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Search for TeV γ-ray emission from giant radiogalaxies with the HEGRA Cherenkov Telescopes

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Abstract. Giant radiogalaxies contain huge amounts of mass and exhibit large scale jets, probably powered by a supermassive black hole in the center of these objects. In contrast to Blazars, the jet of a radiogalaxy and the observer's line of sight are not aligned. A large amount of nonthermal particles which are supposed to emit TeV γ-radiation by several processes is expected to be confined within giant radiogalaxies. The three prominent objects M 87, NGC 1275 and Cygnus A have been observed in the years 1998 to 2000 using the stereoscopic system of Cherenkov telescopes operated on the Canary island of La Palma by the HEGRA Collaboration. Results of a search for TeV emission are presented.

1 Giant Radiogalaxies as possible TeV γ-Ray Emitters

Extragalactic TeV γ-ray emission has been observed from several nearby Blazars ejecting matter in a jet oriented very close to the observer's line of sight. Other types of Active Galactic Nuclei (AGN) like giant radiogalaxies, however, also create relativistic mass outflows, though in contrast to Blazars under large viewing angles.

Giant radiogalaxies contain huge amounts of mass. The object M 87, a well studied example in the Northern hemisphere, encloses a mass of approximately $10^{13}\ M_\odot$ in its inner 100 kpc (Dermer & Raphaeli, 1988). The central "engine" of these objects is supposed to be a supermassive black hole powering the development of the distinct large scale jets. In addition, a large amount of nonthermal particles is expected to be confined within giant radiogalaxies.

The emission of TeV γ-radiation seems to be conceivable regarding these properties. Several production processes and different emission regions have been suggested, respectively: The acceleration of charged particles to very high energies in the jet production region gives rise to TeV γ-ray emission. The jets can furthermore terminate in the ambient gas at large distances from the core region of the radiogalaxy. This shock process, leading to the development of huge radio lobes, can also cause ultrarelativistic electrons to radiate large parts of their energy as TeV photons. Finally, hadronic interactions of the nonthermal particles with the interstellar medium of the radiogalaxy produce a large amount of π^0 mesons. These particles will then decay into photons observable at TeV energies.

Recently, M 87 was suggested to be a misaligned Blazar and thus to be a source of TeV γ-rays (Bai & Lee, 2001). According to the unified scheme of AGNs the properties of the established TeV sources are generalized to radiogalaxies. M 87 would therefore be a high-energy-peaked Blazar seen under a large angle to its jet axis. In this scenario, TeV γ-radiation would be produced as the inverse Compton component in a synchrotron-self-Compton model (Urry, 1999).

Giant radiogalaxies are promising candidates to extend the number of extragalactic TeV γ-ray sources. Observations at photon energies above 0.5 TeV have been performed using the HEGRA Cherenkov telescopes to investigate three prominent representatives of the class of giant radiogalaxies.

2 The HEGRA Cherenkov Telescopes

Six imaging atmospheric Cherenkov telescopes (IACTs) are operated by the HEGRA[1] Collaboration on the site of the Observatorio Astrofísico del Roque de los Muchachos on the Canary island of La Palma (28.8° N, 17.9° W) at an atmospheric depth of approx. 800 g/cm^2 overburden (2200 m above sea level). The telescope IACT 1 works as a standalone detector (Mirzoyan et al., 1994), while the other five telescopes stereoscopically observe the Cherenkov light of extended air showers (Daum et al., 1997).

These five telescopes used in this work are arranged at the corners of a square area with an side length of about 110 m. One IACT is located in the center of the telescope system.

