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THE STEREOSCOPIC SYSTEM OF IMAGING ATMOSPHERIC CHERENKOV TELESCOPES OF THE HEGRA–COLLABORATION

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ABSTRACT

The HEGRA–Collaboration is installing a stereoscopic system of five imaging atmospheric Cherenkov telescopes (IACT) for the search and the investigation of sources of TeV γ-rays. The telescopes system has been especially designed for simultaneous observations of air showers, to fully exploit the advantages of stereoscopic observations. First measurements of the Crab Nebula with a four telescope system indicate, that the technique fully comes up the expectations. Experimentally the angluar resolution could be proven to be better than 0.1^o. Together with a hadron suppression of almost 100 on the software level, this results in a flux sensitivity for pointlike sources of about 3 % of the Crab Nebula within 100 hours of observation time. We will describe the implementation of the telescope system and first measurements on its performance.

INTRODUCTION

One of the main aims of the HEGRA–Experiment (see Lindner et al., OG 10.3.36) is the clarification of the question of the origin of the galactic Cosmic Rays. In the TeV energy range this question is attacked by making use of the imaging atmospheric Cherenkov technique. Meanwhile 6 IACTs of the HEGRA–collaboration are in operation: two prototype telescopes, which operate as stand alone detectors since several years and a system of 4 IACTs for stereoscopic observations, which takes data since December 1996. To complete the system, which will finally consist of 5 telescopes, it is planned to include one of the prototype telescopes after its refurbishment during 1997. While the prototype telescopes are described elsewhere (Rauterberg et al. 1995, Wiedner et al. 1994, Mirzoyan et al. 1994), this article concentrates on the stereoscopic system.

THE STEREOSCOPIC IACT SYSTEM

The principle of the stereoscopic technique is based on simultaneous observations of air showers with

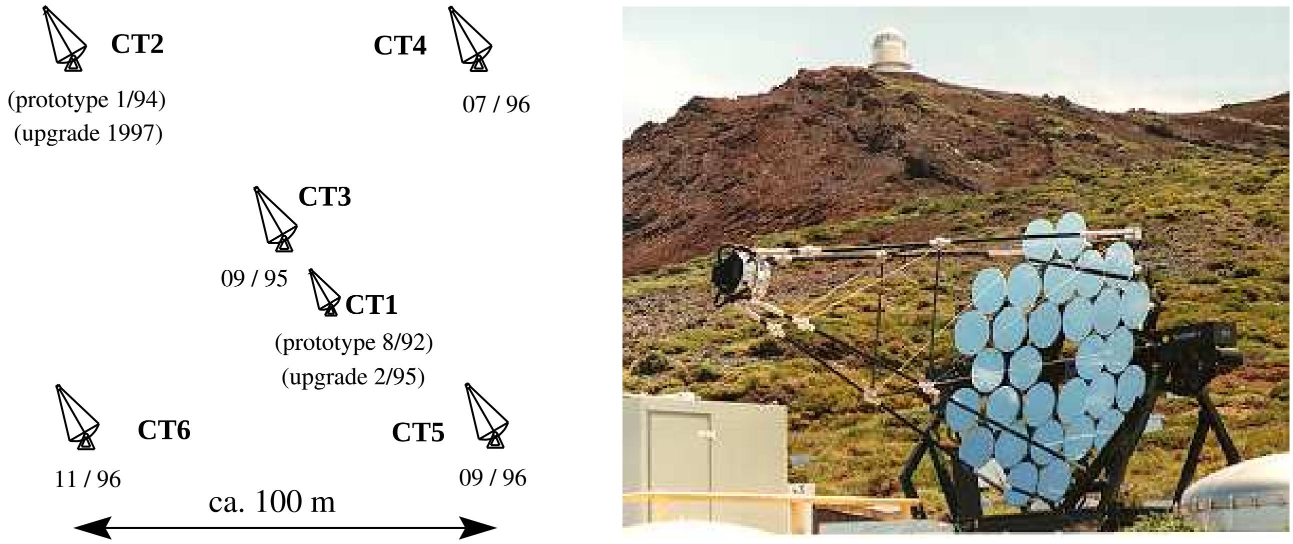

Fig. 1: Principle layout of the HEGRA IACT system, and photograph of the central telescope (CT3).

