An overview of AGN observations with H.E.S.S.

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***Abstract*. The Imaging Air Cherenkov telescopes of the H.E.S.S. array have detected ten blazars and two radio galaxies so far, providing us with an unprecedented view of the extragalactic sky at very high energies. Flux and spectral variability have been observed for some of these sources. Upper flux limits were derived for many more AGN of different types. We summarize the main characteristics of the detected sources and discuss the constraints that the available H.E.S.S. data, in combination with data at other wavelengths, put on the emission processes in AGN. We briefly mention constraints on the EBL and on fundamental physics.**

***Keywords*: VHE gamma rays, AGN, IACT**

I. Introduction

Until now Active Galactic Nuclei (AGN) are the only extragalactic sources that can be detected in the Very High Energy regime (VHE; $>\sim$100 GeV) by ground based Cherenkov telescope arrays, such as H.E.S.S., MAGIC, VERITAS or CANGAROO. The H.E.S.S. array of four telescopes, situated in Namibia, has by now detected 12 AGN, including mostly high frequency peaked BL Lac (HBL) and two radio galaxies, M87 and Centaurus A. H.E.S.S. is also searching for signals from gamma-ray bursts [1], [2] and galaxy clusters [3], but so far they have proven more elusive than the continuously growing list of detected AGN.

Since VHE emission is purely non-thermal, it provides direct access to the particle acceleration processes in the source. AGN observations at TeV energies probe the emission zones that are thought to be located close to the central black hole or inside the jets. Variability in the observed light curves and the spectral behaviour of the emission yield valuable information on the size of the emission region and the radiative processes in the source. VHE data from Cherenkov telescope arrays are thus crucial to complete the picture of AGN derived from observations at longer wavelengths.

II. Upper limits on AGN

25% of the available observation time of the H.E.S.S. experiment is spent on the observation of AGN that seem likely VHE sources and on the monitoring of already detected AGN. Candidates for new detections are mostly X-ray and radio selected HBL, but other classes of AGN are also included in the observation program.

Data taken from January 2005 through July 2007 placed upper flux limits on 14 AGN with good-quality exposure [4]. Integral flux limits ranged from 0.9% to 4.9% of the Crab Nebula flux and were the most stringent for 8 of these sources, the remaining 6 being more strongly constrained by previous H.E.S.S. observations [5].

Apart from dedicated observations, upper flux limits have also been derived for a much larger number of AGN that happened to be in the field of view of a source followed by H.E.S.S. or in the region of the sky covered by the Galactic Plane scan. Based on data from March 2004 through December 2007, corresponding to a sky coverage of about 0.6 sr, flux limits of $<\sim$10% of the Crab Nebula flux have been derived for 63 AGN with distances of less than 100 Mpc [6].

III. AGN detections

Blazars of the HBL class are the most numerous AGN detected in the VHE range (cf. Figure 1, Table I). The observed fluxes from these objects are strongly amplified due to relativistic beaming of the jets that point close to the direction of the line of sight. These sources are characterised by a spectrum dominated by non-thermal emission, extending over the whole detectable wavelength range from radio to VHE, and by variability on time scales ranging from years to the sub-hour scale.

Up to now, 10 HBL have been detected by H.E.S.S., out of which 8 were first detections and one (Mrk 421) was a first confirmation of a detection by the Whipple telescope. Two radio galaxies of the FR I class have also been detected. VHE emission from M87 had been discovered by HEGRA in 2003 at 4.1σ and was confirmed by H.E.S.S. with data collected between 2003 and 2006. Very recently H.E.S.S. also discovered VHE γ-rays from Centaurus A [7], the most nearby radio-galaxy. The source of VHE emission from this object was found to be compatible with the radio core and the inner kpc jets.

Out of the 26 confirmed AGN that have been detected by now by the different Cherenkov telescope experiments, only 6 are not HBL, including the two FR I seen by H.E.S.S., three LBL or IBL (W Comae, 3C66A and BL Lacertae) and one FSRQ (3C 279). While the collection of data from a growing number of HBL allows the search for common characteristics of the source mechanisms, the discovery of members from different classes of AGN provides crucial tests for unification schemes. The prospects of discovering additional AGN with H.E.S.S. are very good, since many candidate sources have not yet been observed or only for a fraction of the necessary exposure.

