Highlights from 6 years of TeV gamma-ray astrophysics with the HEGRA imaging Cherenkov telescopes

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Abstract

The HEGRA (High Energy Gamma Ray Astronomy) experiment achieved outstanding results during the operation of the six Cherenkov telescopes (end of 1996 - end of 2002), pioneering with 5 telescopes the stereoscopic observation mode. Concerning the Galactic sources these include the detection of Cassiopeia A, being the only shell type supernova remnant at TeV energies seen up to now in the northern sky and recently the observation of a yet unidentified TeV gamma-ray source TeV J2032+4130 in the Cygnus region. Also a scan of a large fraction of the Galactic plane has been achieved. Concerning the extragalactic sources most precise spectra at the highest energies have been obtained from the well studied blazars Mkn 501 and Mkn 421 as well as from H1426+428 and 1ES1959+650 established in the last two years only. Also extensive multi-wavelength campaigns have been successfully performed. Recently strong evidence for the nearby giant radio galaxy M87 being a TeV γ-ray source has been obtained. Some of the highlight results are addressed below.

1. Introduction and experimental method

The imaging atmospheric Cherenkov telescopes (Table 1) of HEGRA (Canary island La Palma, 28.75^0 N, 17.89^0 W, 2200m a.s.l.) started with a prototype telescope in 1992 and consisted in fall 1996 of a stand alone telescope (CT1) [1] pioneering observations during partial moon time and 5 telescopes (CT2-CT6) [2] introducing the very successful stereoscopic observation mode adopted by most of the next generation experiments. The stereoscopic observation of an air shower i.e. the simultaneous measurement of an air shower with several telescopes, under different viewing angles, allows to reconstruct unambiguously the shower direction and impact point and also the shower height on an event by event basis. This leads to an improved angular and energy resolution, an improved gamma/hadron separation and suppression of background from night sky light and muons (due to the coincidence method). The stereoscopy also allows to record simultaneously events from well defined background regions giving the quoted errors a high credibility and to perform sky searches in the field of view of the camera. The flux sensitivity achieved is a 10 σ detection within 1 hour for a source with a flux of

pp. 2559–2562

Table 1. Properties of the HEGRA Cherenkov telescopes (end of 2002)

Telescope	Observ. mode	Mirror area [m^2]	PM-Camera #pixels	FoV [deg]	E_{thres} [GeV]	$\delta\theta$ [deg]	$\delta E/E$ [%]
CT1	alone	5 $\rightarrow$10	37 $\rightarrow$ 127	3	700-900	< 0.2	$\sim$25
CT2-CT6	stereo	5 x 8.5	5 x 271	4.3	500-600	< 0.1	10-20

1 Crab. The telescopes CT2-CT6 ceased operation end of 2002.

2. Galactic sources and Galactic accelerators of nuclei

It is one of the main goals of the TeV γ-astronomy to find the sources of the Galactic cosmic rays commonly believed to be the shell type supernova remnants. In fact HEGRA detected [3] with Cassiopeia A the only shell type supernova remnant seen so far at TeV energies in the northern sky after a long observation time of 210 h (in 3 years) resulting in a flux of ~ 3 % of the Crab nebula. Although not yet unequivocally proven it is very likely [4] that Cas A is one of the long sought hadronic accelerators. A scan of 1/4 of the Galactic plane (longitude l= -2^o to 85^o) yielded upper limits in the range of 0.15-0.5 Crab flux units for 63 SNR's, 86 pulsars and 9 unidentified EGRET sources [5]. Recently HEGRA detected [6] with TeV J2032+4130 (Fig. 1) a new source up to now unidentified (i.e. no counterpart at radio, optical and X-ray energies) in a direction about 0.5 degrees north of Cygnus X-3. The source is detected meanwhile with a significance above 7σ [6], exhibits a hard spectrum (index $\alpha \sim$ -1.9) and is possibly extended (on a 3σ level). Several source mechanisms are conceivable and it may turn out that this source plays an important role in the context of the Galactic accelerators.

Table 2. Galactic and extragalactic sources seen by HEGRA. The fluxes are given in units of the Crab-flux [$dJ_\gamma/dE = (2.79 \pm 0.02 \pm 0.5) \cdot 10^{-7} (E/1TeV)^{-2.59\pm0.03\pm0.05}$ photons m^{-2} s^{-1} TeV^{-1}]. (C=CAT, H=HEGRA, V=VERITAS, T=7Tel. Array)

	Type	distance	significance [σ] (HEGRA)	Flux [Crab flux]	Experim.
Crab nebula	Plerion	1.6 kpc	> 10	1.0	many
Cas A	SNR (shell)	3.4 kpc	~ 6	0.03	H
TeV J2032+4130	unknown	unknown	~ 7	0.03	H
Mkn 421	BL Lac	(z = 0.030)	> 10	0.04-7.40	many
Mkn 501	BL Lac	(z = 0.034)	> 10	0.33-6.00	many
1ES 1959+650	BL Lac	(z = 0.047)	> 10	0.05-2.20	H,V,C,T
H1426+428	BL Lac	(z = 0.129)	~ 7	0.03-0.08	H,V,C
1ES 2344+514	BL Lac	(z = 0.044)	~ 4	0.03	H,V
M87	radio gal.	(z = 0.0044)	~ 4	0.03	H

