ICRC'07 Mérida, México

Discovery of fast variability of the TeV γ-ray flux from the radio galaxy M 87 with H.E.S.S.

M. BEILICKE[1], F. AHARONIAN[2], W. BENBOW[2], G. HEINZELMANN[1], D. HORNS[3], O. MARTINEAU-HUYNH[4], M. RAUE[1], J. RIPKEN[1], G. ROWELL[5], H. SOL[6] FOR THE H.E.S.S. COLLABORATION
[1] *Institut für Experimentalphysik, Univ. of Hamburg, Luruper Chaussee 149, D-22761 Hamburg, Germany*
[2] *MPI-K Heidelberg, P.O. Box 103980, D-69029 Heidelberg, Germany*
[3] *Institut für Astronomie und Astrophysik, Universität Tübingen, Sand 1, D-72076 Tübingen, Germany*
[4] *Laboratoire de Physique Nucleaire et de Hautes Energies, IN2P3/CNRS, Universites Paris VI & VII, 4 Place Jussieu, F-75252 Paris Cedex 5, France*
[5] *School of Chemistry & Physics, University of Adelaide 5005, Australia*
[6] *LUTH, UMR 8102 du CNRS, Observatoire de Paris, Section de Meudon, F-92195 Meudon Cedex, France*
matthias.beilicke@desy.de

Abstract: The giant radio galaxy M 87 was observed at GeV/TeV γ-ray energies with the H.E.S.S. (High Energy Stereoscopic System) Cherenkov telescopes in the years 2003-2006. The observations confirm M 87 as the first extragalactic TeV γ-ray source not of the blazar type (first indications of a signal were reported by the HEGRA collaboration earlier). The TeV γ-ray flux from M 87 as measured with H.E.S.S. was found to be variable on time-scales of years and surprisingly also of days which strongly constrains the size of the emission region. The results (position, energy spectrum and light curve) as well as theoretical interpretations will be presented.

Introduction

Observations of extragalactic objects at GeV/TeV γ-ray energies play a key role in the understanding of non-thermal processes and emission models of relativistic plasma jets. Meanwhile, more than 15 extragalactic TeV γ-ray sources are established, whereas only the giant FR I radio galaxy M 87 [1, 2, 3] is not a blazar [1], making it an important object for the understanding of jet formation and VHE γ-ray emission processes in AGN. M 87 is well studied in various wavelengths – allowing to constrain different system parameters, as for example the black hole mass, the accretion rate, etc.

The H.E.S.S. collaboration operates an array of four Cherenkov telescopes [4, 5] situated in Namibia. The telescopes measure cosmic γ-rays in the energy range between $100\,\mathrm{GeV}$ and several $10\,\mathrm{TeV}$ by recording the Cherenkov light which is emitted from an air shower which develops when a very high energy (VHE) particle (hadron or photon) enters the Earth's atmosphere. The stereoscopic observation together with a corresponding hardware trigger assures that an air shower is recorded by at least two of the four telescopes, allowing for an angular and energy resolution per event of $\delta\Theta < 0.1^{\circ}$ and $\Delta E/E \leq 15\%$, respectively, as well as an improved cosmic ray (CR) background suppression.

Variable TeV γ-ray emission from M 87

Radio-loud galaxies contain AGN with jets, but in contrast to blazars the emission is not (strongly) Doppler boosted due to larger viewing angles between the jet and the observer's line of sight. The radio-loud galaxy M 87 is located in the Virgo cluster of galaxies at a distance of $\sim\ 16\,\mathrm{Mpc}$ ($z\ =\ 0.0043$) and hosts a central black hole of

1. Blazars are active galactic nuclei (AGN) with their plasma jet pointing closely towards the observer's line of sight (the energy and flux of the emitted photons are boosted due to relativistic effects, making blazars detectable at TeV energies).