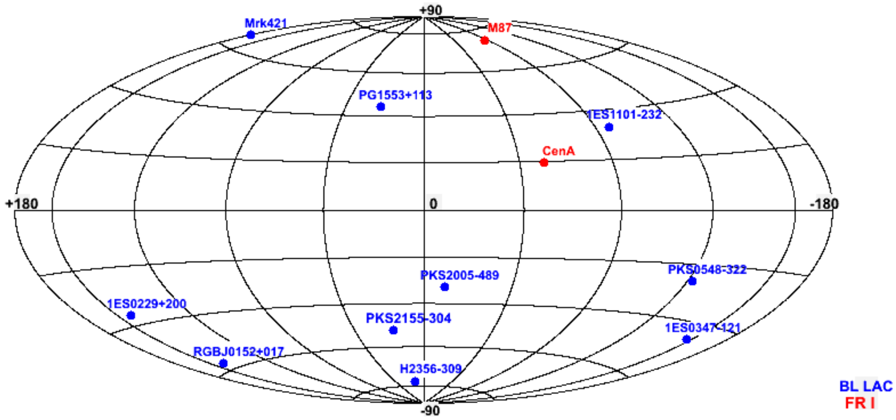

Fig. 1: Sky map in Galactic Coordinates showing the positions of the 12 AGN detected by H.E.S.S.

IV. An overview of the observed characteristics

A. *Flux variability*

BL Lac objects are seen in varying states of activity, with variability time scales ranging from years to several minutes. Periods of low fluxes and little or no variability can be followed by active states of high variability and rapid outbursts. Based on light crossing time arguments, one can derive constraints on the size of the emission region from the determination of the variability time scale.

The average flux of most HBL detected by H.E.S.S. is roughly 2% of the flux from the Crab Nebula above 200 GeV, with the exception of PKS 2155-304, which is the brightest blazar in the southern sky and is regularly monitored by H.E.S.S. This source is seen at 15% of the Crab during low states and was observed with a flux of up to 15 times the Crab during the 2006 high state [8]. A quiescent state, i.e. a level of minimal activity, has for the first time been extracted for PKS 2155-304 from the 2005 to 2007 data [9].

Mrk 421 is also known to have a high flux level of $\sim$15% at low states [10]. Due to its position in the northern sky, this BL Lac can be observed only under large zenith angles by H.E.S.S., which implies high energy thresholds. A high flux state of up to 5 times the Crab above 2 TeV was detected in 2004, while the source showed only marginal excess in later observations.

The shortest variability, on time scales of down to $\sim$3 minutes, has been observed in the two exceptional flares of PKS 2155-304 in July 2006. The two flares, detected during a high state of the source showed flux variations by a factor of $\sim$20 in only a few hours.

Variability on the scale of a few minutes implies either very large Doppler factors (of the order of 100) in AGN jets or the existence of emission regions of a size that does not scale with the Schwarzschild radius of the central black hole. Small, dense emission regions inside the jet provide a possible explanation.

Short term variability was also seen for Mrk 421 in 2004, where H.E.S.S. detected intra-night variability with a decay time of less than 1 h [11], consistent with the rapid variability of $<$ 15 min seen by Whipple [10]. The radio-galaxy M87 saw its flux increase by factor of $\sim$5 between 2004 and 2005. Variability on flux-doubling time scales of 2 days was seen in 2005. This requires a compact emission region of comparable size to the Schwarzschild radius, which excludes the extended jet and also the brightest knot in the jet ("knot A"). Variability at a scale of 1 day was detected in 2008 by MAGIC and VERITAS, during a joint campaign with H.E.S.S. [12].

Variations on a monthly scale were observed for PKS 2005-489, which showed flux variations by a factor of $\sim$3 in 2006, and for H 2356-309 [13]. Evidence for monthly variability is also seen in the latest data from RGB J0152+017[1].

The fluxes from 1ES 1101-232 and 1ES 0347-121 were constant during the observations that led to their discovery, but analysis of recent data suggests a variability at the scale of about a year. Significant flux variations on a yearly scale were also seen for PG 1553+113 in the 2005 and 2006 data from the MAGIC telescope [14], but not in the H.E.S.S. data, which were not taken simultaneously with MAGIC in 2006.

For the remaining AGN - Centaurus A, PKS 0548-322 and 1ES 0229+200 - no variability could yet be detected by H.E.S.S. due to their low flux levels. In the case of Centaurus A for example, given the current sensitivity of the experiment, only flux increments by more than a factor of about 15 to 20 on the time scale of days would be detectable.

