On the Potential of the HEGRA IACT Array

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Abstract. The status of the HEGRA array of five imaging atmospheric Cherenkov telescopes is briefly discussed. Our current understanding of the telescopes based on Monte Carlo studies and recent stereoscopic observations of TeV γ-rays from the Crab Nebula, allows the following conclusions on the performance of the instrument: effective energy threshold $E_{\rm eff} \simeq 500\,{\rm GeV}$; angular resolution $\delta\theta \simeq 0.1^\circ$; energy resolution $\Delta E/E \leq 25\%$; minimum detectable flux for 100 h observations of point sources $J_{\rm min} \simeq 25\,{\rm mCrab}$; minimum detectable energy fluence of transient $\leq 1\,{\rm h}$ flares of TeV γ-rays $S_{\rm min} \simeq 5 \cdot 10^{-8}\,{\rm erg/cm^2}$.

STATUS

The HEGRA collaboration is close to complete an array of five imaging atmospheric Cherenkov telescopes (IACTs) located on the Roque de los Muchachos, Canary Island La Palma $(28.8^\circ\ {\rm N}, 17.9^\circ)$. The excellent optical conditions and good infrastructure provided by the Instituto de Astrophysica de Canarias make the area a prime site for ground-based γ-ray astronomy.

The telescope array, primarily designed for stereoscopic observations of γ-radiation at energies above several hundred GeV [1], is formed by five identical IACTs - one at the center, and four others at the corners of a 100 m by 100 m square area. The multi-mirror reflector of each telescope has an area $8.5\,{\rm m}^2$. Thirty 60 cm diameter front aluminized and quartz coated spherical mirrors with focal length of about 5 m are independently installed on an almost spherical frame of an alt-azimuth mount. The point spread function of the reflector is better than 10 arcminutes. Each telescope is equipped with a 271-channel camera [2] with a pixel size of about 0.25° which results in the telescope's effective FoV$\approx 4.3^\circ$. The digitization of the PMT pulses is performed with a 120 MHz FADC system. The system trigger demands *at least two* fired pixels in each of *at least two* telescopes.

A partially completed system 'CT3/4/5/6' consisting of four telescopes, is taking data in the stereoscopic mode since 1996 [3]. The last nominal telescope of the system will be available after replacement of the 61-channel camera of the second (prototype) HEGRA telescope CT2 by a standard 271-pixel high resolution camera. We plan to run, after the test and calibration work, the whole telescope array as a *single detector* at the end of 1997.

The basic concept of the HEGRA IACT array is the *stereoscopic approach* based on simultaneous detection of air showers by ≥ 2 telescopes, which allows unambiguous and precise reconstruction of the shower parameters on an *event-by-event* basis, superior rejection of hadronic showers, and effective suppression of the background light of different origins (night sky background, local muons, *etc.*). The recent observations of the Crab Nebula [3] and Mkn 501 [4] by the 'CT3/4/5/6' system strongly support the theoretical expectations concerning the features of the stereoscopic imaging technique [5] and confirm the predictions for the performance of the HEGRA IACT array [1]. These data demonstrate that (1) the accuracy of reconstruction of the direction of *individual* γ-ray primaries can be as good as 0.1°, (2) the suppression of hadronic showers at the hardware and software levels can essentially exceeds factor of 100, and (3) the energy threshold of the telescopes operating in coincidence mode can be reduced by $\approx 50\%$. In particular the confinement of the γ-ray signal in the angular region $\sim 0.1^{\circ}$, in addition to the significant suppression of hadronic showers at the *trigger* level, provides '4σ-per-1 h' signal from the Crab, already before the application of 'shape' cuts to the shower images. The 'shape' cuts allow further, by a factor of 100, suppression of the CR background which results in only ≈ 1 (!) background event/h in the 'signal domain', while the number of γ-ray events exceeds 20 events per 1 h [3].

PERFORMANCE

The *energy domain* of the instrument, for the given spectrum of γ-rays, is characterized by the detection rate of primaries in the energy interval $\Delta E \approx E$, i.e. by the function $E \cdot \mathrm{d}R/\mathrm{d}E$, where the differential detection rate $\mathrm{d}R/\mathrm{d}E$ is determined by the shower collection area and the spectrum of primary particles. In Fig.1 we present detection rates for 4 different spectra of primary γ-rays from point sources, as well as for isotropic fluxes of CR protons and electrons. The maximum of the photon statistics is achieved at energies between 500 GeV (for steep spectra) and 1 TeV (for flat spectra). For power-law spectra from a point source, with a flux $10^{-11}\,\mathrm{ph/cm^2s}$ above 1 TeV, the total detection rates vary between $70\,\mathrm{h}^{-1}$ ($\alpha = 2$) to $150\,\mathrm{h}^{-1}$ ($\alpha = 3$). In the case of the Crab Nebula we expect, after application of 'shape' cuts to the shower images at different viewing angles, and parametrized as functions of the image amplitude and distance to the shower core [6], about $50\,\mathrm{h}^{-1}$ γ-rays on top of the CR contamination with a rate of only few events per 1 hour.

