is true they should be observable first of all in the TeV

energy range. Especially SNR expanding into a dense surrounding medium should be detectable with present or next generation ground based instruments. Since the region of emission is expected to be extended, detectors need to have a sufficiently large field of view for a successful detection and a good angular resolution to resolve its structure.
Up to now no SNR could be observed in the TeV energy range.

- Active Galactic Nuclei (AGN) have been proven to be emitters of TeV–γ–rays[5 6 7]. Besides the question on the acceleration mechanisms in AGNs these sources are of special interest, because γ–rays from extragalactic sources are absorbed by the IR background photon field due to photon-photon pair production processes. The strength of the absorption strongly depends on the density of the IR background photon field. By the measurement of cutoffs in the observed spectra of AGNs an independent determination of the IR background would be possible. In order to detect these cutoffs the instrument needs excellent spectroscopic capabilities.

The experimental technique which is applied by the HEGRA–Experiment to observe these sources is based on stereoscopic observations of air showers with several IACTs simultaneously. It combines an excellent angular resolution with a very good energy resolution for spectroscopic measurements. The telescope system in its final stage will consist of five identical telescopes arranged on the corners and in the center of a square with a side length of $\approx$ 105 m . The telescopes (fig. 1) have an alt–azimuthal mount with a mirror area of 8.5 m^2 and a focal length of about 5 m. The cameras contain 271 pixels with a size of 0.24^o, which form an overall field of view[a] of 4.3^o. Since December 1996 four of the five system telescopes are operational.

Figure 1: Photograph of the central telescopes of the HEGRA IACT system.

In addition to the telescopes of the system two prototype telescopes are taking data since several years. The (historically called) CT1 [1] started operation in 1992. It has an equatorial mount with a segmented mirror of 5 m^2 area. Since beginning of 1995 this telescope is equipped with a 127 pixel camera. The so–called CT2 is operational since beginning of 1994. It is build on an alt–azimuthal mount, similar to that of the system telescopes. The camera consists of 61 pixels with 0.43^o diameter each. After a renewal of the mirror dish in 1997, this telescope will be equipped with the new high resolution camera to complete the telescope system.
In the following results of observations with the two prototype telescopes and the first system

[a]The actual field of view is hexagonal; given here is the diameter of a circle with the equivalent area

telescope are summarized. Then the principle of stereoscopic observations is described and first measurements on the performance of the telescope system are presented.

2 Observations with the Prototype Telescopes

2.1 Analysis Procedure and Sensitivities

The analysis procedure applied for HEGRA single telescope observations follows the 'standard' second moment analysis. Herein the light distribution generated by air showers in the focal plane of an IACT is described by an elliptical intensity distribution. Since the shapes of the images are indicate the type of the primary particle it is possible to enrich γ–like showers and to suppress hadronic background by selecting events in a given parameter space. The optimum cuts for the event selection are derived by Monte Carlo simulations. With these cuts hadron showers are typically suppressed by a factor of about 20 while 60 % of γ–showers are maintained, corresponding to a Q–factor of about 2.7. For pointlike sources additional improvement of the sensitivity of telescopes can be achieved: the main axis of the ellipses points towards the direction of the shower and thus towards the source position. The orientation of background images, however, is randomly distributed. As an example figure 2 shows the distribution of

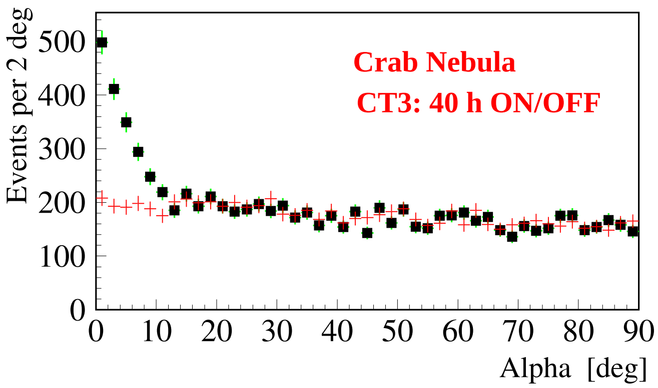

Figure 2: Distribution of the orientation angle Alpha of the images for 40 hours of ON–source (squares) and OFF–source (crosses) observation after application of the hadron suppression by the shape of the images.

the orientation angle Alpha as obtained from observations of the Crab–Nebula with the first system telescope (CT3) after application of shape selection criteria. (This telescope was run as stand alone detector after its comissioning until the second system telescope started operation). While the Alpha distribution for the OFF–source observation is flat, a significant increase of the counting rate appears at small Alpha values for the ON–source observation. In this case the number of excess events with small $\alpha < 8^o$ amounts to 800 with a statistical significance of 14.5 σ .