several telescopes under widely different angles . This allows a full 3–dimensional reconstruction of the air showers and an unambiguous determination of the shower parameters, namely the shower direction, the core location, the energy, and the height of the shower maximum with high accuracy on an event by event basis (Aharonian et al. 1997 a,b). The expected resolution for the HEGRA system amounts to 0.1^o for the direction, 15 m for the core location, and 25 % for the primary energy.
The HEGRA IACT system has been especially designed for this purpose. It will finally consist of 5 identical telescopes arranged on the corners and in the center of a square with a length of about 100 m (Fig. 1). Each telescope is equipped with its local readout– and control electronics which is based on the VME–standard and controlled by a 68040 CPU, operating on LynxOS. These CPUs communicate with a central computer (Pentium PC), from which an operator controls the whole system. The telescopes have a mirror area of 8.5 m^2 each, with a focal length of about 5 m. The cameras consist of 271 pixels, which are built of photomultipliers (PMT), with the appropriate voltage divider and preamplifier, and light guides in front of the PMTs to optimize the light collection from air showers and to suppress background light. The pixel size amounts to 0.25^o, resulting in an overall field of view of 4.3^o. This large field of view is necessary to be able to observe extended sources, one of the main aims of the experiment. The digitization of the camera signals is done with a 120 MHz Flash ADC system, which also incorporates ring buffers for the digitized signals of each channel with a depth of 4k. The use of an FADC system provides different advantages: it allows an effective charge integration time as short as 16 nsec. The measurement of the time structure of the pulses allows additional suppression of background light and also makes it possible to intercorrelate the relative timing of different telescopes of the system with an accuracy of about 1 nsec. Finally, by buffering the digitized signals, it is possible to wait for a delayed system trigger.
The telescope system is triggered by a coincidence of telescopes. The trigger decision is kept on two levels: locally each telescope releases a trigger signal, when the pulse amplitudes of at least two pixels exceed a preset threshold whithin 12 nsec. In addition, already on the hardware level, the triggering pixels are required to be neighbors. By this way, the rate of accidental triggers, generated by the background light of the night sky are strongly suppressed by a factor of 48, while maintaining approximately all genuine γ–triggers. The trigger signals of the telescopes are routed to a central station. There the signals are delayed by programmable VME–units, to compensate for differences in the arrival time of the light front at the different telescopes. A majority unit then generates the central, second level trigger, if at least two telescopes have triggered within 70 nsec. Together with an event number the trigger signals are sent to the telescopes, where the FADCs are stopped and the readout of the events by the local CPUs is started. The event data are tagged by the event number and sent via Ethernet to the central computer, which does the event building. Triggering the telescopes of the system in coincidence has several advantages: accidental triggers by the light of the night sky are further reduced, thus allowing to decrease the single pixel threshold and to significantly lower the energy threshold of the system. Triggers generated by local muons are strongly suppressed. Finally, also hadron showers are suppressed already on the trigger level, due to their diffuse light distribution.
Presently the pixels are operating at a threshold of $\sim$ 8 photoelectrons. The coincidence rate for the 4 telescope system typically amounts to 12 Hz at an effective energy threshold of about 500 GeV.