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[1] HEGRA stands for "High Energy Gamma Ray Astronomy"

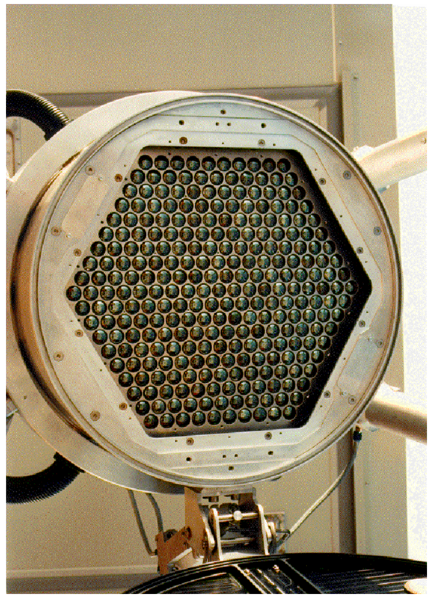

Fig. 1. View of one of the five identical HEGRA Cherenkov telescopes operated in stereoscopic observation mode (left). An IACT camera consisting of 271 photomultipliers arranged on a hexagonal grid leading to a geometrical field of view of approx. 4.3° (right).

Each telescope has a tesselated mirror area of 8.5 m^2 with a focal length of 5 m. A camera consisting of 271 photomultipliers (see Figure 1) in the focal plane of the mirror detects the Cherenkov photons from the air shower. The pixels have a diameter of 0.25° leading to a geometrical field of view of the whole camera of approximately 4.3° in diameter. This large field of view allows to search for sources of γ-rays in the TeV energy range in a wide area around the sky position the telescopes are pointed to.

The stereoscopic HEGRA telescope system operates with an energy threshold of E_γ >500 GeV for photons of vertical incidence into the atmosphere. The flux sensitivity

$$\Phi_\gamma(E > 1\,\mathrm{TeV}) \geq 10^{-12}\,\mathrm{ph.\,cm^{-2}\,s^{-1}}$$

is reached for an excess of $5\,\sigma$ within 20 hours of observation time. The stereoscopic reconstruction method provides an energy resolution $\Delta E/E \leq 20\,\%$, an angular resolution $\Delta\Theta/\Theta \leq 0.1°$ and a sufficiently small error $\Delta x_{\mathrm{Core}} \leq 20\,\mathrm{m}$ on the shower core position at the observation level (Konopelko et al., 1999).

The HEGRA telescope system records events with *stereoscopic air shower imaging*, i. e. events with at least 2 coincident trigger signals from the single telescopes. The image shape depends on the primary particle's type, energy, angle of incidence and the distance from the shower core to the telescope (impact parameter). A powerful separation of events induced by γ-rays and charged cosmic rays is applied using the image shape of the Cherenkov light detected by the telescope cameras. According to the image's *width* parameter (Hillas, 1985) as predicted using Monte Carlo simulations of γ-showers at the same zenith angle, core distance and image amplitude, the image parameter *width* is converted into a scaled value. The image parameter *mean scaled width* $\langle\tilde{w}\rangle$ is then calculated to be the mean value of the *scaled width* parameters of the single telescopes contributing to the event. A cut on $\langle\tilde{w}\rangle$ provides a separation between γ and hadron induced showers with a cosmic ray rejection of up to a factor of 100.

A good data quality is required for the search for TeV γ-radiation. This leads to specific conditions on the weather situation and the detector performance during data taking. The rate of events observed due to the isotropical background of charged cosmic ray particles as a function of the zenith angle is a useful indicator for the atmospheric observation conditions. In addition, the image parameter distributions of the background events are used to provide the necessary data quality.

3 Observations of Giant Radiogalaxies with the HEGRA Cherenkov Telescopes

A sample of relatively nearby objects has been selected for HEGRA observations of giant radiogalaxies. Prominent candidates in the Northern sky are NGC 1275 (Perseus A) and 3C 405 (Cygnus A) and M 87 (Virgo A) already introduced in Chapter 1. These radiogalaxies are located at distances in the range between about 20 Mpc (M 87) and 260 Mpc (Cygnus A). Details of the HEGRA radiogalaxy observations are given in Table 1.