Since these fluxes are detected at background-free conditions, the HEGRA IACT array with it's energy resolution $\leq 25\%$ allows, for an observational

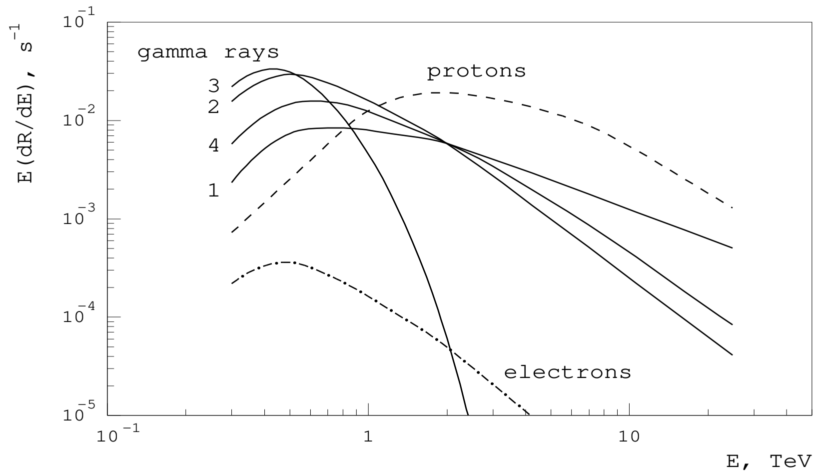

FIGURE 1. Detection rates of γ-rays from point sources. For comparison the rates for the CR protons and electrons are also shown. The rates correspond to showers which trigger the 5-IACT system operating in the '2-telescope coincidence' mode, and are contained in the 'source domain' $\theta \leq 0.15°$. Curves 1 and 2 correspond to power-law spectra of photons $\mathrm{d}J/\mathrm{d}E \propto E^{-\alpha}$ with $\alpha = 2$ and 3 respectively; the curve 3 corresponds to power-law spectrum with exponential cutoff: $\mathrm{d}J/\mathrm{d}E \propto E^{-2}\exp(-E/250\,\mathrm{GeV})$; curve 4 corresponds to the inverse Compton spectrum of the Crab. The γ-ray spectra are normalized to an integral flux above 1 TeV: $10^{-11}\,\mathrm{ph/cm^2s}$ for curves 1,2,4, and $10^{-12}\,\mathrm{ph/cm^2s}$ for curve 3.

time $\sim 100\,\mathrm{h}$, good spectroscopic measurements of strong TeV sources in a broad energy region from 0.3 TeV to $\geq 30\,\mathrm{TeV}$. Furthermore, the excellent angular resolution $\leq 0.1°$ enables a study of the spatial distribution of γ-ray production regions in such strong sources on *arcminute* scales. Therefore, *the detailed study of angular and spectral characteristics of established TeV sources is considered as one of the important objectives of the HEGRA IACT array.*

The *second* feature of the HEGRA IACT array is its high sensitivity for *search for new TeV sources with fluxes down to the level of* $\approx$25 mCrab. This program is planned to be realized in 2 general modes:

Survey Mode

The superior background rejection by the HEGRA telescopes allows a search for TeV γ-rays from point-like sources with fluxes $\geq$ 0.1 Crab at almost background-free conditions. This allows drastic reduction of the observation time allocated to individual targets, and opens a unique possibility for effective *sky surveys* with an observatio time $\approx 1\,\mathrm{h}$ per $2° \times 2°$ region at a sensitivity which for $t_{\rm obs} \leq$ few hours is determined essentially by the photon statistics ('at least 10 detected γ-rays'):

$$J_{\rm min} \simeq 0.2\,(t_{\rm obs}/1\,\mathrm{h})^{-1}\,\mathrm{Crab}\,.$$

In particular, this implies that all *persistent* Galactic TeV emitters with apparent luminosity $L_\gamma(\geq 0.5\,\mathrm{TeV}) \simeq 1.5 \cdot 10^{33} (\mathrm{d}/1\,\mathrm{kpc})^2\,\mathrm{erg/s}$ would be revealed by a survey of the Galactic Disk, an essential part of which ($10^\circ \leq l \leq 250^\circ$) is effectively observable from La Palma at zenith angles $\leq 50^\circ$.