EVENT RECONSTRUCTION AND OBSERVATION MODE

Our present analysis technique is based on the standard second moment description of the light distributions in the cameras. It gives measures of the shape of the images, e.g. the *width* and *length* and of the orientation of the light distribution. For the calculation of the image parameters typically only pixels are included whose amplitude is above 6 photoelectrons (pe) or above 3 pe with a neighbor pixel above 6 pe. The shower direction and core location are derived geometrically by intersecting the symmetry axes of the images in a common camera coordinate system and in space. Finally, the energy of the events is calculated from the light yield in each camera together with the knowledge of the core

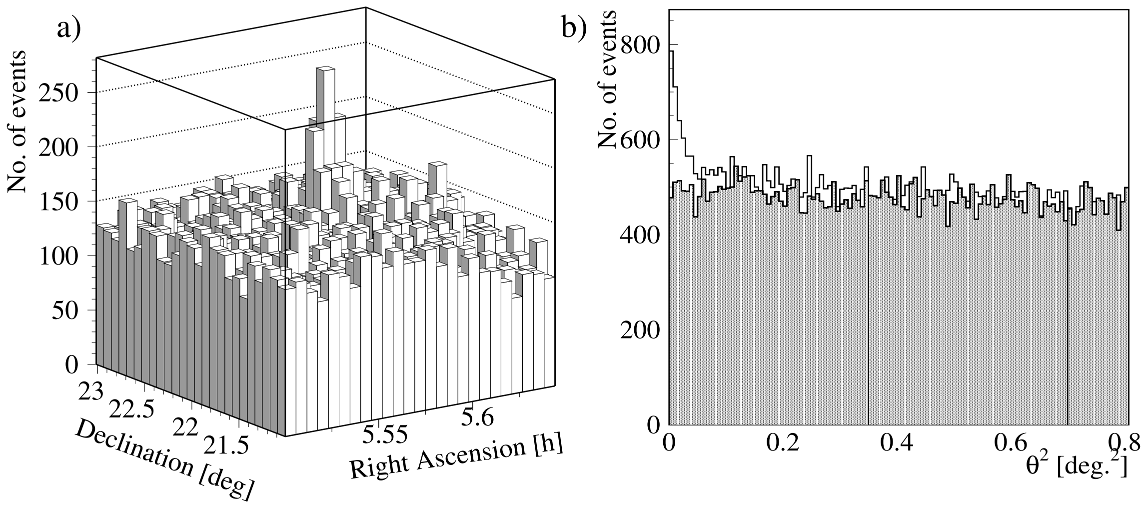

Fig. 2: (a) Distribution of the reconstructed shower directions for 11.7 h of Crab observations before cuts. (b) Distribution of the solid angle relative to the position of the Crab Nebula, also before cuts. The shaded area represents the background.

position on an event by event basis.

Two kinds of observation modes are applied: during the test phase of the experiment and for the search of extended sources, the measurements are performed in the conventional ON/OFF–mode. For the search and investigation of pointlike sources, objects are observed in a mode where the optical axis are shifted by 0.5^o with respect to the source position, with the sign of the offset changing typically every 20 min. For the background determination, a region symmetrically displaced in the opposite direction is taken. This mode is possible due to the large field of view of the cameras and due to the unambiguous determination of the shower direction in stereo mode. It effectively doubles the exposure time of the telescopes on a given object and automatically compensates possible angular inhomogenities of the acceptance.

OBSERVATIONS AND PERFORMANCE

Four system telescopes became subsequently operational during 1995/1996 (dates are quoted in Figure 1). Since August 1996 the telescopes take data in stereoscopic mode. Several astrophysical objects have been observed and the analysis of these data is in progress. Positive signals of TeV γ–rays could be detected from the Crab Nebula and from the Active Galactic Nucleus (AGN) Markarian 421. Since March 1997 the outburst of the AGN Markarian 501 is monitored. While the flux from the two AGNs is highly variable, the intensity of TeV γ–rays from the Crab Nebula is known to be constant. Therefore it is used as a kind of standard candle to calibrate and understand the properties of the telescope system. With the measurements of the Crab Nebula with the HEGRA IACT system it is now for the first time possible to test the stereoscopic approach under realistic conditions (Daum et al. 1997).