M 87, NGC 1275 and Cygnus A have been observed with the HEGRA telescope system in the years 1998 to 2000. The angular extent of all three candidates is small compared to the instrument's angular resolution. Therefore, a search for *pointlike* sources of TeV γ-radiation is performed as described in the following Chapter. All observations have been performed at small zenith angles due to the appropriate declination of the selected radiogalaxies. The mean zenith angles

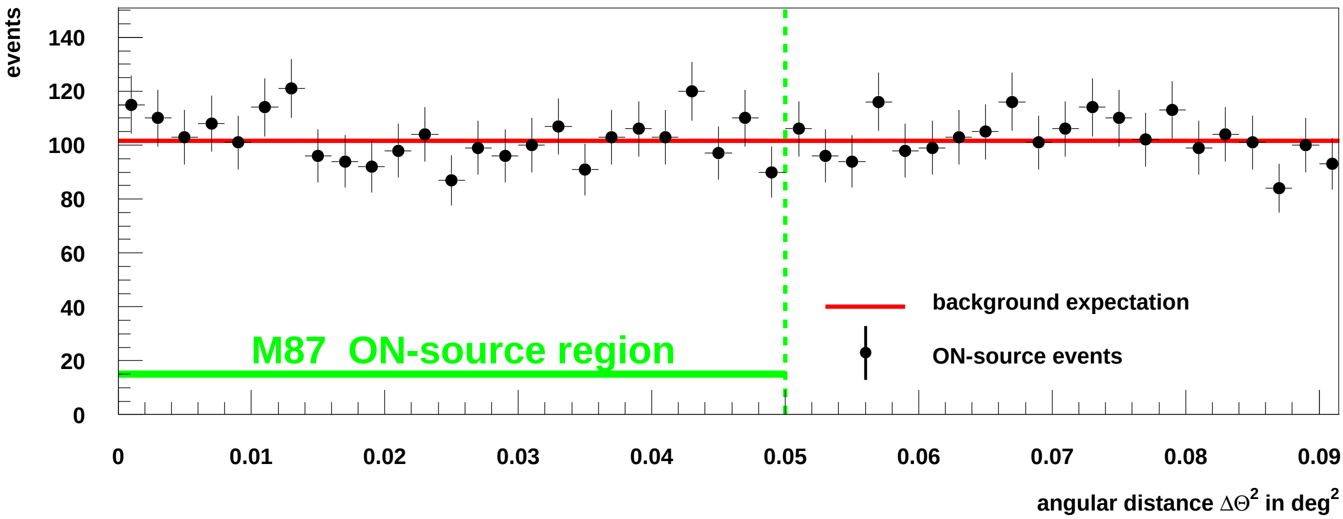

Fig. 2. Number of reconstructed events observed from the M 87 direction (preliminary) as a function of the squared angular distance $\Delta\Theta^2$ to the object. The *mean scaled width* cut $\langle\tilde{w}\rangle < 1.2$ is applied in order to perform a separation of photon and hadron induced events. The horizontal line indicates the mean number of background events while the region at $\Delta\Theta^2 < 0.05\,\mathrm{deg}^2$ (left of the dashed line) is the so-called "ON-source" region in case of a *pointlike* γ-ray source. The statistical uncertainties are indicated by the error bars.

$\langle\vartheta\rangle \approx 15°$ lead to an energy threshold of $E_{\mathrm{thr}} \approx 700\,\mathrm{GeV}$.

Time-near observations of the Crab nebula were performed during the same observation seasons. The Crab nebula is the "standard candle" for TeV γ-ray astronomy in the Northern hemisphere showing a very stable photon flux and energy spectrum (Aharonian et al., 2000). It is possible to independently control the systematic effects of the taken data using Crab nebula data sets with similar zenith angle distributions. The observations of the Crab nebula are also used to calculate upper limits on the TeV photon flux from the sample of investigated radiogalaxies.

