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ORIGINAL ARTICLE

HESS observations of extragalactic objects

Results from HESS observations 2003–2005

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Abstract The HESS experiment (High Energy Stereoscopic System), consisting of four imaging atmospheric Cherenkov telescopes (IACTs) in Namibia, has observed many extragalactic objects in the search for very high energy (VHE) γ-ray emission. These objects include active galactic nuclei (AGN), notably Blazars, Seyferts, radio galaxies, starburst galaxies and others. Beyond the established sources, γ-ray emission has been detected for the first time from several of these objects by HESS, and their energy spectra and variability characteristics have been measured. Multi-wavelength campaigns, including X-ray satellites, radio telescopes, and optical observations, have been carried out for AGNs, in particular for PKS 2155-304, H 2356-309 and 1ES 1101-232, for which the implications concerning emission models are presented. Also results from the investigations of VHE flux variability from the giant radio galaxy M 87 are shown.

Keywords γ-rays · Extragalactic · AGN · PKS2155-304 · H2356-309 · 1ES1101-232 · M87 · NGC253

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1 Introduction

Observations of extragalactic objects at GeV/TeV energies play a key role in the understanding of the non-thermal processes in the universe. Using these observations emission models of particle distributions in relativistic plasma jets (found in blazars), the distribution and density of cosmic rays in galaxies as well as the level of the diffuse extragalactic background light (which generates an imprint due to absorption effects on the energy spectra measured from distant sources) can be tested. The simultaneous observation in different wave bands (radio, optical, X-rays up to TeV energies) is of general importance for the modelling of the emission processes.

The first extragalactic object detected at TeV γ-rays was the BL Lac type AGN Mkn 421 (Punch et al. 1992) located at a redshift of $z = 0.030$. Mkn 421 belongs to the class of blazars, i.e. 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). Meanwhile, more than 10 extragalactic TeV γ-ray sources are established (see Table 1), whereas only one of them, the giant FR I radio galaxy M 87 (Aharonian et al. 2003; Götting et al. 2004; Beilicke et al. 2005), is not a blazar.

The HESS collaboration operates an array of four IACTs (Hofmann 2005; Benbow 2005) situated in Namibia, see Fig. 1. The telescopes measure cosmic γ-rays in an energy range between 100 GeV and several 10 TeV by recording

Fig. 1 The HESS array of 4 imaging atmospheric Cherenkov telescopes located in Namibia at 1 800 m a.s.l.

For the HESS Collaboration.

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Table 1 Name, redshift z and references (discovery; HESS) for the so far known extragalactic TeV γ-ray sources ordered in redshift (†: the redshift of this object is not known). Except for M 87 all listed objects are blazars

Name	z	Reference
M 87	0.004	Aharonian et al. (2003), Götting et al. (2004); Beilicke et al. (2005)
Mkn 421	0.030	Punch et al. (1992); Astron. Astrophys. **437**, 95 (2005)
Mkn 501	0.034	Astrophys. J. **456**, L83 (1996); –
1ES 2344+514	0.044	Astrophys. J. **501**, 616 (1998); –
Mkn 180	0.045	Astrophys. J. **648**, L105 (2006); –
1ES 1959+650	0.047	26th ICRC, vol. 3, p. 370 (1999); –
PKS 2005-489	0.071	Aharonian et al. (2005b); Aharonian et al. (2005b)
PKS 2155-304	0.116	Astrophys. J. **513**, 161 (1999); Aharonian et al. (2005a)
H 1426+428	0.129	Astrophys. J. **571**, 753 (2002); –
H 2356-309	0.165	Aharonian et al. (2006b, 2006e); Aharonian et al. (2006b, 2006e)
1ES 1218+304	0.182	Astrophys. J. **642**, L119 (2006); –
1ES 1101-232	0.186	Aharonian et al. (2006b, 2006c); Aharonian et al. (2006b, 2006c)
PG 1553+113	$>0.09^{\dagger}$	Aharonian (2006a), astro-ph/0606161; Aharonian (2006a)

the Cherenkov light which is emitted from an air shower which develops when a 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 background suppression as compared to a single telescope.