Given a signal from a source the calculation of the flux follows in two steps. First the index of the spectrum is estimated under the assumption of a power law spectrum of the primaries. The procedure compares the differential image size distribution of the signal with Monte Carlo simulations for different assumed spectral indices of the primary spectrum. The spectral index of the primary is then derived from the minimum deviation between the measured and the simulated size distribution. In the second step, again by Monte Carlo simulations, the expected count rate for a 'standard' source with the given spectral index and an assumed norm flux is calculated, including the trigger and selection efficiencies [2]. The flux of the source is then calculated from the ratio of the measured count rate and the expected rate for the norm flux.

The sensitivity of an instrument, defined as the minimum observable flux within a given time, can be derived in a similar way from Monte Carlo simulations. Table 1 summarizes some principle

Table 1: Operational parameters of the prototype telescopes and of the first system telescope in standalone mode. The γ–detection rates Γ_γ and the relative sensitivites $\sigma/\sqrt{h}$ refer to measurements of the Crab Nebula.

CT	Operational since	E_{thr} (TeV)	$\Gamma_\gamma [h^{-1}]$	$\sigma/\sqrt{h}$	Φ_{min}(E>1 TeV)$[cm^{-2}s^{-1}]$
1	08/92	1.5	8	1.5	$6 \cdot 10^{-12}$
2	01/94	1.0	14	1.1	$8 \cdot 10^{-12}$
3	09/95	<0.8	23	2.3	$4 \cdot 10^{-12}$

numbers concerning the physics performance of the prototype telescopes and of the first system telescope in standalone mode. The γ–detection rates Γ_γ and the relative sensitivites $\sigma/\sqrt{h}$ refer to measurements of the Crab–Nebula. The minimum detectable flux Φ_{min} is extrapolated from the Crab measurements, assuming 50 hours of ON/OFF observation time and demanding a statistical significance of 5 σ. For the extrapolation a Crab Flux of $1.2{\cdot}10^{-11}s^{-1}cm^{-2}$ was taken, which is the average of two recent HEGRA measurements[3,4].

2.2 Results of Mrk421 Data Analysis

The BL Lac object Markarian 421 (Mrk421) has been discovered as emitter of TeV–γ–rays by the Whipple group [5] in 1992. It was the first extragalactic object which could be observed in the TeV light.

The HEGRA experiment observed this object with its two prototype telescopes CT1 and CT2 from December 1994 to May 1995 [4] . During this periode an ON–source time of about 26 hours (CT1) and 41 hours (CT2) could be accumulated in the ON/OFF observation mode at zenith angles less than 25°. After hadron suppression an excess of 111 and 218 γ–candidates could be detected with a statistical significance of 4.0 σ and 4.2 σ, respectively. Since only a small fraction of the excess events has been observed by both telescopes simultaneously the combined statistical significance can be calculated to about 5.8 σ.

Contemporary observations of the Crab Nebula give the indication that the spectrum of Mrk421 is steeper at energies above 1 TeV than that of the Crab Nebula. From the Monte Carlo analysis, as described above, follows a differential spectral index α=3.6$\pm$1. However, due to the large error on α no further conclusions on the spectral characteristics of the source are possible.

Given this spectral index the average integral flux is calculated to be

$$\Phi\,(E > 1TeV) = 8 \pm 2_{stat} \left(\begin{array}{c} +6 \\ -3 \end{array} \right)_{Sys} \cdot 10^{-12} s^{-1} cm^{-2},$$

which is lower by a factor of 2.0 $\pm$ 0.8 than that of the Crab Nebula.

As it is known from the Whipple measurements, Mrk421 is a highly variable source. However during the observation time of the HEGRA telescopes no flare could be observed.

