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Recent results from HEGRA

Gamma-ray observations with the HEGRA stereoscopic system of 5 Cherenkov telescopes

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Abstract. The HEGRA collaboration has achieved outstanding results during the operation of the six imaging atmospheric Cherenkov telescopes from 1996 to 2002. The experimental work pioneered the field of TeV γ-ray astronomy with observations during partial moon time and mainly by applying the stereoscopic observation mode using a system of five Cherenkov telescopes. Concerning Galactic objects the HEGRA observations have led to a precise measurement of the energy spectrum of the Crab nebula between 0.5 and 80 TeV, the detection of the first shell type supernova remnant in the Northern hemisphere (Cassiopeia A) and the investigation of the yet unidentified HEGRA TeV γ-ray source TeV J2032+4130 in the Cygnus region. In addition, a large fraction of the Galactic plane has been studied during dedicated scans. Following the most precise measurements of the energy spectra of the well known extragalactic objects Mkn 421 and Mkn 501, the blazars H 1426+428 and 1ES 1959+650 have just been established as sources of TeV photons in the last two years. Extensive multi-wavelength campaigns have been successfully performed and spectroscopy of these four objects gives important clues for the understanding of the nonthermal emission processes and also on the optical to infrared part of the spectrum of the extragalactic background light. Recently, strong evidence for the nearby giant radio galaxy M 87 being a TeV γ-ray emitter has been obtained. Some of these results are highlighted in this article.

PACS. 95.85.Pw observations: gamma-rays – 98.70.Rz unidentified gamma-ray sources

1 Introduction

The HEGRA[1] collaboration has operated six imaging atmospheric Cherenkov telescopes (IACTs) on the Canary island of La Palma (28.75° N, 17.89° W) at a height of 2200 m above sea level. The prototype telescope CT 1 [9] was used as a stand alone detector introducing for the first time observations during partial moon time. With the operation of the 5 telescopes CT 2 - CT 6 in stereoscopic observation mode (HEGRA IACT system) [4] HEGRA has pioneered the stereoscopic technique adopted by most of the next generation experiments. The stereoscopic observation of an extended air shower, i. e. the simultaneous measurement of the Cherenkov light initiated by the particle cascade in the atmosphere with several telescopes under different viewing angles, allows for an unambiguous reconstruction of the shower direction, the impact point of the shower axis on the observation level and the height of the shower maximum on an event by event basis. This leads to an improved angular and energy resolution along with a significantly improved γ/hadron separation. Furthermore, the coincidence method results in a strong suppression of the background from night sky light and from local muons. The stereoscopic observation mode in combination with the relatively large field of view of the HEGRA telescopes also allows for a simultaneous observation of events from well defined background regions and for the performance of sky searches in the whole field of view (see e. g. [10]). The sensitivity achieved with the HEGRA IACT system is a $10\,\sigma$ detection within 1 hour for a source with a flux of 1 Crab. The operation of the telescopes CT 2 - CT 6 was terminated at the end of the year 2002.

2 Galactic TeV γ-ray sources

2.1 Highest photon energies from the Crab nebula

The Crab nebula is the standard candle for TeV γ-ray astronomy in the Northern hemisphere. Due to its outstanding role for calibration purpose of the HEGRA IACT system a very long observation time of nearly 400 hours allowed to measure the energy spectrum of the Crab nebula in the wide energy range from 0.5 up to 80 TeV [7] (see Fig. 1). The detection of this object above 50 TeV with a

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[1] HEGRA stands for *High Energy Gamma-Ray Astronomy*

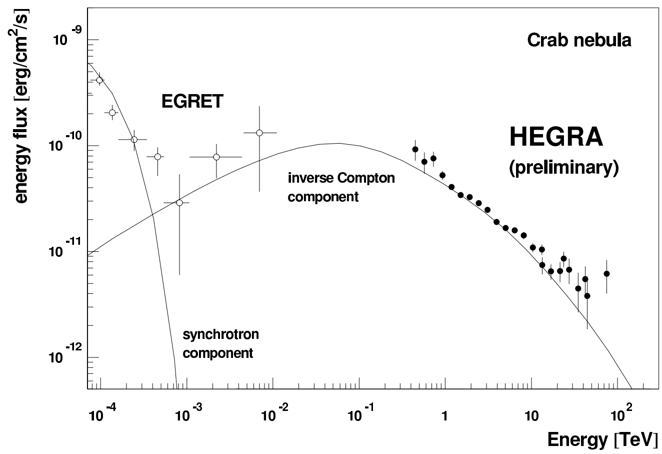

Fig. 1. The unpulsed energy spectrum of the Crab nebula ($E > 100$ MeV) as measured by the EGRET experiment (*open circles*) as well as with the HEGRA IACT system (*filled circles*). A deep observation of nearly 400 hours with the HEGRA telescopes allowed for a measurement of the Crab spectrum in the energy range from 0.5 to 80 TeV [7]. The *solid lines* indicate model expectations (from [7]) for synchrotron and inverse Compton radiation