B. *Spectral shape and spectral variability*

The intrinsic spectral shape of the observed AGN, after correction for the γ-ray absorption by the Extragalactic Background Light (EBL), yields information

[1] see S. Kaufmann et al. (for H.E.S.S.), in these proceedings

on the acceleration process of the underlying particle distribution. Spectral variability during flaring episodes is directly related to the dynamics of particle injection or acceleration, and cooling.

With the exception of the high flux states of Mrk 421 and PKS 2155-304, all AGN detected by H.E.S.S. can be characterized by a simple power law with a photon index between 2.2 and 4.5 before correction for absorption in the EBL. A curvature, break or cutoff in the spectrum can only be observed for sufficiently high photon statistics, i.e. during very active states of bright sources.

The 2004 data from Mrk 421 were best fit by a power law with an exponential cutoff at about 3 TeV, which is thought to be intrinsic to the source [11]. The spectral shape of this source was seen to change with the varying flux between different nights, being consistent with either a hardening of the spectrum or an increasing E_{cut} with an increasing flux.

The spectrum of the 28 July flare of PKS 2155-304 in 2006 was best fit by a broken power law, while the spectrum during the peak of the 30 July flare is best fit with a power law with exponential cutoff at $\sim$1 TeV or with a log-parabolic function. A hardening of the spectrum with increasing flux is observed for the second flare, whereas there is no significant change in the spectral index during the first flare. Spectral hardening with increasing flux may be accounted for by the injection of fresh high energy particles into the emission zone.

C. Multi-wavelength correlations

The detection of correlations between flux variations at different wavelengths can provide evidence of a common origin or a causal connection between the emission at different energies. Correlation studies of multi-wavelength data are thus a very important tool for the analysis of the emission processes in AGN.

During the joint H.E.S.S., MAGIC and VERITAS campaign in 2008, which was triggered by a flare from M87 detected by MAGIC in February 2008 [12], contemporaneous X-ray data from Chandra showed increased activity from the nucleus, while the innermost knot in the jet (HST-1) was found in a low state. This is in contrast to the high state of HST-1 found by Chandra during the 2005 VHE active flare and sheds new light on the question of the emission region.

Several multi-wavelength campaigns have led to a wealth of information from PKS 2155-304. While no correlation of H.E.S.S. data from the 2003 low state with the X-ray, optical or radio band was observed [15], the 2004 H.E.S.S. data showed a linear correlation with X-ray data from RXTE, when the source was in a more active state.

A strong and very steep correlation between the VHE and X-ray band was observed during the 2006 flares and active state of the source, both on intra-night scales (Chandra data) and on the scale of several nights (RXTE, Swift-XRT) [9]. There is no clear evidence for a direct correlation with the optical or radio flux, but both fluxes were elevated during the VHE high state and increased to a maximum with a delay of the order of a few months after the VHE flares.

A very recent joint H.E.S.S., Fermi, RXTE and ATOM campaign found the source again in a low state with no correlation between VHE and X-rays [17]. However there is some evidence for a correlation between the VHE and optical (ATOM) data. PKS 2155-304 seems to show a correlated behavior between VHE and X-ray emission only for active states, which could be a statistical effect, but could also indicate different populations of underlying charged particles that are responsible for emission in the two bands.

V. Interpretation with SSC models

One-zone Synchrotron Self-Compton (SSC) models provide a simple interpretation for the emission processes in HBL with a minimum number of free parameters. The double-peak structure that is characteristic of the spectral energy distribution (SED) observed from HBL is explained by a population of relativistic electrons in an emission zone with a tangled magnetic field inside the jet. Synchrotron emission is responsible for the peak in the UV to X-ray range, while a part of the radiation is up-scattered by the same electrons and provides the second peak at γ-ray to VHE energies. These scenarios are rather successful in reproducing the observed SED from HBL. The constraints they yield on the parameters of the emission region, magnetic field and electron population provide a valuable characterization of the emission process.

SSC models (mostly based on [31], [32]) have been applied to SED including H.E.S.S. data from PKS 0548-322, RGB J0152+017, PKS 2155-304, H 2356-309, 1ES 1102-232 and 1ES 0347-121. Typical values of the model parameters that were found for these sources range from 0.04 G to 0.6 G for the magnetic field, 3×10^{15} to 3×10^{16} cm for the size of the emission region, 18 to 25 for the Doppler factor and 3×10^{2} to 3×10^{4} cm^{-3} for the normalization of the electron spectrum, but these values do not represent unique solutions and can depend on the model.