Several extragalactic objects have been observed by HESS during the past years for which the main results are presented in Sect. 2 (blazars and their multi-wavelength interpretation), Sect. 3 (radio galaxies) and Sect. 4 (starburst galaxies).

2 TeV γ-ray blazars and multi-wavelength observations

Table 1 gives an overview over the so far established extragalactic TeV γ-ray sources. Except for M 87 (see Sect. 3.1) all of them belong to the class of blazars.

AGN are known to emit photons over the whole electromagnetic spectrum. The spectral energy distribution (SED) of blazars shows a double-humped structure with a first bump in the radio to X-ray regime, which can be explained by synchrotron emission of high energy electrons. Leptonic as well as hadronic models are discussed to explain the second bump in the GeV/TeV energy regime. Variations of the flux level have been observed in the TeV energy regime (as well as in other energy bands) on time-scales of days and shorter, underlining the importance of simultaneous multi-wavelength (MWL) observations. Also variations of the spectral shape with the TeV γ-ray flux were reported, i.e. for Mkn 421.

Energy dependent pair absorption processes of the TeV photons on the extragalactic background light (EBL) $\gamma_{\rm TeV} + \gamma_{\rm EBL} \rightarrow e^+e^-$ must be taken into account when interpreting the data from distant sources, since it imprints a corresponding signature to the measured energy spectrum. An indication for such a signature was first seen in the TeV energy spectrum of the blazar H 1426+428 ($z = 0.129$) by HEGRA (Aharonian et al. 2002). In 2005, even more distant blazars (H 2356-309 at $z = 0.165$ and 1ES 1101-232 at $z = 0.186$) were detected by HESS which allowed for the first time to put strong constraints on the level of the EBL which is discussed elsewhere (Aharonian et al. 2006b; Costamante 2007).

The measurements of (correlated) flux variability in different wave bands as well as the spectral variations provide the most important information for the modelling of particle distributions and their radiation processes of blazars. This is shortly discussed for PKS 2155-304 (Sect. 2.1), H 2356-309 (Sect. 2.2) and 1ES 1101-232 (Sect. 2.3), for which extensive MWL campains have been performed together with HESS observations.

2.1 PKS 2155-304

The high-frequency peaked BL Lac (HBL) PKS 2155-304 ($z = 0.116$) was first discovered at TeV energies by the Mark 6 Telescope (see Table 1) and was also detected by EGRET. It was observed in 2002/2003 by HESS during the construction phase and was confirmed as a TeV γ-ray source with a significance of $\sim 45\sigma$ (Aharonian et al. 2005a). The flux varied on time-scales of days and also hours, but no correlation between the spectral shape and the flux level was found. The overall spectrum is well fit by a power-law $\mathrm{d}N/\mathrm{d}E = N_0 \cdot (E/1\ \mathrm{TeV})^{-\Gamma}$ with a photon index of $\Gamma = 3.32 \pm 0.05$.

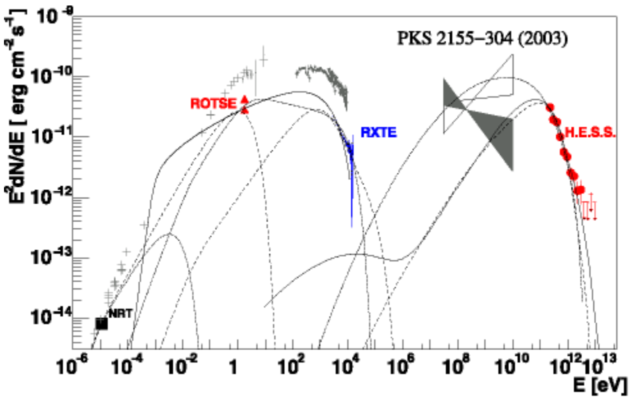

Fig. 2 Spectral energy distribution (SED) of PKS 2155-304 obtained from the Oct./Nov. 2003 MWL campaign (NRT, ROTSE, RXTE, HESS). *Grey points* indicate archival data. The *curves* show leptonic (*dashed*) and hadronic (*solid*) model fits, details can be found in (Aharonian et al. 2005e)