It is important to note that the individual telescopes of the HEGRA system, operating in the 'stand alone' (mono) mode, have energy threshold of about 750 GeV and sensitivity which allows detection of a signal from the Crab with a statistical significance $\simeq 2.5\sigma\,(t/1\,\mathrm{h})^{1/2}$. Thus the '$5\sigma$' detection of faint sources at the flux level of 0.2 Crab by a single telescopes of the system requires exposure time of about 100 h, while only 1 h observation time would be sufficient for detection of such fluxes by the telescope system which operates in the 'stereo mode'. This clearly demonstrates the principally new level of the imaging technique which can be gained by implementation of the stereoscopic approach.

The HEGRA IACT array is an effective instrument in the search for possible *transient* or *burst-like* sources. In particular, the minimum detectable fluence $S_\gamma \simeq 5 \cdot 10^{-8}\,\mathrm{erg/cm^2}$ during the burst time $\leq 1\,\mathrm{h}$ would allow detection of possible VHE counterparts of GRBs, if only a small part of the total energy of the burst were released in TeV photons. Moreover, the HEGRA IACT array can explore new types of highly sporadic nonthermal phenomena from different classes of astrophysical objects which may appear well below the sensitivities of satellite-borne detectors at MeV and GeV energies.

Target Mode

The minimum detectable fluxes of faint VHE sources at the level of $\leq$ 0.1 Crab are determined essentially by the signal-to-noise ratio $S/\sqrt{(B)}$. In particular, the detection of a γ-ray signal at the 5σ level

$$J_{\min} \simeq 0.05\,(t_{\mathrm{obs}}/25\,\mathrm{h})^{-1/2}\,\mathrm{Crab}\,.$$

Note that in the *target* mode the accumulation of 25 h requires typically 1 or 2 weeks of continuous observations during moonless and cloudless nights. Since in some cases the observation time of a target of special interest could be increased up to 100 h, the minimum detectable flux may reach a level of 25 mCrab which corresponds to the *energy flux* above 500 GeV approximately $(1.5-2) \cdot 10^{-12}\,\mathrm{erg/cm^2s}$. This implies, in particular, that all blazars emitting γ-rays at energies $E' \geq 50/\delta_{10}\,\mathrm{GeV}$ (in the frame of the jet; $\delta_{10} = \delta_{\mathrm{j}}/10$ is the jet's Doppler factor), should be detected by the HEGRA IACT array if the intrinsic γ-ray luminosity of the source exceeds $L'_\gamma \simeq 3 \cdot 10^{39} (z/0.1)^2\,\mathrm{erg/s}$ ($H_0 = 75\,\mathrm{km/s\,Mpc}$).

Although from the point of view of the nonthermal energy budget the search for γ-rays from distant blazars with redshifts $z \geq 0.1$ could be easily justified, the effective energy threshold of the HEGRA around 500 GeV cannot guarantee success in the case of such distant sources due to possible absorption of TeV γ-rays in the intergalactic photon fields. Nevertheless it should be emphasized that the HEGRA IACT array can provide reasonable sensitivities also below 500 GeV. Indeed, conservative estimates show that long-term ($t_{\rm obs} \sim 100\,{\rm h}$) observations should enable detection of a flux around 300 GeV as low as $f_{\rm E} \simeq 10^{-11}\,{\rm erg/cm^2s}$, which extends the extragalctic distance scales available for the HEGRA up to 1 Gpc.

Extended Sources

The HEGRA IACT array with its superior γ/hadron separation efficiency, in combination with its high γ-ray detection rates, allows an effective study of moderately extended sources with angular radius $\phi \simeq 1^\circ$. The minimum detectable flux, integrated over the angular size of the source,

$$J_{\rm min} \simeq 0.15\,(t_{\rm obs}/100\,{\rm h})^{-1/2}\,{\rm Crab}\,,$$

is sufficient to probe the energy budget of SNRs in accelerated cosmic ray protons and nuclei down to $10^{49}\,{\rm erg}$, as well as to study the π^0-decay and inverse Compton components of the diffuse radiation of the Galactic Disk at the flux level of $10^{-9}\,{\rm cm^{-2}s^{-1}ster^{-1}}$.

SUMMARY

The HEGRA telescope array perhaps can be considered as the first (scaled-down) model of the next generation of very large IACT arrays. Therefore it is difficult to overestimate the importance of the recent observations of the Crab Nebula by the HEGRA telescopes, which convincingly confirm the Monte Carlo predictions concerning the potential of the stereoscopic approach, and give an optimistic view for the forthcoming '100 GeV' threshold telescope arrays like HESS and VERITAS. On the other hand, even with its relatively high energy threshold, the HEGRA IACT array already demonstrates very good performance. This assures that this instrument will serve as one of the most powerful tools of TeV γ-ray astronomy during the next several years.

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