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Observation of the giant radio galaxy M 87 at TeV energies with the H.E.S.S. Cherenkov telescopes

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The giant radio galaxy M 87 was observed at TeV energies with the High Energy Stereoscopic System(H.E.S.S.) Cherenkov telescopes in 2003, during the construction phase, and in 2004/2005, with the full four-telescope setup. M 87 is of special interest for TeV observations since it is an active galactic nucleus (AGN) which does not belong to the class of blazars, which are so far the only confirmed extragalactic objects found to emit very-high-energy (VHE) γ-rays. The observations were motivated by the HEGRA evidence for TeV γ-ray emission from the direction of M 87. The results of the H.E.S.S. observations establishing M 87 as a TeV γ-ray emitter are presented.

1. Introduction

The giant radio galaxy M 87 is located at a distance of $\sim$ 16 Mpc ($z = 0.00436$) in the Virgo cluster of galaxies. The angle between the parsec scale plasma jet – well studied at radio, optical and X-ray wavelengths – and the observer's line of sight has been estimated to be in the range of $20° - 40°$. The mass of the black hole in the center of M 87 is $(3.2 \pm 0.9) \cdot 10^9\, M_\odot$ [1]. M 87 is believed to be a powerful accelerator of high energy particles, possibly even up to the highest energies [2, 3]. It is of particular interest for observations at TeV energies: The large jet angle makes it different from the observed TeV emitting active galactic nuclei (AGN) which are of the blazar type, i. e. with their plasma jets pointing directly towards the observer. Various models exist to describe the emission of TeV photons from M 87. Leptonic models (i.e. inverse Compton scattering) are discussed in [4], whereas [5] consider the TeV γ-ray production in large scale plasma jets. From the experimental point of view, the TeV γ-ray production in large scale jets would be of interest since the extension of the M 87 jet structure could be resolved at TeV energies with the typical angular resolution of stereoscopic Cherenkov telescope arrays of $\leq 0.1°$ per event. Hadronic models also exist [6, 7] as well as TeV γ-ray production scenarios correlated with the cosmic ray population of the radio galaxy [8]. Finally, the hypothesis of annihilating exotic particles (i.e. neutralinos) has been discussed by [9].

M 87 was observed with the HEGRA stereoscopic telescope system in 1998/1999 for a total of 77 h (after quality cuts). An excess of TeV γ-rays was found with a significance of 4.7 σ [10, 11]. The integral flux above an energy threshold of 730 GeV was calculated to be 3.3% of the flux of the Crab Nebula. The VERITAS collaboration reported upper limits obtained from observations between 2000 and 2003 above an energy threshold of 400 GeV with the 10 m Whipple telescope [12].

2. Observations of M 87 with H.E.S.S.

The H.E.S.S. collaboration operates an array of four imaging atmospheric Cherenkov telescopes optimized for an energy range between 100 GeV and several 10 TeV. The telescopes are located in the Khomas Highlands