The Oct./Nov. 2003 HESS observations were accompanied by a MWL campaign together with RXTE (PCA), ROTSE and NRT (Aharonian et al. 2005e). Flux variations were found in the X-ray band (with a spectral hardening at higher flux levels), but no significant flux correlations between the different wave bands could be established. The SED is shown in Fig. 2 and can be described by either leptonic or hadronic one zone emission models (when correcting the models for the EBL absorption), see (Aharonian et al. 2005e) for more details. Comparing the measured SED to the archival data generally underlines the need for strictly simultaneous MWL observations.

Extensive monitoring was performed by HESS between Jul. and Sep. 2004 for more than 100 h, in which PKS 2155-304 was found to be in a higher flux state. Again, these observations were accompanied by RXTE X-ray observations, whereas the correlation factor between the TeV and X-ray fluxes derived from a subset of 44 data segments (within a period of 2 weeks) was found to be $r = 0.71 \pm 0.05$; analysis of the whole 2004 data set is underway.

2.2 H 2356-309

The HBL object H 2356-309 is located at a redshift of $z = 0.165$ and was detected for the first time at GeV/TeV energies with more than 10σ in a 40 h HESS observation campaign conducted from June to Dec. 2004 (Aharonian et al. 2006e). No significant variability of the integral photon flux was found. The energy spectrum is well described by a power-law above a threshold energy of 165 GeV with a photon index of $\Gamma = 3.06 \pm 0.21$. Implications of the detection of this distant TeV γ-ray source on the EBL are discussed elsewhere (Aharonian et al. 2006b; Costamante 2007).

The HESS observations were accompanied by simultaneous MWL observations in the radio (NRT, June and

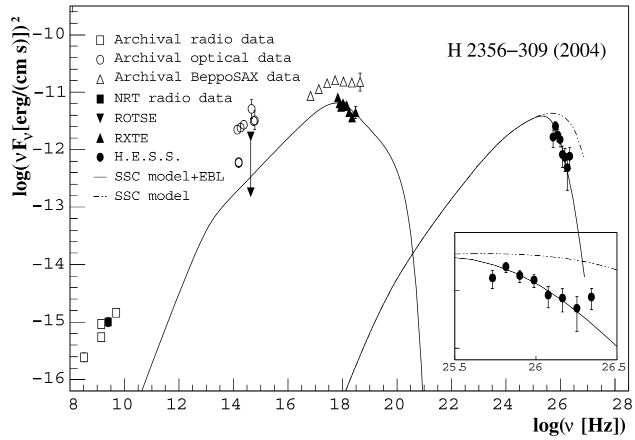

Fig. 3 SED of H 2356-309 obtained from the simultaneous 2004 MWL observations (*filled symbols*: NRT, ROTSE, RXTE, HESS). *Open symbols* indicate archival data. The *curve* shows a single-zone homogeneous SSC model, corrected for the EBL absorption, see (Aharonian et al. 2006e) for more details

Oct. 2004), optical (ROTSE, June to Dec. 2004) and X-ray (RXTE ToO: 5.4 ks, 11th of Nov. 2004) wave bands. Although being lower than earlier reported measurements by BeppoSAX (indicating a possible low state), no flux variations were found within the RXTE data. The SED is shown in Fig. 3 and can be well described by a single-zone homogeneous SSC model (taking into account the effects of the EBL absorption) with a spherical emission region of $R = 3.4 \times 10^{15}$ cm and a homogeneous magnetic field of $B = 0.16$ G, propagating with a Doppler factor of $\delta = 18$ with respect to the observer, see (Aharonian et al. 2006e) for more details.

