Observation of the Giant Radio Galaxy M87 at TeV Energies with H.E.S.S.

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The giant radio galaxy M 87 was observed at TeV energies with the Cherenkov telescopes of the H.E.S.S. collaboration (High Energy Stereoscopic System). The observations have been performed in the year 2003 during the comissioning phase and in 2004 with the full four telescope setup. The observations were motivated by the measurement of the HEGRA collaboration which reported a $4.7\,\sigma$ excess of TeV γ-rays from the direction of M 87. The results of the H.E.S.S. observations – indicating a possible variability of TeV γ-ray emission from M 87 (compared to the HEGRA result) – are presented.

1. INTRODUCTION

The giant radio galaxy M 87 is located at a distance of $\sim 16\,\mathrm{Mpc}$ ($z = 0.00436$) 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 order of $20° - 40°$. The mass of the black hole in the center of M 87 is of the order of $2 - 3 \cdot 10^9\,M_\odot$. M 87 is discussed to be a powerful accelerator of high energy particles, possibly even up to the highest energies [17, 18]. This makes M 87 an interesting candidate for TeV γ-ray emission. M 87 was observed with the HEGRA stereoscopic telescope system in 1998/1999 for a total of 77 h (after quality cuts) above an energy threshold of 730 GeV. An excess of TeV γ-rays has been found with a significance of $4.7\,\sigma$ [9, 10]. The integral flux was calculated to be 3.3% of the flux of the Crab Nebula.

M 87 is of particular interest for observations at TeV energies: The large jet angle makes it different from the so far 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 emission of TeV photons from M 87. Leptonic models (i.e. inverse Compton scattering) are discussed in [11], whereas [12] consider the TeV γ-ray production in large scale plasma jets. From the experimental view, the TeV γ-ray production in large scale jets would be of particular 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 do also exist [13, 14] as well as TeV γ-ray production scenarios correlated with the cosmic ray population of the radio galaxy [15]. Finally, the hypothesis of annihilating exotic particles (i.e. neutralinos) has been discussed by [16].

Observations with the H.E.S.S. telescopes have been initiated to confirm the HEGRA result and to further clarify the origin of the TeV γ-ray emission,

2. THE H.E.S.S. EXPERIMENT

The High Energy Stereoscopic System (H.E.S.S.) collaboration operates an array of four imaging atmospheric Cherenkov telescopes optimized for an energy range between 100 GeV and 10 TeV. The telescopes are located in the Khomas Highlands in Namibia (23d 16′ 18″ S, 16d 30′ 1″ E) at a height of 1 800 m above sea level, see Fig. 1. Each telescope has a $107\,\mathrm{m}^2$ tessellated mirror surface [2, 3] and is equipped with a 960 photomultiplier tube (PMT) camera with a field of view of $\sim 5°$ [4]. The full four telescope array is operational since December, 2003. Since July 2003 the telescopes are operated in a coincident mode [5] assuring that at least two telescopes record images for each 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 [6].

3. OBSERVATIONS OF M 87 WITH H.E.S.S.

M 87 has been observed with the H.E.S.S. Cherenkov telescopes between March and May, 2003 and February to May, 2004. The 2003 data were taken during the comissioning phase of the experiment with only two telescopes. The stereo events have been merged offline based on their individual GPS time

Figure 1: The four imaging atmospheric Cherenkov telescopes (IACTs) operated by the H.E.S.S. collaboration in Namibia. Since December 2003 the full four telecope array is operational.

stamps. The 2004 data were taken with the full four telescope array with the hardware coincidence trigger. The sensitivity of the full setup increased by more than a factor of two compared to the sensitivity of the instrument during the 2003 observation campaign on M 87. The average zenith angle of the observations was $\sim 40°$ for both 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 leaving a dead-time corrected observation time of 13 h for the 2003 data and 32 h for the 2004 data. After data calibration [7] and application of image cleaning tail-cuts Hillas parameters [8] are calculated for the individual recorded images. The geometric shower reconstruction (direction, energy, etc.) follows the standard H.E.S.S. analysis technique [1].