Table 1. Observations of giant radiogalaxies and the Crab nebula with the HEGRA Cherenkov telescopes. All objects have been observed in the years 1998 to 2000. E_{thr} marks the energy threshold of the telescope system for the particular data set. The number of excess events is given with its statistical error. The value $\Phi_{90\,\%}$ means an upper limit on the TeV γ-ray flux Φ_γ at the 90 % confidence level. Flux limits are given in units of the flux of the Crab nebula ("Crab") and in units of $10^{-12}\,\mathrm{ph.\,cm^{-2}\,s^{-1}}$ ("abs."). The calculation of upper limits on the TeV γ-ray flux is described in the text.

Object Name	Redshift z	Time (h)	E_{thr} (GeV)
M 87	0.0043	44.1	720
NGC 1275	0.0176	71.5	690
Cygnus A	0.0561	25.0	750
Crab nebula		81.4	680

	excess events ($N_{\mathrm{ON}} - N_{\mathrm{OFF}}$)	$\Phi_{90\,\%}$ (Crab)	$\Phi_{90\,\%}$ (abs.)
M 87	28 ± 57	0.030	0.92
NGC 1275	14 ± 71	0.022	0.73
Cygnus A	-62 ± 40	0.020	0.57
Crab nebula	6929 ± 112	–	–

4 Results of the Radiogalaxy Observations

The observation of the giant radiogalaxy M 87 does not result in any indication of TeV γ-ray emission. In Figure 2 the distribution of events around the position of M 87 is plotted versus the (squared) angular distance $\Delta\Theta^2$. The number of background events is derived from an OFF-source region simultaneously observed with the investigated object. For this purpose the telescopes are operated in the so-called *wobble* mode (Aharonian et al., 1997). As the observed radiogalaxies and the Crab nebula are *pointlike* objects for the HEGRA telescope system, a cut on the primary's incidence direction is set to $\Delta\Theta^2 \leq 0.05\,\mathrm{deg}^2$ regarding the instrument's angular resolution. The image shape cut $\langle\tilde{w}\rangle < 1.2$ is applied to provide a separation between γ and hadron induced events.

The analysis of the observations of the objects NGC 1275 and Cygnus A has not shown evidence for TeV γ-ray emission either (see Table 1). Upper limits on the TeV γ-ray flux (at a confidence level of 90 %) can be calculated using the contemporaneous observations of the Crab nebula. The procedure as described by Helene (1983) is used for this purpose. The upper limits on the flux can be converted from units of the TeV photon flux of the Crab nebula to absolute flux units using the well measured photon flux and spectrum of the Crab nebula around 1 TeV (Aharonian et al., 2000):

$$\Phi_{\gamma,\,\mathrm{Crab}}(E > 1\,\mathrm{TeV}) = 1.8 \cdot 10^{-11} (E/\mathrm{TeV})^{-1.59}\,\mathrm{ph.cm^{-2}s^{-1}}$$