2.3 1ES 1101-232

1ES 1101-232 is located in an elliptical host galaxy at a redshift of $z = 0.186$ and is classified as a HBL. Observations with HESS were performed in April and June 2004 in which 1ES 1101-232 was detected for the first time at GeV/TeV energies (Aharonian et al. 2006b). Further observations were done in March 2005. An excess of γ-rays with a statistical significance above 10σ was found in the whole data set (Aharonian et al. 2006c). No variations of the integral photon flux were found. The energy spectrum derived from the entire data set is well fit by a power-law with a photon index of $\Gamma = 2.88 \pm 0.17$. Taking this unexpectedly hard spectrum for this distant object, strong constraints on the level of the EBL could be derived from 1ES 1101-232 (Aharonian et al. 2006b; Costamante 2007).

Contemporaneous observations in other wave bands were performed in June 2004 at X-ray energies (XMM: 19.6 ks) as well as in March 2005 (RXTE: 110.2 ks, 11 nights) and optical wave bands (ROTSE). Small variations of the 2005 X-ray flux were found on a night-by-night basis. The SED

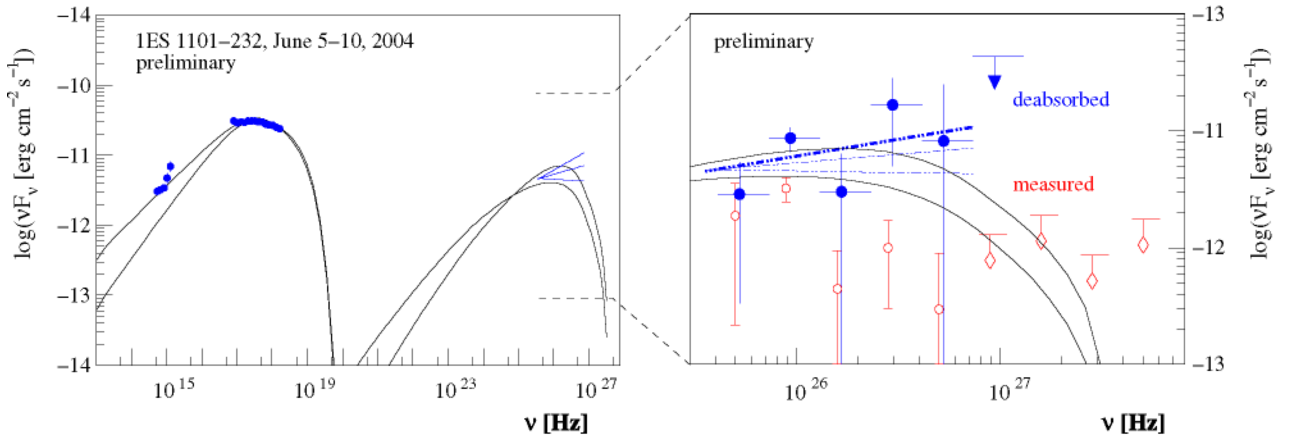

Fig. 4 *Left*: The simultaneously measured SED of 1ES 1101-232 from June 2004. The GeV/TeV spectra (shown as a power-law) were deabsorbed assuming three different levels of the EBL, see (Aharonian et al. 2006c) for more information. The curves show an one-zone homogeneous, time-independent SSC model. *Right*: Zoomed GeV/TeV energy region of the SED