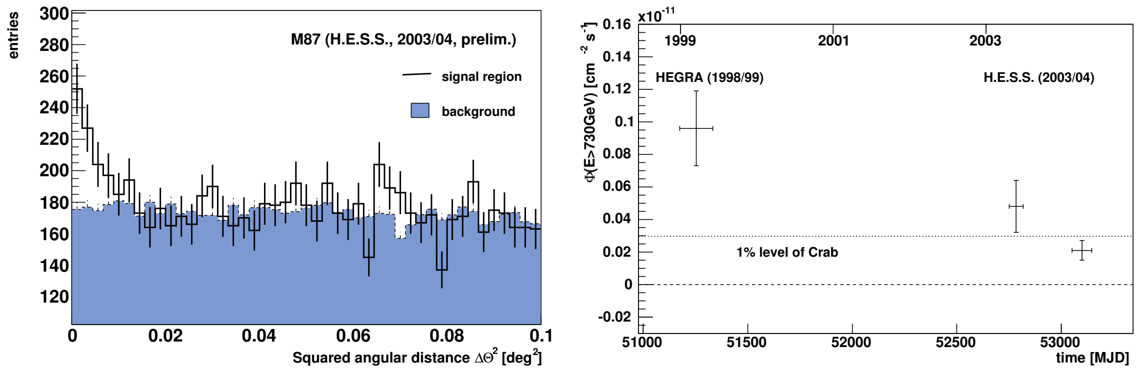

Figure 1. Left: Distribution of ON-source events (solid histogram) and normalized OFF-source events (filled histogram) vs. the squared angular distance $\Delta\Theta^2$. **Right:** The integral photon flux above a threshold of 730 GeV assuming of a power-law energy spectrum with a photon index of $\Gamma = 2.9$ (as reported by HEGRA [10]). The recent H.E.S.S. measurement in 2004 is not compatible with the HEGRA flux which indicates variability. However, additional systematic uncertainties between the different experiments need to be taken into account. The 1 % flux level of the Crab Nebula is also indicated.

in Namibia (23d 16′ 18″ S, 16d 30′ 1″ E) at a height of 1800 m above sea level. Each telescope has a 107 m^2 tessellated mirror surface [13, 14] and is equipped with a 960 photomultiplier tube (PMT) camera providing a field of view of $\sim 5°$ [15]. The full four-telescope array is operational since December, 2003. Since July 2003 the telescopes are operated in a coincident mode [16] assuring that at least two telescopes record an image for the corresponding event, which is important for an improved reconstruction of the shower geometry, and γ-hadron separation. More information about H.E.S.S. can be found in [17].

M 87 has been observed with the H.E.S.S. Cherenkov telescopes between March and May 2003 and February to May 2004. More observations were performed in 2005. The 2003 data were taken during the commissioning phase of the experiment with only two telescopes. The 2004/2005 data were taken with the full four-telescope array and a hardware coincidence trigger, increasing the sensitivity by more than a factor of two compared to the data taken during the 2003 observation campaign. The average zenith angle of the observations was $\sim 40°$ for all years. Due to technical reasons one of the four telescopes was excluded from the analysis in the February/March 2004 observation period, affecting ~ 9 h of the data by a slightly reduced sensitivity.

Standard cuts on the data quality (stable weather and detector status) have been applied, resulting in a dead-time corrected observation time of 13 h for the 2003 data and 32 h for the 2004 data. The 2005 data are still under analysis. After data calibration the H.E.S.S. standard analysis [18] was applied to the data. Some minor improvements to the analysis reported earlier [19] have been implemented.

3. Results

The distribution of events as a function of the squared angular distance, $\Delta\Theta^2$, between the reconstructed shower direction and the nominal position of M 87 is shown on the left side of Fig. 1 for the combined 2003/2004 data set. An excess of (211 ± 38) events was obtained corresponding to a significance of $5.8\,\sigma$, establishing M 87 as a TeV γ-ray emitting AGN. A preliminary analysis of the 2005 data shows an excess of $> 6\,\sigma$ which will be reported in more detail later. In order to calculate the integral flux above the energy threshold of the HEGRA measurement (730 GeV) for the 2003 and 2004 H.E.S.S. observations a power-law spectrum $\mathrm{d}N/\mathrm{d}E \sim E^{-\Gamma}$