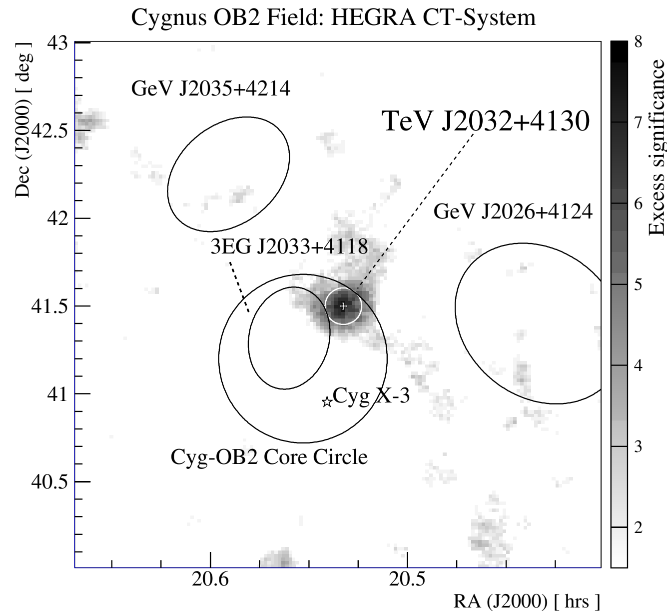

Fig. 2. Skymap of the Cygnus region with the center of gravity of the TeV γ-ray excess and the $2\,\sigma$ *error circle* for TeV J2032+4130 [12]. Also marked are the 95 % *error ellipses* of three nearby EGRET GeV sources, the core of Cygnus OB2 and the location of Cygnus X-3

significance $> 5\,\sigma$ in the HEGRA data makes it the γ-ray source detected at the highest photon energies so far.

2.2 Detection of TeV J2032+4130 in Cygnus

Recently, with TeV J2032+4130 a yet unidentified (i. e. no counterpart at radio, optical nor X-ray energies) TeV γ-ray source has been detected above $7\,\sigma$ with the HEGRA IACT system in a direction about 0.5° to the North of Cygnus X-3 [12] (see Fig. 2). The object shows a hard spectrum ($\mathrm{d}N/\mathrm{d}E \propto E^{-1.9}$) and is possibly extended (on a $3\,\sigma$ level). Several γ-ray production mechanisms are discussed and it may turn out that this first unidentified source plays an important role in the search for the Galactic accelerators of the cosmic radiation. The HEGRA detection of TeV J2032+4130 points out that more up to now unexplored regions of the nonthermal universe may be studied soon with the new generation of Cherenkov telescopes.

3 Extragalactic TeV γ-ray sources

3.1 The TeV blazars H 1426+428 and 1ES 1959+650

H 1426+428 is the most distant TeV γ-ray source established so far and was detected by HEGRA (and also by the Whipple and CAT groups) in 1999/2000 and again in 2002 at a lower flux level [2]. Due to its large distance ($z = 0.129$) that is a factor of four greater than the distances of the well known blazars Mkn 421 and Mkn 501 a precise γ-ray spectrum of this third TeV blazar may be used to infer the density of the extragalactic background light (EBL) in the optical to near-infrared range due to the TeV photon absorbing pair production process $\gamma_{\mathrm{TeV}} + \gamma_{\mathrm{EBL}} \rightarrow e^+ + e^-$. Indeed, the present spectrum of H 1426+428 as measured with the HEGRA IACT system already indicates a modulation of the spectral shape [2].

The blazar 1ES 1959+650, reported in 1999 by the 7 TA collaboration to be a weak TeV γ-ray emitter ($3.9\,\sigma$), has been detected in the years 2000/2001 at $5.2\,\sigma$ with the HEGRA IACT system in a deep exposure of 94 hours at a value of 5.3 % of the Crab flux. Subsequently, strong outbursts ($> 20\,\sigma$) have been observed in May and July 2002 [3] making 1ES 1959+650 the fourth established TeV blazar with third best event statistics. The large HEGRA 1ES 1959+650 data set also allowed to determine the energy spectra during high (> 1 Crab) and low (< 0.5 Crab) flux levels. Furthermore, the detection of the strong flares in 2002 has initiated an extended multi-wavelength campaign combining contemporaneously taken data from radio, optical, X-ray, and γ-ray telescopes. Using the light curves and spectral measurements over this broad range of energies it is possible to study in detail the nonthermal emission and particle acceleration processes inside the relativistic jet of this object [8].