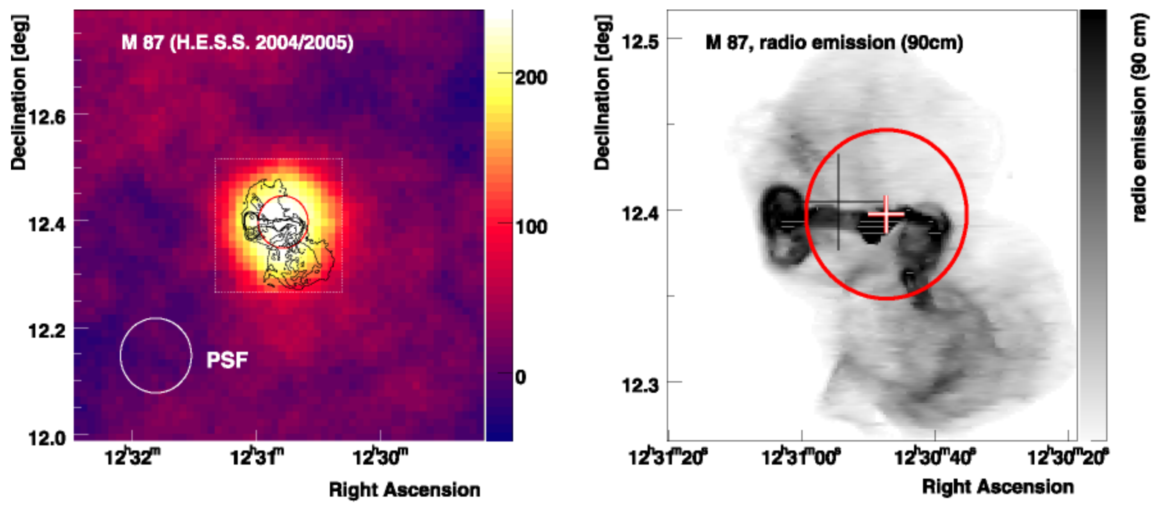

Fig. 5 *Left*: Smoothed TeV γ-ray excess map as measured by HESS together with the 90 cm radio contours adopted from (Owen et al. 2000). The *circle* indicates the upper limit on the intrinsic extension of the TeV γ-ray source (99.9% c.l.). The HESS point spread function (PSF, r_{68}) is also indicated. The *white box* indicates the cut-out of the right image. *Right*: The 90 cm radio image showing the large scale structure (∼80 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 (Aharonian et al. 2003). The central 2 kpc plasma jet can not be seen in this image

for the 2004 MWL campaign is shown in Fig. 4. The hard intrinsic (EBL deabsorbed) energy spectrum at GeV/TeV energies indicates that most of the measured excess comes from energies lower than the position of the intrinsic inverse Compton (IC) peak; the impact on the modelling of the SED is currently under investigation and will be discussed elsewhere (Aharonian et al. 2006c).

3 Radio galaxies

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. In radio-quiet galaxies the outflow is generally less (or not at all) collimated. Different radio-loud (e.g. 3C 120, Pictor A, Cen A and most intensively M 87) as well as radio-quiet galaxies (e.g. NGC 1068, NGC 3783, and NGC 7469) have been observed by HESS, whereas only M 87 and Cen A are addressed in this paper.

3.1 Variable TeV γ-ray emission from M 87

The giant radio galaxy M 87 is located in the Virgo cluster of galaxies at a distance of ∼16 Mpc ($z = 0.0043$) and hosts a central black hole of $(3.2 \pm 0.9) \times 10^9$ $M_\odot$ (Macchetto et