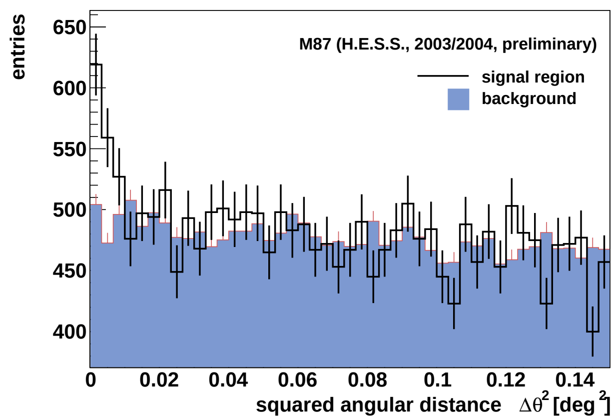

Figure 2: Distribution of ON-source events (solid histogram) and normalized OFF-source events (filled histogram) vs. the squared angular distance $\Delta\Theta^2$ between the reconstructed shower direction and the nominal object position.

4. RESULTS

Cuts which were optimized on Monte Carlo simulated sources comprising 10% of the flux of the Crab Nebula have been applied to the data including a tight angular cut of $\Delta\Theta^2 < 0.0125\,\mathrm{deg}^2$. Although the software stereo telescope setup in 2003 would legitimate a separately optimized set of cuts, the same cuts as for the 2004 data were applied to the 2003 data[1]. The distribution of excess 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 in Fig. 2 for the combined data set. An excess of 216 ± 49 events is obtained from the direction of M 87 corresponding to a significance of $4.6\,\sigma$. The sky map of the combined data set is shown in Fig. 3. The ring background model was used in which the background is determined from a ring region with a radius $r = 0.5°$ centred around the putative source position. The position of the TeV excess as measured by H.E.S.S. is plotted in the radio map of M 87 together with the TeV position reported by HEGRA (see Fig. 4). The TeV excess is compatible with a point-source and its position was found to be compatible with the center of the extended structure of M 87 as well as the position reported by the HEGRA collaboration within statistical errors. More observations are needed to reduce the statistical error on the derived position to further exclude regions within the extended structure of M 87.

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 $\mathrm{d}N/\mathrm{d}E \sim E^{-\Gamma}$ with a

[1]Investigations of improved analysis techniques optimized for faint sources are underway.

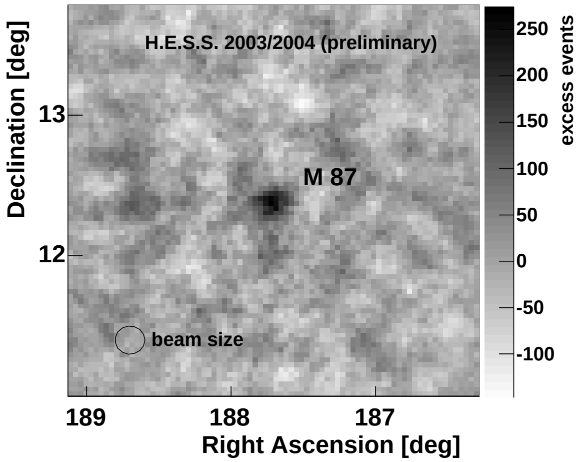

Figure 3: The TeV excess sky map showing a $3^\circ \times 3^\circ$ sky region centered around the position of M 87. The number of events are integrated within the optimal point-source angular cut of $\Theta \leq 0.11^\circ$ for each of the correlated bins. The background is estimated using the ring background model. The event-by-event angular resolution is indicated by the circle (beamsize).

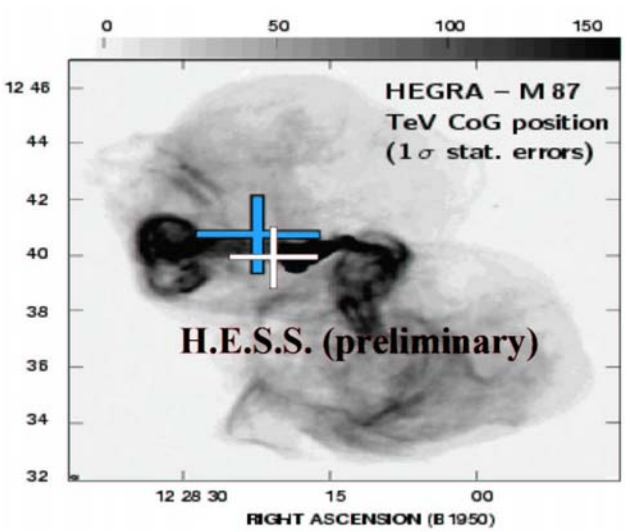

Figure 4: The positions of the H.E.S.S. TeV excess (white cross) together with the position measured by HEGRA (filled cross) plotted in the radio map of M 87 (adopted from [19]). Within statistical errors, both positions are compatible with the M 87 central region.

photon index of $\Gamma = 2.9$ (as reported in [10]) was assumed. The integral flux points are shown in Fig. 5 together with the HEGRA measurement. Note, that the 2004 flux of M 87 is below the 1% flux level of the Crab Nebula. Although the H.E.S.S. fluxes of 2003 and 2004 seem still to be compatible – taken the large statistical error of the 2003 measurement – 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.

