The Giant Radio Galaxy M 87 as a TeV γ-Ray Emitter observed with the HEGRA Cherenkov Telescopes

Niels Götting, Martin Tluczykont and Götz Heinzelmann
for the HEGRA Collaboration
Institut für Experimentalphysik, Universität Hamburg, Luruper Chaussee 149, D-22761 Hamburg, Germany

Abstract

For the first time an excess of photons above an energy threshold of 730 GeV from the giant radio galaxy M 87 has been measured with a significance of 4.1 σ. The data have been taken during the years 1998 and 1999 with the HEGRA stereoscopic system of 5 imaging atmospheric Cherenkov telescopes. The excess corresponds to an integral flux of 3.3 % of the Crab flux. Making use of the imaging atmospheric Cherenkov technique, this is the first object of the AGN class observed in this energy range not belonging to the BL Lac type objects.

1. Introduction

Extragalactic TeV γ-ray emission has been observed with the imaging atmospheric Cherenkov technique so far from AGN only of the BL Lac type, i. e. objects ejecting matter in a relativistic jet oriented very close to the observer's line of sight. In BL Lacs, TeV photons are commonly believed to originate in the jets, most popularly due to inverse Compton scattering. The well studied objects Mkn 421 ($z = 0.030$), Mkn 501 ($z = 0.034$), 1ES 1959+650 ($z = 0.047$) and H 1426+428 ($z = 0.129$) belong to this type of TeV γ-ray emitters. However, other types of AGN, e. g. giant radio galaxies, also show jets, though, in contrast to BL Lac type objects, under large viewing angles. Amongst these the nearby radio galaxy M 87 ($z = 0.00436$) – containing a supermassive black hole with $M_{\rm BH} \approx 2\text{–}3 \times 10^9\,{\rm M}_\odot$ [11] – has been speculated to be a powerful accelerator of cosmic rays, including the highest energy particles observed in the universe, see e. g. [10, 8]. The angle of the M 87 jet axis to the line of sight was determined to be $30° - 35°$ [7].

The HEGRA collaboration has extensively observed M 87 in 1998 and 1999 with the stereoscopic system of 5 imaging atmospheric Cherenkov telescopes (IACT system) [9] as one of the prime candidates for TeV γ-ray emission from the class of radio galaxies. In this paper the encouraging results of these observations are reported, applying a very sensitive analysis method (see also [3]). Astrophysical conclusions concerning the nature of the observed excess are discussed.

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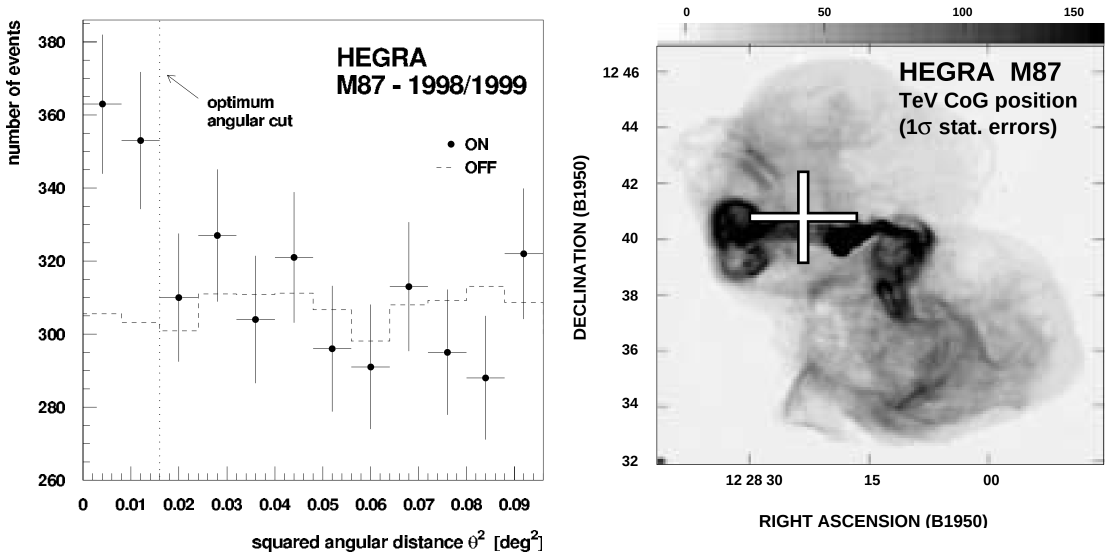

Fig. 1. Left: Number of events vs. squared angular distance to M 87 as observed in 1998 and 1999 with the HEGRA IACT system (dots: ON-source events, dashed histogram: background). The significance of the excess amounts to $4.1\,\sigma$. Right: The center of gravity position of the HEGRA M 87 TeV γ-ray excess is marked by the cross indicating the statistical $1\,\sigma$ errors (radio image adapted from [17]).

2. Observations and results of analysis

M 87 was observed in 1998 and 1999 with the HEGRA IACT system for a total of 83.4 h [3] above a mean energy threshold of 730 GeV for a Crab-like spectrum [14]. Only data of good quality were considered for the analysis.