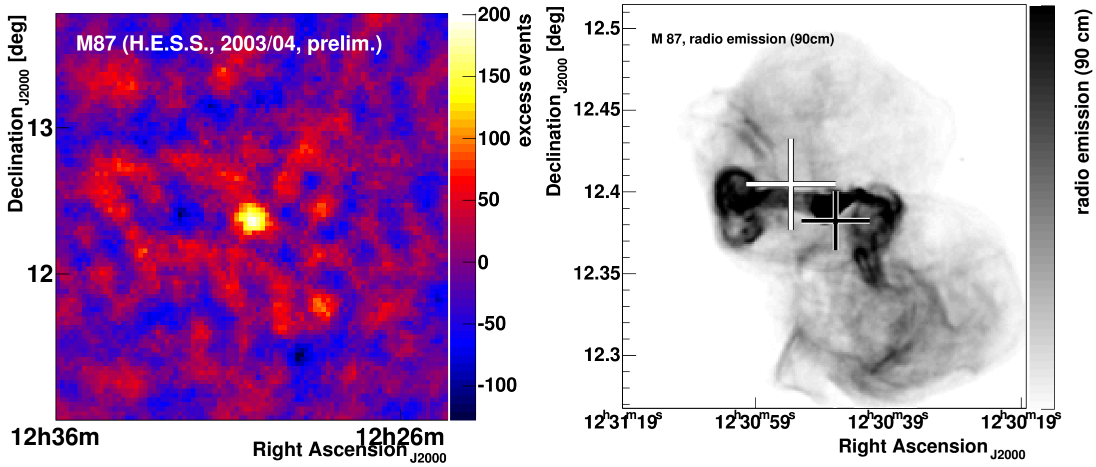

Figure 2. Left: The TeV excess sky map showing a $3° \times 3°$ sky region centered around the position of M 87. The number of events are integrated within the optimal point-source angular cut of $\Theta \leq 0.11°$ for each of the correlated bins. The background is estimated using the ring background model. **Right:** The mean positions of the H.E.S.S. TeV excess (black cross, including $1\,\sigma$ statistical and $20''$ pointing uncertainty error) together with the position measured by HEGRA (white cross, $1\,\sigma$ statistical error) plotted on the radio map of M 87 adopted from [20].

with a photon index of $\Gamma = 2.9$ (as reported by HEGRA) was assumed. The integral flux points for the individual years of 2003/2004 are shown on the right side of Fig. 1 together with the HEGRA measurement. A preliminary energy spectrum and a flux in 2005 have been determined, but are still under investigation. While the fluxes measured by H.E.S.S. in 2003 and 2004 seem to be compatible, the comparison of the H.E.S.S. 2004 flux with the HEGRA measurement indicates variable TeV γ-ray emission from M 87 on time scales of years. However, for such a comparison between results obtained from different experiments the systematic uncertainties of $\sim 20\%$ on the absolute flux calibration must be taken into account.

The TeV sky map is shown on the left side of Fig. 2. The mean position of the TeV excess as measured by H.E.S.S. in 2003/2004 is plotted in the radio map of M 87 together with the TeV mean position reported by HEGRA, see Fig. 2, right. The TeV excess is consistent with that of a point-source and its mean position is compatible, within statistical errors, with the center of the extended structure of M 87, as well as the position reported by the HEGRA collaboration. A more accurate position determination, including the 2005 H.E.S.S. data, is under analysis.

4. Summary & Conclusion

The giant radio galaxy M 87 has been observed with H.E.S.S. in 2003, 2004, and 2005. An excess of (211 ± 38) γ-ray events has been measured from the direction of M 87 in the 2003/2004 data with a significance of $5.8\,\sigma$, followed by an independent detection also in 2005 of $> 6\,\sigma$. This established M 87 as a TeV γ-ray emitting source. In the 2004 data, the measured flux is $\sim 1\%$ of the flux from the Crab Nebula, which indicates flux variability when compared to the $3.3\,\%$ flux level in 1998/99 reported by the HEGRA collaboration. The TeV excess is compatible with a point-source located the central M 87 position.

More observations are needed to confirm the indications of variability of the TeV γ-ray emission from M 87. Such a result is very important since several models for the TeV γ-ray production in M 87 could be ruled out. Mechanisms correlated with cosmic rays [8], large scale jet structures [5] and exotic dark matter particle annihilation [9] cannot explain variability in the TeV γ-ray emission on these time scales. The measurement of an accurate energy spectrum could further help to eliminate possible models, as could a more precise location determination of the emission region. Simultaneous observations at other wavelengths – especially in X-rays, such as the Chandra monitoring of the HST-1 knot in the inner jet region [21] – are of great importance since a correlation would further reveal the TeV γ-ray production mechanism of this AGN, which is the first confirmed extragalactic TeV γ-ray source not belonging to the blazar class.

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