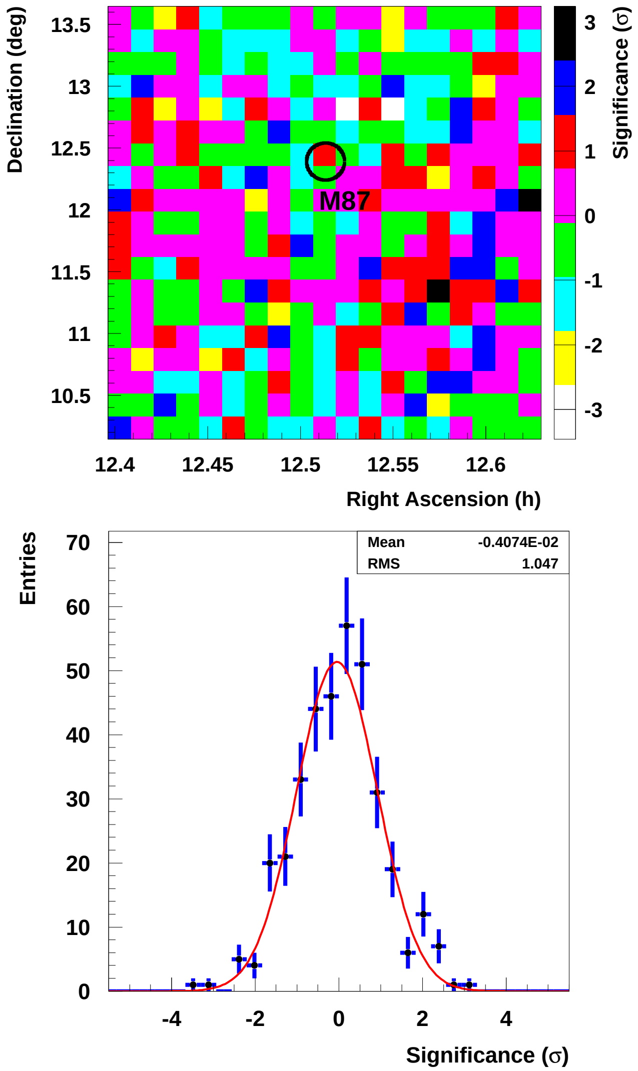

Fig. 3. *Top:* Result of the search for pointlike sources of TeV γ-rays in the sky region of M 87. The sky map shows the significances of the search bins derived using the grid search method described in the text. *Bottom:* The distribution of the significances in the individual search bins. The result is compatible with the null hypothesis of a sky region free of sources.

Following the model of Bai & Lee M 87 is a source of TeV γ-rays with a flux level of approx. $1 \times 10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$. Assuming an energy spectrum like the Crab nebula around 1 TeV, the HEGRA upper limit on the TeV flux from M 87 is at the same order of magnitude as the model prediction.

The three observed giant radiogalaxies are also the central objects of the prominent Virgo, Perseus and Cygnus *clusters of galaxies*. The HEGRA observations therefore also provide valuable information on TeV γ-ray emission from the core regions of these clusters of galaxies. As the HEGRA telescope system provides a relatively large field of view and a good angular resolution, a search for pointlike sources in the observed field of view is performed. A grid search method (Horns, 2000) is used in this analysis to search for hot spots around the investigated radiogalaxies. This approach subdivides the sky region into search bins regarding the angular resolution of the telescope system. The background estimation for each search bin is done using events with the similar angular distances to the center of the field of view excepting the search bin itself. Doing this, the radial acceptance of the camera does not have a systematic effect on the result. The significances of the excess in the individual search bins are calculated using the maximum likelihood method of Li and Ma (Li & Ma, 1983). Again, no evidence for a source of TeV γ-radiation can be found. To exemplify this result, a sky map of the M 87 region and the distribution of significances is shown in Figure 3. The distribution of significances is compatible with a Gaussian distribution with a mean value of 0 and an RMS value of 1 as expected from the null hypothesis of a sky region free of TeV photon sources.

As a further step of the data analysis, a search for diffuse TeV γ-radiation from the regions of the observed giant radiogalaxies will be performed in order to investigate the central areas of the Virgo, Perseus and Cygnus clusters of galaxies. Results of this study will be shown at the conference.

Conclusion: The HEGRA observations of giant radiogalaxies did not reveal evidence for TeV γ-ray emission from the investigated objects. No pointlike sources could be found in the surroundings of the observed candidates. The upper limit on the TeV photon flux from the nearby radiogalaxy M 87 calculated from a deep observation with the HEGRA Cherenkov telescopes is of the same order of magnitude as a model prediction assuming M 87 being a misaligned Blazar. Observatories using next-generation Cherenkov telescopes like MAGIC or VERITAS with a lower energy threshold and a larger sensitivity will give the possibility to verify or rule out this model.

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