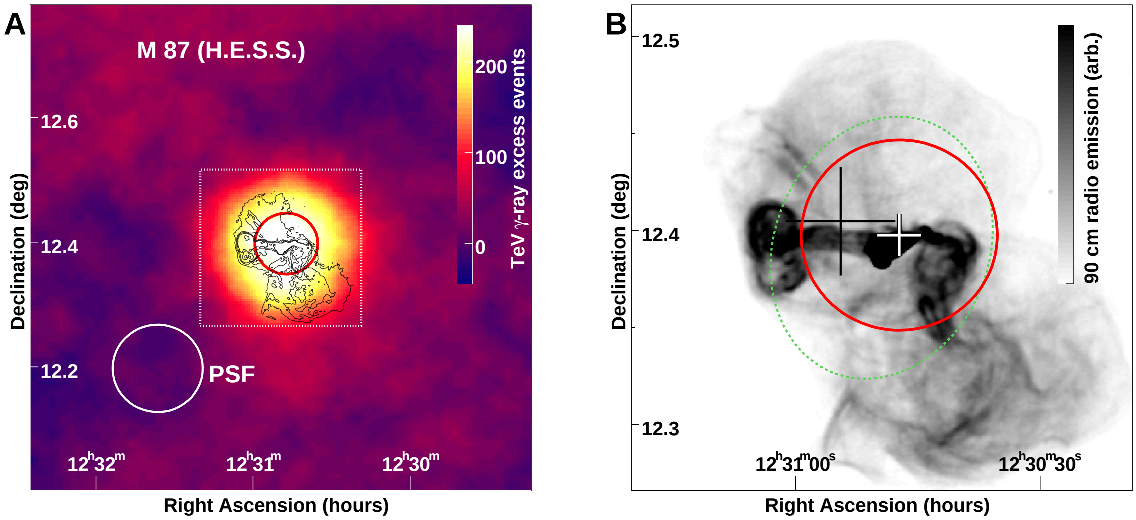

Figure 1: **Left:** Smoothed TeV γ-ray excess map and the upper limit on the intrinsic source extension (99.9% c.l., red circle) together with the $90\,\mathrm{cm}$ radio contours adopted from [13] as well as the H.E.S.S. point spread function (PSF, r_{68}). The white box indicates the cut-out of the right image. **Right:** The $90\,\mathrm{cm}$ radio image [13] showing the large scale structure ($\sim 80\,\mathrm{kpc}$ in diameter) of M 87 together with the TeV position (white cross, including the statistical as well as the $20''$ pointing uncertainty error) and again the extension limit (circle). The black cross indicates the position of the excess reported by HEGRA [1]. The green ellipse shows the extension of the M 87 galaxy in the optical band.

$(3.2 \pm 0.9) \cdot 10^9\,\mathrm{M}_\odot$ [6]. Due to its proximity M 87 is discussed as a possible source of the highest energy ($10^{20}\,\mathrm{eV}$) CRs [7]. The $2\,\mathrm{kpc}$ scale plasma jet (inclination angle of $30°$ [8]) is spatially resolved in different wavelengths, ranging from radio, optical to X-rays. Previously, evidence ($> 4\,\sigma$) for $E > 730\,\mathrm{GeV}$ γ-ray emission from M 87 in 1998/1999 was reported by HEGRA [1, 2] and no significant emission above $400\,\mathrm{GeV}$ was observed by Whipple [9] in 2000-2003.

M 87 was observed by H.E.S.S. between 2003 and 2006 for a total of $89\,\mathrm{h}$ after data quality selection. Using hard event selection cuts [5] an excess of 243 γ-ray events ($13\,\sigma$) was found in the whole data set. The position of the excess is compatible with the nominal position of the nucleus of M 87. With the given angular resolution of H.E.S.S., the extension is consistent with a point-like object with an upper limit for a Gaussian surface brightness profile of $3'$ (99.9% c.l.), corresponding to a radial distance of $14\,\mathrm{kpc}$ in M 87, see Fig. 1.