The simple one-zone SSC approach, which predicts in general a correlation between the VHE γ-ray and X-ray fluxes, has been challenged by several observations that seem to require more than one emission zone to account for the VHE and X-ray spectra. A strong increase in the X-ray flux was seen in PKS 2005-489 between 2004 and 2005, while the VHE flux remained almost constant. The very hard spectrum from 1ES 1101-232 in 2005 is also difficult to reproduce with a single emission zone.

The nightly averaged SED of the 2006 active state of PKS 2155-304 can be quite well reproduced with the standard scenario, even though a large Doppler factor of $\sim$60 is needed to account for the high fluxes of the flares. However a time-dependent model with more than one emission zone is necessary to account for the very steep

Object name	Redshift	Type	First VHE detection	Flux level	Photon index	Shortest var. time scale
Centaurus A	0.0018	FRI	2008 (H.E.S.S.) [18]	0.8	2.7±0.5	–
M 87	0.004	FRI	2003 (HEGRA) [19]	∼1.4	2.20±0.15	∼1 day
Mrk 421	0.030	HBL	1992 (Whipple) [20]	300 (high state)	2.1±0.1 (E_c = 3.1 TeV)	<1 hour
PKS 0548-322	0.069	HBL	2007 (H.E.S.S.) [21]	1.4	2.8±0.3	–
PKS 2005-489	0.071	HBL	2005 (H.E.S.S.) [22]	2.8	4.0±0.4	∼1 month
RGB J0152+017	0.080	HBL	2007 (H.E.S.S.) [23]	2	2.95±0.36	∼1 month
PKS 2155-304	0.116	HBL	1999 (Mark VI) [24]	15 (up to 1500)	3.32±0.06 (low state)	∼3 min
1ES 0229+200	0.139	HBL	2006 (H.E.S.S.) [25]	1.8	2.50±0.19	–
H 2356-309	0.165	HBL	2006 (H.E.S.S.) [26]	2.3	3.09±0.24	∼1 month
1ES 1101-232	0.186	HBL	2006 (H.E.S.S.) [27]	2.3	2.94±0.20	∼1 year
1ES 0347-121	0.188	HBL	2007 (H.E.S.S.) [28]	2	3.10±0.23	∼1 year
PG 1553+113	>0.250	HBL	2006 (H.E.S.S.) [29], [30]	3.4	4.5±0.3	–

TABLE I: Overview of some characteristics of the AGN detected by H.E.S.S., ordered by redshift. The average flux level is given in % of the Crab Nebula integrated flux above the corresponding analysis threshold energy. The photon indices (H.E.S.S. results) have been determined from a power law and are not corrected for absorption by the EBL.

correlation between the VHE and X-ray flux evolution observed during the flare of the 30th of July [33].

VI. EBL DENSITY AND QUANTUM GRAVITY

Observations of distant AGN with H.E.S.S. have been exploited to constrain the energy density of the EBL in the optical to mid-infrared range. The hard spectra of the distant AGN 1ES 1101-232, H 2356-309, 1ES 0229+200 and 1ES 0347-121 yield upper limits that are very close to the lower limit derived from the emission from resolved galaxies [34], [28], [25].

H.E.S.S. data from the PKS 2155-304 flare on 28 July 2006 have also been searched for indications of an energy-dependence of the vacuum speed of light, predicted by quantum gravity models [35]. The high photon statistics of this flare allowed a search for time-lags between different energy ranges. No lags have been found and a lower limit has been determined for the energy scale of a potential Lorentz Invariance violation.

VII. AGN OBSERVATIONS WITH H.E.S.S.-II

Phase II of the H.E.S.S. experiment consists of the addition of a fifth, very large telescope with an effective mirror surface of ~ 600 m^2 , which is currently under construction. The combination of a larger collection surface, a larger number of pixels (2048 PMT) and a smaller field of view (3.5°) will lead to a greatly improved reconstruction of weak air shower signals. The energy threshold will thus be decreased to a few tens of GeV[2], where absorption by the EBL is less important. This will provide H.E.S.S. with access to AGN at higher redshifts, as well as improve the current sensitivity of the array.

Improvement in the sensitivity and energy range, with currently built instruments such as H.E.S.S.-II or the next generation Cherenkov Telescope Array (CTA), will lead to important advances in the study of VHE AGN. No less important is the continued progress of coordinated multi-wavelength campaigns, which have proven to be crucial for a complete study of the physical processes in AGN.

[2]see J. Masbou et al. (for H.E.S.S.) in these proceedings

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