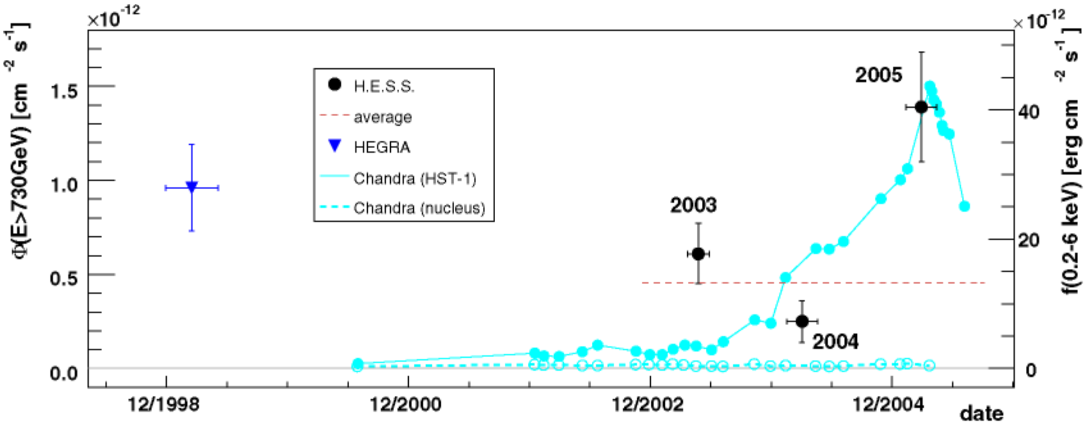

Fig. 6 Integral photon flux $I(E > 730\text{ GeV})$ from M 87 as a function of time for the years 2003–2005 together with a fit of a constant function (*dashed line*), as well as the flux reported by HEGRA. The *green/grey curves* correspond to the 0.2–6 keV X-ray flux of the knot HST-1 (*solid* Harris et al. 2006) and the nucleus of M 87 (*dashed*, provided by D. Harris) as measured by Chandra

al. 1997). Due to its proximity M 87 is discussed as a possible source of the highest energy (10^{20} eV) cosmic rays (Biermann et al. 2000). The 2 kpc scale plasma jet (inclination angle of 20°–40°) is resolved in different wavelengths, ranging from radio, optical to X-rays. Previously, evidence ($>4\sigma$) for $E > 730$ GeV γ-ray emission from M 87 in 1998/1999 was reported by HEGRA (Aharonian et al. 2003; Götting et al. 2004) and no significant emission above ~400 GeV was observed by the Whipple collaboration (Le Bohec et al. 2004) in 2000–2003.

M 87 was observed by HESS between 2003 and 2005 for a total of 83 h after data quality selection.[1] Using hard event selection cuts (Benbow 2005) an excess of 232 γ-ray events was found in the whole data set corresponding to a significance of 13σ. This establishes M 87 as the first extragalactic TeV γ-ray source which does not belong to the class of blazars. The position of the excess is found to be compatible with the nominal position of the nucleus of M 87. With the given angular resolution of HESS, 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 kpc in M 87, see Fig. 5.

The differential energy spectra obtained for the 2004 and 2005 data sets are well fit by a power-law $\mathrm{d}N/\mathrm{d}E \propto (E/1\text{ TeV})^{-\Gamma}$ each, resulting in photon indices of $\Gamma = 2.62 \pm 0.35$ (2004) and $\Gamma = 2.22 \pm 0.15$ (2005). The integral γ-ray flux above 730 GeV is shown in Fig. 6 for the years from 2003 to 2005 together with the flux reported by HEGRA. The indication for variability on a yearly basis within the HESS data corresponds to a statistical significance of 3.2σ. 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 4σ. The results of investigations of variability on shorter time-scales, which strongly constrain the size of the TeV γ-ray emission region, will be reported elsewhere (Aharonian et al. 2006d) together with implications on theoretical models.

M 87 was monitored during the past years by the Chandra X-ray satellite, see Fig. 6. 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 (Harris et al. 2006), whereas the emission of the nucleus remained rather constant. However, no unique correlation between the X-ray and TeV fluxes can be stated, since the measurements were not performed simultaneously which strengthens the need for simultaneous observations of M 87 in the different wave bands.

3.2 Observation of Centaurus A

The FR I radio galaxy Centaurus A (Cen A) is located at a distance of 3.4 Mpc ($z = 0.0018$), even closer than M 87. Cen A (with a jet angle of $\theta > 50°$) is the only AGN not belonging to the class of blazars which was detected in the GeV energy regime by EGRET (Sreekumar et al. 1999). Not only the $8° \times 4°$ large-scale radio structure but also the host galaxy ($14' \times 18'$) could be theoretically resolved in the GeV/TeV energy regime by ground-based IACTs (with an angular resolution of ~$6'$ per event). Similar to M 87, GeV/TeV γ-ray emission is expected from different models (Bai and Lee 2001) and evidence ($>4\sigma$) for γ-ray emission above 300 GeV has been reported earlier (Grindlay et al. 1975) which motivated observations of Cen A with HESS. No excess was found in the ~5 h of data taken in 2004 and 2005. The upper limit of the integral flux (assuming a power-law spectrum with $\Gamma = 3.0$) was calcu-

[1] The 2003 data were taken during the construction phase with only two operational telescopes and reduced sensitivity.

lated to be $I(E > 190 \text{ GeV}) < 5.7 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ at 99.9% c.l. (Aharonian et al. 2005c). Deeper observations of Cen A were performed in 2006 which are currently under investigation.