The energy spectra for the 2004 and 2005 data sets are shown in Fig. 2 (left) and are well fit by a power-law function $\mathrm{dN/dE} = \mathrm{I_0(E/1\,TeV)^{-\Gamma}}$ with photon indices of $\Gamma = 2.62 \pm 0.35$ (2004) and $\Gamma = 2.22 \pm 0.15$ (2005). The systematic error on the photon index and flux normalisation are estimated to be $\Delta\Gamma = 0.1$, and $\Delta I_0/I_0 = 0.2$, respectively. The hard spectrum measured in 2005 (reaching beyond an energy of $10\,\mathrm{TeV}$) challenges hadronic as well as leptonic VHE γ-ray emission models discussed for M 87 in the literature, see [10] and references therein.

The integral γ-ray flux above $730\,\mathrm{GeV}$ is shown in Fig. 3 (right) for the years 2003-2006 with a statistical significance for variability on a yearly basis of $3.2\,\sigma$. This is confirmed by a Kolmogorov test comparing the distribution of photon arrival times to the distribution of background arrival times yielding a significance for burst-like behaviour above $4\,\sigma$. Surprisingly, variability on time-scales of days (flux doubling) was found in the high state data of 2005 (Fig. 3, upper right panel) with a statistical significance of more than $4\,\sigma$. This is the fastest variability observed in any waveband from M 87 and strongly constrains the size of the emission region of the TeV γ-rays to $R \leq c \cdot \Delta t \cdot \delta \approx 5 \times \delta\, R_s$, where δ is the relativistic Doppler factor of the source of γ radiation and $R_s \approx 10^{15}\mathrm{cm}$ is the Schwarzschild radius of the supermassive black hole in M 87. This very compact emission region excludes a variety of models for the emission of the TeV γ radiation, i.e. CR interaction with matter in M 87, radiation due to annihilation of dark matter particles, the kpc plasma jet or even individual knots of the jet, and leaves only a region very close to the central black hole as a reasonable production site of the TeV γ rays with possibly novel mechanisms involved, see [10] for a more detailed discussion. Neronov and Aharonian (2007) explain the observed γ-ray flux by inverse Compton emission of ultrarelativistic electron-positron pairs which are produced in an electromegnetic cascade in the black hole magnetosphere [11].

M 87 was monitored during the past years by the Chandra X-ray satellite, see Fig. 3 (right). The X-ray flux of the knot HST-1 (located very close to the nucleus) increased by a factor of ~ 50 between 2003 and 2005 [12], whereas the emission of the nucleus itself remained rather constant. However, no unique correlation between the X-ray and TeV γ-ray fluxes can be stated, since the measurements were not performed simultaneously.

Summary and Conclusion

H.E.S.S. confirmed the giant radio galaxy M 87 as the first extragalactic TeV γ-ray source which does not belong to the class of blazars. The hard energy spectrum in 2005 challenges hadronic as well as leptonic models. The surprisingly discovered variability of the TeV γ-ray emission on short timescales of days strongly constrains the size of the emission region and excludes several models discussed for M 87, leaving a location close to the central black hole as reasonable production site of the TeV γ-ray emission. Simultaneous multiwavelengths observations and observations in the MeV/GeV energy range with GLAST are of special importance to estimate the position of the max-

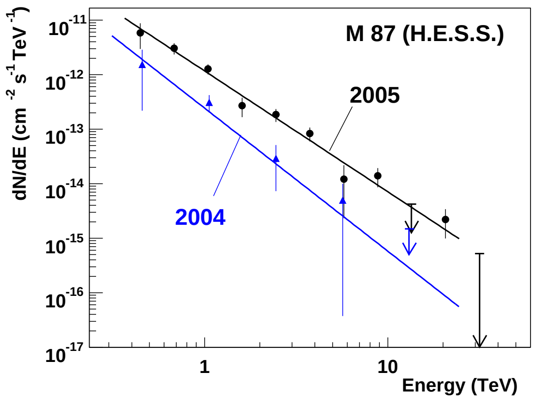

Figure 2: Energy spectra of M 87 (2004/05 data, using standard event selection cuts [5]) covering a range of $\sim 400\,\mathrm{GeV}$ to $\sim 10\,\mathrm{TeV}$. Spectra for the 2003 and 2006 data sets could not be derived due to limited event statistics. The lines show the fits of a power-law function.