2.3 Results of Mrk501 Data Analysis

The BL Lac object Markarian 501 (Mrk501) has been discovered as an emitter of TeV–γ–rays by the Whipple group [6] in 1995. It is the second extragalactic object of which γ–ray emission could be detected.

The HEGRA–collaboration allocated an essential part of observation time with the first prototype telescope (CT1) on this source in 1996 [7]. Between March and August 147 hours of data could be accumulated at zenith angles between 11° and 25°. In order to obtain maximum exposure time Mrk501 was observed in tracking mode. For the determination of the background

distributions, OFF–source observations were performed during and after the Mrk501 observation period. About 86 hours of background data at zenith angles between 5^o and 25^o have been evaluated.
The Alpha distribution of Mrk501 shows after hadron suppression an excess of 351 events over 974$\pm$57 expected background events. This corresponds to a statistical significance of 5.2 σ. Given this signal the average flux of Mrk501 during this observaton periode could be deter-

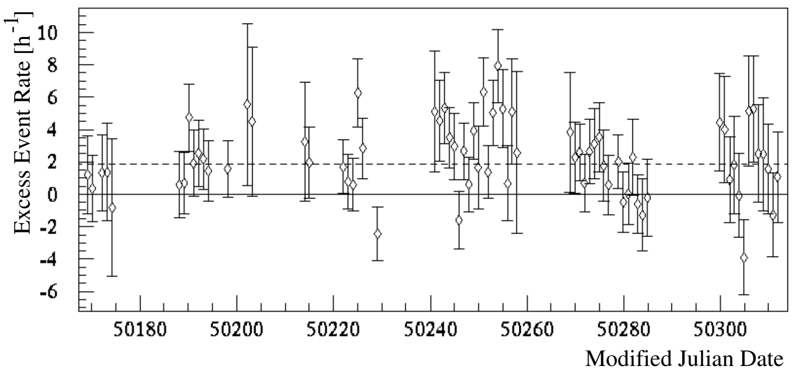

Figure 3: Daily rate of excess events from Mrk501 for nights with more than 20 minutes of observation time.

mined to be

$$\Phi\left(E > 1.5TeV\right) = 2.3 \pm 0.4_{stat} \left(\begin{array}{c} +1.5 \\ -0.6 \end{array}\right)_{Sys} \cdot 10^{-12} s^{-1} cm^{-2},$$

which is about 30 % of the Crab flux.
The shape of the spectrum of Mrk501 does not show significant deviations from that of the Crab Nebula. The numerical analysis gives a power law index of α=2.6$\pm$0.5 .
The search for possible variability of the source during that observations gives a negative result. Figure 3 shows the daily excess rate for nights with more than 20 minutes observation time. Within the statistical limitations the counting rate was constant through the whole periode.

3 Stereoscopic Observation with the HEGRA IACT System

3.1 The Principle of Stereoscopic Observations

A significant improvement of the IACT technique is expected by stereoscopic observations of air showers with several telescopes simultaneously. Two or more images of an air shower allow a complete 3–dimensional reconstruction of air showers on an event by event basis [11] [8]. Figure 4 illustrates the geometrical reconstruction of the shower direction. The image of the source has to lie on the symmetry axis of the shower images. Thus the images are projected into a common camera coordinate system and the shower direction is calculated from the intersection point of the axis. Similarly the location of the shower core is derived by intersecting the image axis emerging from the telescope positions. In addition to the shower direction, the core location and the height of the shower maximum can be measured.
In comparison to observations with single telescopes, the stereoscopic approach, as followed with the HEGRA–IACT system, promises different advantages:

- By triggering on at least 2 telescopes in coincidence, background triggers generated by light of the night sky or by local muons are strongly suppressed. Consequently it is possible to lower the trigger threshold of the telescopes and to significantly reduce the energy threshold of the system.