3.2 Detection of the radio galaxy M,87

The nearby giant radio galaxy M 87 has been speculated for about 40 years now to be a powerful accelerator of cosmic rays including the highest energy particles observed in the universe (e. g. [5]). Furthermore, M 87 is also considered as a source of TeV γ-rays from the hypothetical neutralino annihilation process. At its center M 87 contains a supermassive black hole of $2-3 \times 10^9$ sun masses. The axis of the prominent relativistic kpc scale jet (also

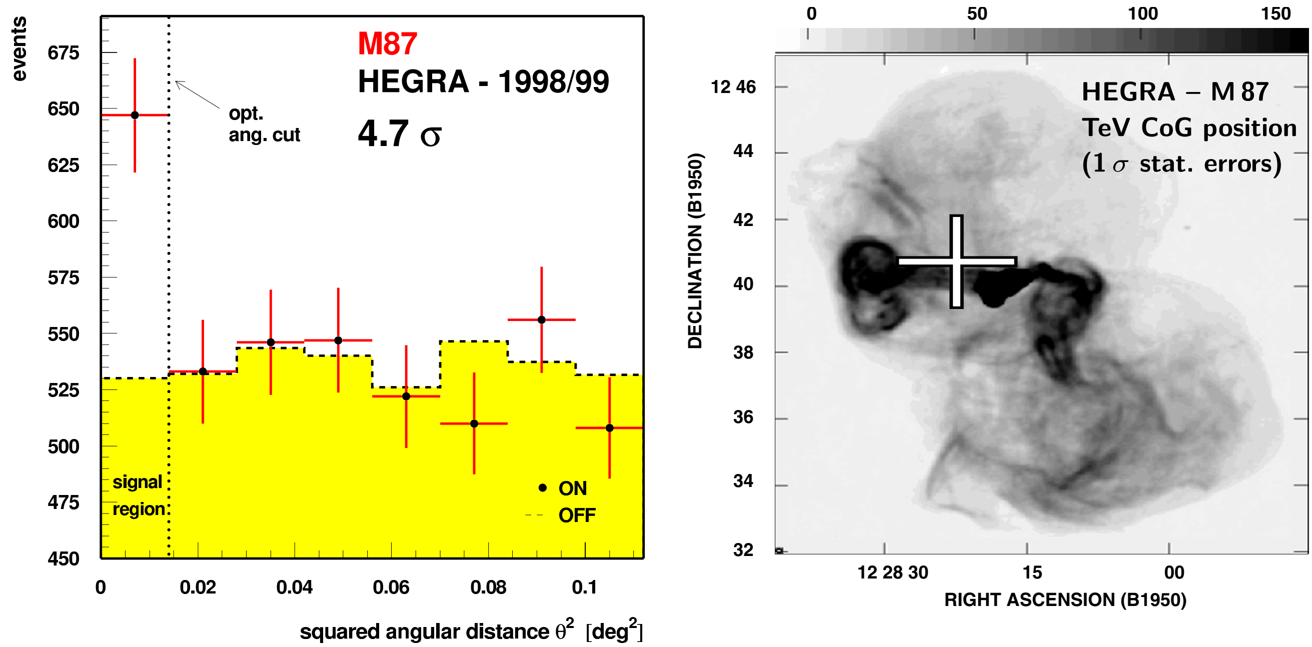

Fig. 3. *Left panel:* Number of events vs. squared angular distance Θ^2 to the core position of M 87 as observed in the years 1998 and 1999 with the HEGRA IACT system. The *dots* show the ON-source events, while the histogram gives the background estimate. Indicated by the vertical *dotted line* is the optimum angular cut as determined from nearly contemporaneous Crab observations at similar zenith angles. The significance of the M 87 excess amounts to $4.7\,\sigma$ *Right panel:* Radio image of M 87 at 90 cm showing the structure of the M 87 halo. The center of gravity position of the TeV γ-ray excess from the HEGRA M 87 observations is marked by the cross indicating the statistical $1\,\sigma$ errors [6]

showing regions of superluminal motion well studied at radio, optical and X-ray frequencies) has an angle of 10-40° to the observer's line of sight in contrast to the blazars with their jets directly pointing to Earth.

M 87 has been observed with the HEGRA IACT system as one of the prime candidates for TeV γ-ray emission from the class of radio galaxies. The deep HEGRA exposure of M 87 of 77 hours in 1998/1999 has revealed for the first time a significant excess of photons above a mean energy threshold of 760 GeV corresponding to $(3.7 \pm 0.8)\,\%$ of the Crab flux [1,6] (see Fig. 3, left panel). Following recent improvements of the data analysis the signal detected with the HEGRA telescopes has now a significance of $4.7\,\sigma$. On the basis of the limited event statistics the signal is compatible with a point-like source for the HEGRA IACT system. The center of gravity (CoG) position of the HEGRA M 87 TeV excess is shown in Fig. 3, right panel. Within the large statistical errors, the CoG is consistent with the M 87 core position, although a small shift of the source position cannot be ruled out.

M 87 is the first Active Galactic Nucleus (AGN) beyond the well-known blazar subclass being detected at TeV energies. With M 87 the AGN subclass of radio galaxies becomes an important new topic of TeV γ-ray astronomy. The TeV flux from M 87 detected with the HEGRA IACT system can be accomodated in different models, e. g. within the Synchrotron Proton Blazar model predicting protons to be accelerated to energies $\geq 10^{19}$ eV [11]. This makes M 87 a promising target for the new generation of Cherenkov telescope projects like the HEGRA succeeding H·E·S·S telescope system and the MAGIC telescope.

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