5. SUMMARY & CONCLUSION

The giant radio galaxy M 87 has been observed with H.E.S.S. in 2003 during the comissioning phase and in 2004 with the full four telescope setup for a total of 45 h remaining after quality cuts. An excess of 216 ± 49 γ-ray events has been measured from the direction of M 87 with a significance of $4.6\,\sigma$. This confirms the HEGRA measurement, although on a lower flux level. The TeV excess is compatible with a point-source and within statistics its position is located at the center of the extended M 87 structure. The measured flux was found to be on the sub 1 % level of the flux from the Crab Nebula in the 2004 data which indicates flux variability if compared to the 3.3 % flux level in 1998/99 reported by the HEGRA collaboration.

To confirm the indications of variability of the TeV γ-ray emission from M 87 more observations are needed. Such a result would be very important since various models for the TeV γ-ray production in M 87 could be ruled out. Mechanisms correlated with cosmic rays [15], large scale jet structures [12] and exotic dark matter particle annihilation [16] could not explain variability in the TeV γ-ray emission on these time-scales. The measurement of an accurate energy spectrum could further help to reduce the amount of possible models as well as a more precise location of the emission region; both goals require a measurement with higher event statistics as currently available by the H.E.S.S. 2003/2004 data set.

M 87 has been observed in a wide range of the electromagnetic spectrum. Simultaneous observations at other wavelengths – especially in X-rays, such as the Chandra monitoring of the HST-1 knot in the inner jet region [20] – are of great importance since a correlation would further reveal the TeV γ-ray production mechanism of this AGN which is the first one not belonging to the blazar class.

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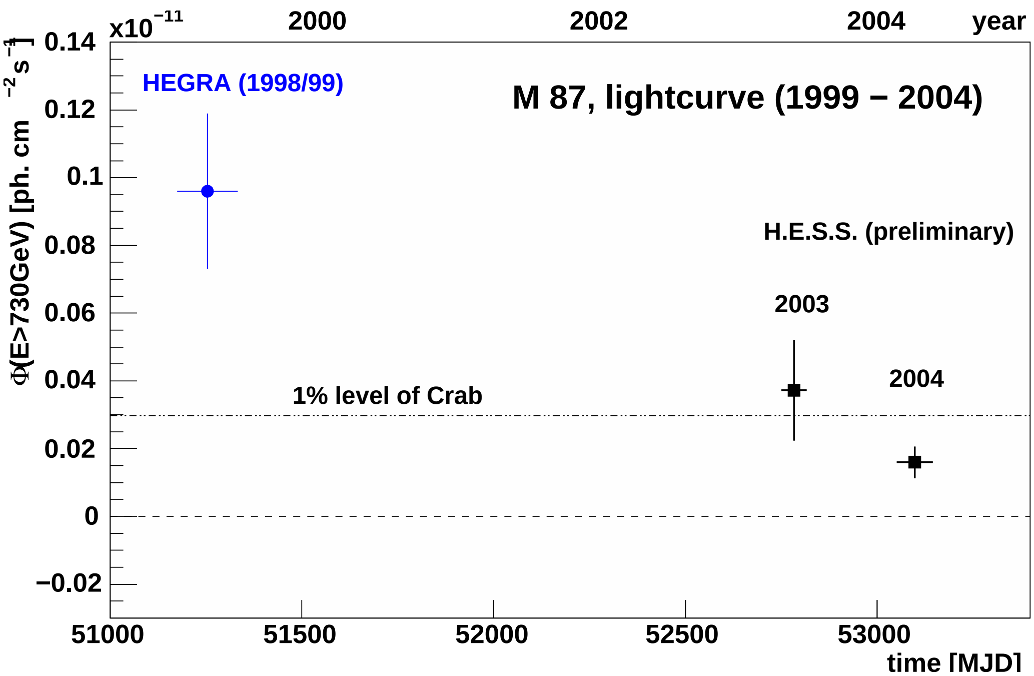

Figure 5: The integral photon flux above an threshold of 730 GeV is shown. The recent H.E.S.S. measurement in 2004 is clearly not compatible with the HEGRA flux (taken from [9]) which indicates variability. The 1 % flux level of the Crab Nebula is also indicated underlining the very low (but significant) flux of M 87 in 2004.

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