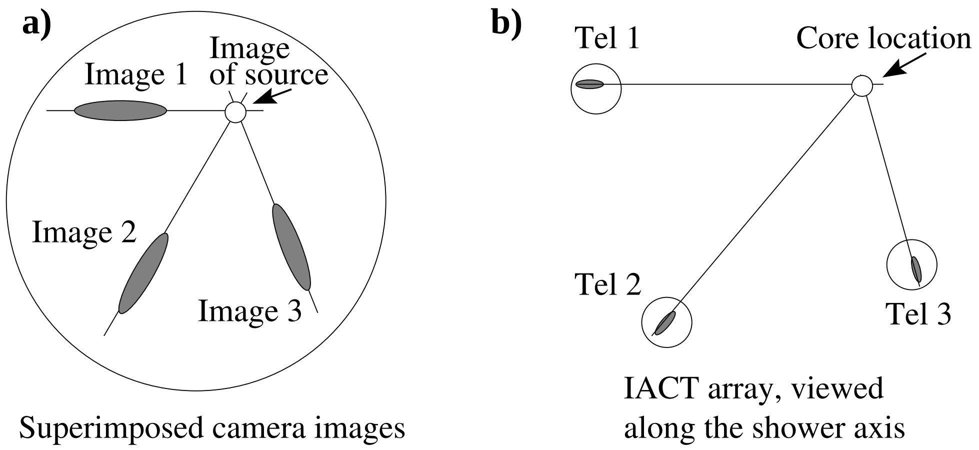

Figure 4: Principle of the geometrical reconstruction of the shower direction a) and the core location b) with a system of IACTs.

- Stereoscopic measurements allow an unambiguous reconstruction the shower direction and location. The expected resolution for the HEGRA–IACT system amounts to 0.1^o and 10–15 m, respectively.
- The knowledge of the core position allows to relate the light yield in the telescopes to the energy of the primary. This results in an energy resolution of about 20 %.
- With the knowledge of the shower energy and the core location it will be possible to apply energy– and distance–dependent cuts on the image shape, resulting in an improved hadron suppression and an enhanced sensitivity.

3.2 Operation of the HEGRA–IACT System

The HEGRA–IACT system has been specially designed for stereoscopic observations. Most parts of the trigger and readout electronics have been newly developed. While a detailed description of the telescopes and their electronics can be found in [9 10], only a brief overview is given here.
The digitization of the camera signals is done with a custom–designed 120 MHz FADC–system. The FADCs provide a ring buffer for the digitized signals with a depth of 34 μsec. This time is ample to wait for a system wide trigger decision. At present three of the system telescopes are read out with the new FADCs, while one is still equipped with an intermediate 40 MHz FADC–system.
The trigger of the HEGRA IACT–system is organized on two levels. It guaranties that the telescopes are read out only when at least two images of an air shower are available. On the first level the trigger requires that the signals of at least two pixels in a camera exceed a given threshold within a time window of 12 nsec. The trigger signals of the single telescopes are routed to the central trigger station of the system. There the pulses are delayed by a programmable VME–unit to compensate differences of the arrival time of the shower front at the individual telescopes. The delays are updated continiously as the source moves across the sky. The second level of the trigger is released if at least two telescopes have triggered within 70 nsec. Then the trigger signal for the system, together with the event number, is sent to all system telescopes, also to those which did not generate a trigger signal themselves. The FADCs are stopped and read out by the CPUs. The event data together with the event number are written via Ethernet to a central PC, where the event building is done.
Presently the threshold of the first level trigger is set to $\approx$8 photoelectrons for the single pixels. This results in an event rate of 11–13 Hz for the four–telescope system.