All M 87 observations were performed in the *wobble* mode allowing for simultaneous estimation of the background ("OFF") rate induced by charged cosmic rays [1]. This analysis uses a ring segment as extended OFF-region reducing the statistical error on the number of background events [3]. The radius and width of the ring are set according to the position and size of the ON-source area in order to provide the same acceptance for ON- resp. OFF-source events. The event reconstruction (described elsewhere, e. g. [2]) makes use of algorithm #3 for the reconstruction of the air shower direction [13]. A "tight shape cut" (parameter $mscw < 1.1$) [14] is applied for an effective γ-hadron separation. The optimum angular cut was derived using γ-ray events from the Crab nebula on the basis of a nearly contemporaneous data set at similar zenith angles.

Figure 1 (left panel) shows the event distribution for the ON-source and the OFF-source regions as a function of the squared angular distance of the shower direction to the source position. The statistical significance of the observed excess from M 87 is $4.1\,\sigma$, calculated using formula (17) from [16]. On the basis of the limited event statistics the excess is compatible with a point-like source for the HEGRA IACT system at the position of M 87, although a slightly extended emission region cannot be excluded.

The event distribution in the field of view was used to determine the center of gravity position (CoG) of the TeV γ-ray excess at $\alpha_{\rm J2000.0} = 12^{\rm hr}30^{\rm m}54.4^{\rm s} \pm 6.9^{\rm s}_{\rm stat} \pm 1.7^{\rm s}_{\rm syst}$, $\delta_{\rm J2000.0} = 12^\circ 24' 17'' \pm 1.7'_{\rm stat} \pm 0.4'_{\rm syst}$ (see Figure 1, right panel). The accuracy of the CoG determination is limited by a systematic pointing error of about $25''$ [18]. Within the large statistical errors, the CoG is consistent with the M 87 position. Currently, it is not possible to localize a candidate TeV γ-ray production site to particular inner radio structures of M 87.

The observed excess can be converted into an integral flux of $(3.3 \pm 0.8)\,\%$ of the Crab nebula flux. A conversion into absolute flux units results in an M 87 γ-ray flux of $N_\gamma(E > 730\,{\rm GeV}) = (0.96 \pm 0.23) \times 10^{-12}\,{\rm phot.\,cm^{-2}\,s^{-1}}$. A spectral analysis of the data of the M 87 data has been performed using the analysis technique described in [4]. The data can be well described with a power law ${\rm d}N/{\rm d}E \sim E^{-\alpha}$ with $\alpha = 2.9 \pm 0.8_{\rm stat} \pm 0.08_{\rm syst}$.

3. Summary and Conclusions

The radio galaxy M 87 has been observed with the HEGRA IACT system for a total of 83.4 h. For the first time a significant excess of $4.1\,\sigma$ has been detected at energies above a mean energy threshold of 730 GeV from a member of this class of objects using the imaging atmospheric Cherenkov technique.

Due to the limited number of excess events detected so far it is difficult to draw a conclusion about the origin of the TeV γ-radiation. Assuming a spectral shape following a power law ${\rm d}N/{\rm d}E \propto E^{-2.9}$ the integral photon flux of $(3.3 \pm 0.8)\,\%$ of the Crab nebula flux converts into an energy flux of $F_\gamma(E > 730\,{\rm GeV}) = (4.3 \pm 1.0) \times 10^{-12}\,{\rm erg\,cm^{-2}\,s^{-1}}$. Given the distance to M 87 of about 16 Mpc, this corresponds to a γ-ray luminosity above 730 GeV of about $10^{41}\,{\rm erg\,s^{-1}}$ under the assumption of isotropic emission. The integral flux observed by HEGRA is not in conflict with an upper limit of 2.2×10^{-11} phot. cm^{-2}s^{-1} above 250 GeV reported by the VERITAS collaboration from data collected in 2000 and 2001 [15].

Several different possibilites for the origin of GeV/TeV γ-radiation are conceivable. M 87 with its pc scale jet has recently been modeled within the Synchrotron Self Compton scenario as a BL Lac object seen at a large angle to its jet axis [5]. Note, that a recent Chandra monitoring of the optical knot HST-1 in the M 87 jet (located only $0.8''$ away from the core) revealed a strong hint for a synchrotron origin of the observed X-ray emission [12]. The TeV γ-radiation of M 87 has also been modeled using the so-called Synchrotron Proton Blazar model [19]. In both models, the flux observed by HEGRA can be accommodated. The large scale (kpc) jets with several knots detected at radio to X-ray frequencies is also a possible γ-ray production site in M 87. Moreover, γ-rays could be produced in the interstellar medium at larger distances from the center of M 87. It should be noted that M 87 is also considered as a possible source of TeV γ-rays from the hypothetical neutralino annihilation process [6].

A weak signal at the centi-Crab level is at the sensitivity threshold for the HEGRA IACT system. Deep observations of M 87 with next generation Cherenkov telescopes like H·E·S·S, MAGIC and VERITAS will provide a high sensitivity together with a low energy threshold. Due to the proximity to M 87 (16 Mpc compared to 110 Mpc for the closest TeV BL Lac Mkn 421) these measurements will allow an accurate location and spectral analysis of the γ-ray emission site in M 87 thus greatly advancing our understanding of its TeV γ-radiation.

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