imum of the VHE peak in the SED and further constrain model parameters. Taken M 87 as an established TeV γ-ray emitting radio galaxy, one should also mention the FR I radio galaxy Centaurus A (Cen A), which is located at an even closer distance of $3.4\,\mathrm{Mpc}$ ($z = 0.0018$) and shows a jet angle of $\theta > 50°$. Cen A is the only AGN not belonging to the class of blazars which was detected in the GeV energy regime by EGRET [14, 15], making a detection with GLAST promising. So far, no excess was found in the $\sim\,5\,\mathrm{h}$ of H.E.S.S. data taken in 2004 and 2005 [16].

Acknowledgements

The support of the Namibian authorities and of the University of Namibia in facilitating the construction and operation of H.E.S.S. is gratefully acknowledged, as is the support by the German Ministry for Education and Research (BMBF), the Max Planck Society, the French Ministry for Research, the CNRS-IN2P3 and the Astroparticle Interdisciplinary Programme of the CNRS, the U.K. Particle Physics and Astronomy Research Council (PPARC), the IPNP of the Charles University, the South African Department of Science and Technol-

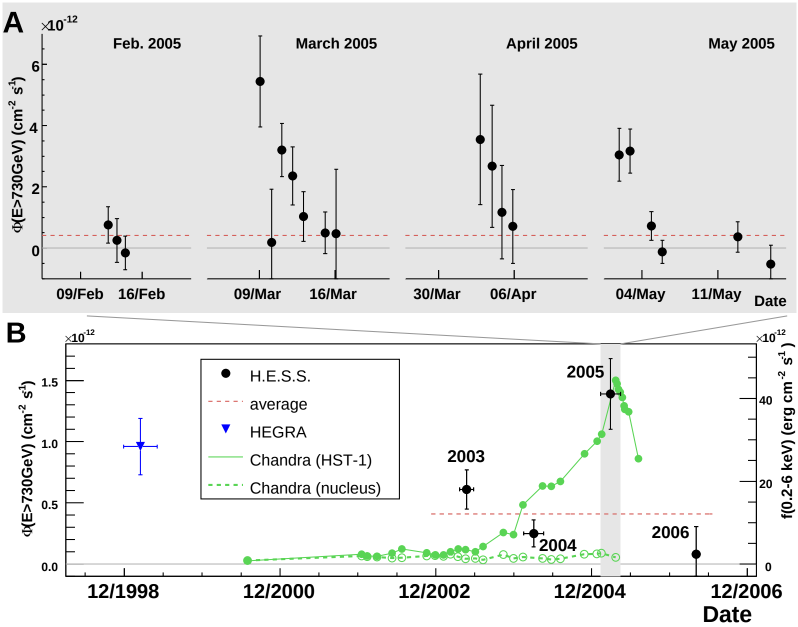

Figure 3: Gamma-ray flux above $730\,\mathrm{GeV}$. (B) The average flux values for the years 2003 to 2006 as measured with H.E.S.S. together with a fit of a constant function (red line). The flux reported by HEGRA is also drawn. (A) The night-by-night fluxes for the four individual months (February to May) of the high-state measurements in 2005 with significant variability on (flux doubling) time-scales of days. The green points in (B) correspond to the $0.2 - 6\,\mathrm{keV}$ X-ray flux of the knot HST-1 (solid, [12]) and the nucleus (dashed, D. Harris, priv. comm.) as measured by Chandra; the lines are linear interpolations of the flux points.

ogy and National Research Foundation, and by the University of Namibia. We thank D. Harris for providing the Chandra X-ray light curve of the M 87 nucleus.

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