4 Starburst galaxies

4.1 The starburst galaxy NGC 253

The spiral galaxy NGC 253 is located at a distance of $d \approx 2.6$ Mpc and is the closest starburst galaxy[2] known. Due to the interaction of relativistic charged nuclei (accelerated in the supernova remnants) with surrounding gas, followed by the $\pi^0 \rightarrow \gamma\gamma$ decay, a detectable γ-ray flux from starburst galaxies is predicted (Völk et al. 1996). Although a detection of NGC 253 was reported by the CANGAROO collaboration, no emission of GeV/TeV γ-rays could be measured by HESS in a 28 h (after quality selection) observation campaign in fall 2003 during the construction phase of the experiment (Aharonian et al. 2005d). The corresponding flux upper limits for extended and point-like emission are shown in Fig. 7. NGC 253 was further observed with the full 4-telescope array in 2005 for roughly 12 h livetime. Again, no emission was detected which reduces the upper limits to even lower flux values as shown in Fig. 7. With these new limits, model predictions for the GeV/TeV emission from NGC 253 (Domingo-Santamaria and Torres 2005) can be tested.

5 Summary and conclusion

A variety of extragalactic objects has been observed by HESS during the past years and several new TeV γ-ray blazars were discovered. With a redshift of $z = 0.186$ 1ES 1101-232 is the most distant blazar detected so far, which allowed (together with H 2356-309) to put strong constraints on the spectral shape of the EBL. Many MWL observation campaigns (together with radio, optical and X-ray instruments) have been performed, allowing for a broadband modelling of the simultaneously measured SED of the different sources. HESS also confirmed the giant radio galaxy M 87 as the first extragalactic TeV γ-ray source which does not belong to the class of blazars. Investigations of variability of this source on short time-scales are currently underway. Other extragalactic object classes have been observed allowing for putting strong upper limits on the TeV γ-ray fluxes for various objects.

[2] Galaxies with enhanced and strongly localised star formation regions and therefore also expected higher supernova explosion rates.

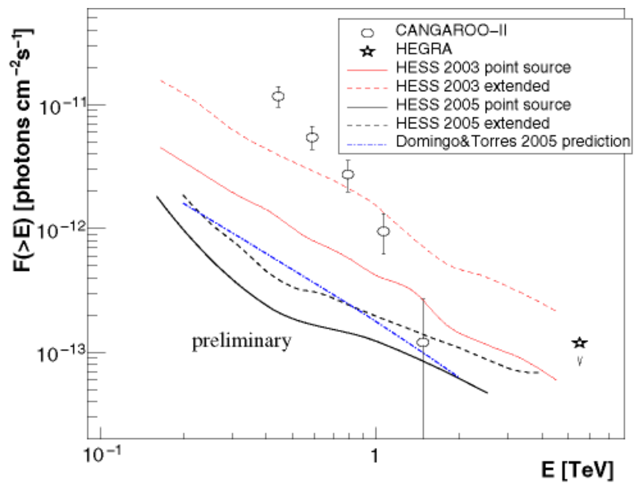

Fig. 7 HESS upper limits on the integral flux of γ-rays from NGC 253 (99% c.l.) for point like emission (*solid line*) and for a source of 0.5° radius (*dashed line*). CANGAROO integral data points and an upper limit from HEGRA (see Aharonian et al. 2005d for references) are shown for comparison. The *dash-dotted line* shows the nominal model value predictions of (Domingo-Santamaria and Torres 2005)

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