The following results are based on observations, which have been performed during December 1996 and January 1997 with the four IACTs CT3-CT6. The dataset contains about 11.7 hours (ON-source) observations, of which about one half was performed in the ON/OFF mode. The zenith angle range extends up to 40^o with a mean value of about 20^o. During that period the neighbor trigger was not yet installed and one IACT was still equipped with an intermediate 40 MHz FADC system.

For the geometrical reconstruction of the showers, at least two telescopes having more than 2 pixels in the image are required. Figure 2 (a) shows the distribution of the shower directions, as reconstructed on an event by event basis. Even without any cuts for hadron suppression a clear signal from the direction of the Crab Nebula is visible. This is due to the high angular resolution of the system and due to the efficient background suppression already on the trigger level. For a numerical analysis the angular distance Θ of the shower direction to the nominal position of the Crab Nebula is calculated. Figure 2 (b) shows $dN/d\Theta^2$. As expected, the distribution of the background events from the charged cosmic rays is flat over a wide range, while the γ–rays generate a significant peak at the position of the source.

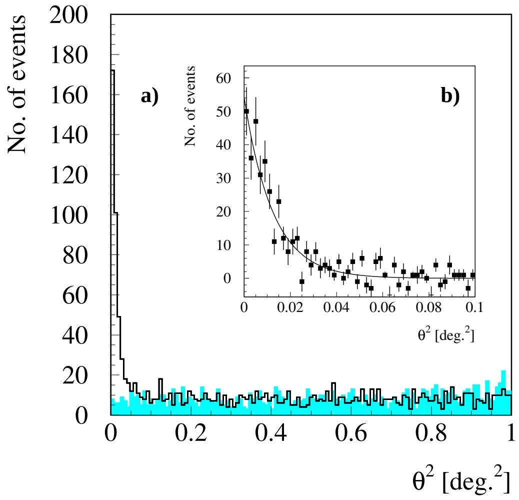

Fig. 3: Distribution of the angle between the reconstructed shower directions and the Crab position after cuts on the image shape (a) and the background subtracted distribution (b).

To improve the signal to noise ratio cuts on the shape of the images are applied. An optimized selection for maximum sensitivity makes use of the knowledge of the core position, which is provided by the stereoscopic reconstruction. Depending on the image amplitude, the distance to the core, and on the zenith angle, the *width*– and *length* distributions for γ– and proton showers are parametrized using Monte Carlo simulations. For each image of an air shower in the telescopes the probability p to be generated by a hadron shower (p_h) or by a γ–shower (p_g) is calculated. In a second step the combined probability over all images of a shower is derived by $P_{g,h} = \Pi p_{g,h}$ for the two hypotheses. An event is accepted, if the probability for a γ–shower (P_g) is greater than that for a hadron shower (P_h) by a certain factor. This method avoids the potentially rather ineffective cuts on individual image parameters. Figure 3 (a) shows the resulting angular distribution with the background reduced by almost a factor of 100. An exponential fit on the background subtracted distribution gives an angular resolution of the telescope system of 0.08^o (Figure 3 b). For an optimum signal to noise ratio only events within 0.13^o from the source position should be selected. The resulting detection rate for the Crab Nebula amounts to 23 γ/h above a background rate of 1.2 h^{-1}. This means, that for short observation times of the order of an hour only about 1 background event is expected. Thus, pointlike sources with about 30 % of the Crab flux can be detected within one hour of observation time. Together with the large field of view this feature allows an effective sky survey with this instrument. For long observation times the background in the signal region can be extrapolated with high accuracy due to its flat distribution. Consequently pointlike sources with $\sim$3 % of the Crab flux are detectable on a 5 σ level within 100 hours. For uniform extended sources with a diameter of 1^o the flux limit amounts to 15 % of the Crab.

SUMMARY AND OUTLOOK

The HEGRA collaboration is close to complete the stereoscopic system of IACTs. With the first measurements of the Crab Nebula the power of the stereoscopic approach could be demonstrated. While the stereoscopic analysis technique is still evolving, even sensitivities of about 3 % of the Crab flux can be reached.

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