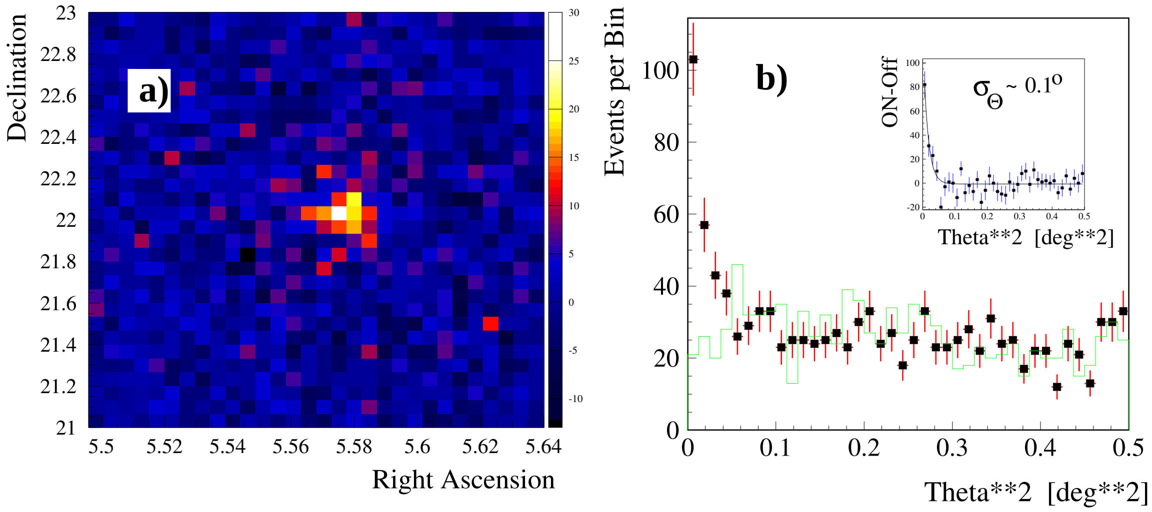

Figure 5: a) Distribution of the reconstructed direction of the excess events of 8.7 hours of Crab observation with the 3 telescopes system. b) Distribution of the angle Θ between the direction of the showers and the direction of the Crab Nebula for 2 hours of 4 telescope data.

3.3 First Measurements on the Performance of the CT–System

With the HEGRA–IACT system it is now for the first time possible to test the concept of stereoscopic observations under realistic conditions. Data taking in stereoscopic mode started in August 1996 with a two telescope system. With the completion of the third and the fourth telescope during fall 1996 the system reached its present stage. Different astrophysical objects have been observed during this time with different configurations. While the analysis of these data is in progress, I want to concentrate on observations on the Crab Nebula, which serves to some extent as a calibration candle for IACTs. 8.7 hours of data [b] with the 3–telescope system could be accumulated in the ON/OFF–mode and, due to bad weather, only 2 hours of 4–telescope data during december 1996.
Two analysis procedures have been applied to the data: The conventional analysis selects events by the shape of the images and by the orientation angle Alpha of the images with respect to the source position in the camera. The second technique uses the 3-dimensional reconstruction of the shower axis. Both techniques give consistent results and a clear signal of the Crab Nebula is found. Figure 5 a) shows the distribution of the reconstructed shower directions for the 3–telescope data after loose shape cuts with an significant excess at the location of the Crab Nebula. To derive a measure for the angular resolution of the telescope system, the distribution of the angle Θ between the reconstructed shower axis and the direction of the Crab Nebula is plotted for the 4–telescope data in figure 5 b) after application of loose shape cuts. As expected, the direction of the background of charge cosmic rays is distributed equally in space, while the ON–source measurement shows again a significant peak at the location of the Crab Nebula. A fit of an exponential function to the distribution of the excess events (insert in figure 5 b) gives a projected angular resolution of 0.09^o for the four telescope system. This result is in good agreement with Monte Carlo simulations, which predict a resolution of 0.1^o [11] for this reconstruction method.

[b]During this time only one telescope was equipped with the 120 MHz FADC–system and two CTs with the interim 40 MHz FADCs

The rate of excess events after loose shape cuts amounts to $\approx 70\ \mathrm{h}^{-1}$ at a statistical significance of about $6\ \sigma/\sqrt{h}$. From this measurement one can estimate the minimum detectable flux within 50 hours for the 4 telescope system to be on the level of 8 % of the Crab flux. This is lower by a factor of 4 than the minimum detectable flux by a single system telescope. Taking into account the preliminary nature of the present stereoscopic analysis significant improvement is expected as our understanding of the system data increases [12].

Summary

The HEGRA–collaboration suceeded in detecting TeV–γ–rays from the two BL Lac objects Markarian 421 and Markarian 501 with its first two prototype telescopes. These measurements represent the first independent detection after the discovery by the Whipple experiment.
With the installation of the system of 4 IACTs for stereoscopic observations the HEGRA–collaboration is now in the position to perform spectroscopic observations with high sensitivity. From first observations of the Crab Nebula follows that the system fully comes up the expectations.

Acknowledgments

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