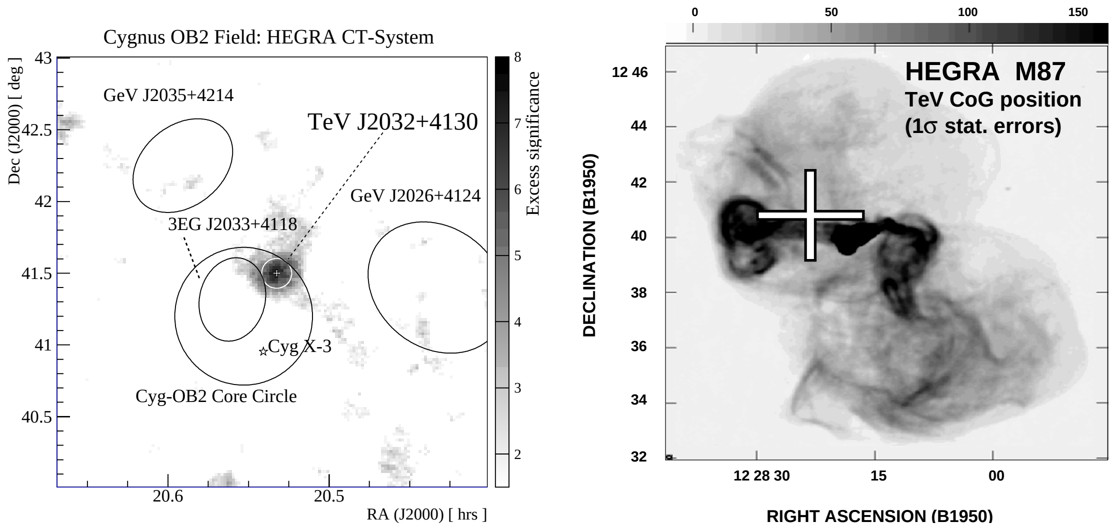

Fig. 1. LEFT: Skymap of the Cygnus region with the center of gravity and the 2σ error circle for **TeV J2032+4130** [6]. Also given are the 95% error ellipses of EGRET sources, the core of Cygnus OB2 and the location of Cyg X-3.
RIGHT: Radio image of **M87** at 90 cm showing the structure of the M87 halo. The center of gravity position of the TeV γ-ray excess from the HEGRA M87 observations is marked by the cross (statistical $1\,\sigma$ errors) [11].

3. Extragalactic sources

Right after the completion of 4 telescopes ready for the stereoscopic observation Mkn 501 showed strong flares in 1997 during the whole observation period, allowing a measurement of an extended light curve and energy spectra of unprecedented precision in this field up to 16 TeV [7]. Remarkably, the shape of the energy spectrum essentially did not depend on the flux level in 1997. This is in contrast to Mkn 421 which exhibited also flaring states and showed examples for a hardening of the spectrum with rising flux level in the HEGRA data [8]. The Mkn 501 spectrum however became softer in the subsequent years. In the last two years two more blazars have now been well established, namely 1ES1959+650 and H1426+428. 1ES1959+650, reported by the Seven Telescop Array with 3.9σ (1998), has been detected by HEGRA end of 2001 with 5.2 σ and showed subsequently strong flares in May 2002 reaching a significance level above 20σ [10] in the HEGRA data (detected also by VERITAS and CAT). H1426+428 is the most distant TeV γ-source up to now and has been detected by all three northern instruments VERITAS, HEGRA and CAT (Table 2).

The precise HEGRA energy spectrum of Mkn 501 has been used by several authors to infer the density of the extragalactic background light (EBL) in the optical to infrared range due to the absorption process $\gamma_{TeV} + \gamma_{EBL} \rightarrow e^+e^-$. In fact, the spectra of Mkn 501 (and Mkn 421) in the TeV range yield the best limits for the EBL density in the mid-infrared range to date, which is of great cosmological interest. With more precise data also from other sources such as H1426+428, which is a factor four more distant (and with a better understanding of the sources) even more stringent results will be possible. The present HEGRA data for H1426+428 already indicate a modulation of the measured energy spectrum [10] due to the imprint of the absorption process mentioned above. To understand the underlying acceleration processes in the jets of the blazars several multi-wavelength campaigns have been performed e. g. together with the X-ray satellite RXTE especially for Mkn 421 and Mkn 501. Correlated flux variations have been observed which indicate that an inverse Compton origin is in general able to describe the TeV data though other processes can not be excluded.

Analyzing the data from observations of further 52 objects from the AGN class with a total observation time of 658 h yielded signals on the 4 σ level from the blazar 1ES2344+514 [11] (reported earlier by Whipple) and very recently from the radio galaxy M87 (Fig. 1) [12] which still has to be confirmed. M87 at the center of the Virgo cluster is of specific interest since it is the first TeV AGN being observed using the imaging technique and not belonging to the blazar class, thus opening the field of TeV γ-astronomy to a new class of sources. This very nearby object may also play an important role for the acceleration of cosmic rays up to the highest energies. Further results will be presented at this conference.

4. Conclusion

The contributions of HEGRA to the TeV γ-astronomy on the way to a mature field have been extremely important by pioneering new experimental techniques and related analysis methods, by obtaining high statistics and precise data for light curves and energy spectra and by detecting new sources such as Cas A, TeV J2032+4130, 1ES 1959+650 and M87, thus promising a great future to the next generation Cherenkov telescopes.

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