Detection of very high energy $\gamma$-ray emission from active galactic nuclei in the central region of the Perseus cluster

Author(s): Hildebrand, Dorothée Maria

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Detection of Very High Energy $\gamma$-ray Emission from Active Galactic Nuclei in the Central Region of the Perseus Cluster

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for the degree of
Doctor of Sciences

presented by
DOROTHEE MARIA HILDEBRAND
Dipl.-Phys., Universität Karlsruhe (TH)
born June 21st, 1982
citizen of Germany

accepted on the recommendation of
Prof. Dr. Felicitas Pauss, examiner
Prof. Dr. Günther Dissertori, co-examiner
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Abstract

Since thousands of years, the visible light is used to explore the universe. Opening up other parts of the electromagnetic spectrum during the last century reshaped astronomy. The advancement into a new energy regime was always followed by ground-breaking discoveries. Twenty years ago the newest energy band was disclosed: the high energy end of the electromagnetic spectrum above 100 GeV, called Very High Energy (VHE) gamma-rays. At these energies the earth’s atmosphere is not transparent for photons, but a technique adapted from particle physics takes advantage of this characteristics. The atmosphere is used as a calorimeter and the resulting flashes of Cherenkov light can be detected with ground-based telescopes using cameras with photomultiplier tubes and very fast electronics.

Starting with the discovery of the first VHE source in 1989, the interesting detections made by the pioneering imaging Cherenkov telescope Whipple lead to the development of a new generation of instruments, MAGIC being one of them. The first MAGIC telescope takes data successfully since 2004. With the start of the operation of an improved second telescope, the MAGIC stereo system is best suited to access energies around 100 GeV. This generation of telescopes, also including H.E.S.S. and VERITAS, turned out to be very successful and increased the number of known VHE sources to more than 140. Amazingly, the VHE band hosts a variety of different astronomical objects emitting at these high energies. No class of object was detected more often than Blazars, a subgroup of the Active Galactic Nuclei (AGN), which can undergo drastic changes in their luminosity. An AGN forms when a super massive black hole in the center of a galaxy is accreting matter and ejects focused streams of particles perpendicular to the accretion disc. If one of those so-called jets points towards the earth, the AGN is classified as a Blazar. Only a small fraction of AGNs belong to the Blazar class and one can ask the question, if only this particular class of AGNs is able to emit VHE gamma-rays.

At the start of my PhD studies only one AGN not belonging to the Blazar class was known to emit VHE gamma-rays: the radio galaxy M87. The most abundant class of AGNs close to the Milky Way are Seyfert galaxies. I tracked down the subclass of radio loud Seyfert 1 galaxies as an interesting class for VHE gamma-ray emission and selected NGC1275, the central galaxy of the Perseus cluster, as the best candidate. I initiated a multi-wavelengths campaign from radio to VHE gamma-rays and became principle investigator of NGC1275 observations in MAGIC. During ongoing discussions about the MAGIC observation program for 2009/10, H.E.S.S. published the discovery of CenA, the second radio galaxy found to emit VHE gamma-rays.

For the first MAGIC stereo observation campaign of NGC1275 in winter 2009/10 the new stereo system was still in commissioning mode. This resulted in a degraded energy threshold, which turned out to be a problem for the NGC1275 campaign, as the VHE signal of this AGN was found to be weak and having a very soft spectrum. The energy threshold was too high for a clear detection. Surprisingly, data
taken for NGC1275 contained a VHE signal of another galaxy situated 0.6 degrees south east of NGC1275: the head tail radio galaxy IC310 was detected. I extract a power law spectrum with an index of $-2.0 \pm 0.3_{\text{stat}}$ and a flux at 1 TeV of $(1.21 \pm 0.19_{\text{stat}}) \cdot 10^{-12} \text{cm}^{-2}\text{s}^{-1}\text{TeV}^{-1}$ without any hint of a cutoff up to several TeV, making it one of the hardest VHE sources found so far. During the follow-up campaign in the next year, no VHE emission from IC310 was detected, a clear proof for variable emission, which rules out one theory about the origin of its VHE emission.

During the campaign 2010/11, MAGIC could finally measure a clear VHE gamma-ray signal from NGC1275 and announced the detection in October 2010. Detailed investigations showed, that the source emits photons at the edge of the MAGIC energy threshold, making the analysis very difficult. I extracted a power law spectrum with an index of $-4.1 \pm 0.4_{\text{stat}}$ and a flux at 150 GeV of $(6.9 \pm 1.7_{\text{stat}}) \cdot 10^{-12} \text{cm}^{-2}\text{s}^{-1}\text{TeV}^{-1}$, establishing NGC1275 as one of the softest VHE sources observed so far. With IC310 and NGC1275, two of the most extreme VHE gamma-ray emitting AGNs are located in the same field of view of MAGIC.

The discovery of VHE emission from NGC1275 and IC310 doubles the number of VHE radio galaxies from two to four. Therefore, the abundant class of radio galaxies might host a large population of VHE sources. When comparing M87, CenA, IC310 and NGC1275 with each other, taking into account the combined information of all wavelengths, evidence grows that parts of their jets might point towards earth. Regarding VHE emission, this would basically put these objects into a special subclass of Blazars. Due to their rather small distance to the Milky Way and their prominent jets, these radio galaxies are excellent laboratories to study the mechanisms of VHE emission in AGNs.

In this thesis I first summarize the current knowledge about cosmic rays, acceleration mechanisms and feasible sources, followed by a description of different types of AGN and the reasoning to select NGC1275 as interesting target. Next, the MAGIC telescopes as well as the other instruments used in the multi-wavelengths campaign are described. Then I briefly present the MAGIC data analysis and the results obtained for the AGNs in the Perseus galaxy cluster, combining them with the multi-wavelengths measurements. In the last part the results are set into a common context and are interpreted.
Zusammenfassung


Während der ersten Beobachtungskampagne von NGC1275 mit MAGIC im Winter 2009/10 wurde das Stereosystem noch im Commissioning Modus betrieben,
was eine Erhöhung der Energieschwelle zur Folge hatte. Das erwies sich als Problem, da sich das VHE Signal von NGC1275 als schwach und extrem niedriger getisch herausstellte. So war die Energieschwelle für eine evidente Entdeckung zu hoch. Überrascherweise fand sind in diesen Daten aber eine zweite Galaxie 0.6 Grad südöstlich von NGC1275, die VHE Photonen abstrahlte: die Head-Tail Radio Galaxie IC310. Ich rekonstruiere ein Spektrum, das bis zu mehreren TeV einem Potenzgesetz mit einem Index von $-2.0 \pm 0.3_{\text{stat}}$ und einem Fluss bei 1 TeV von $(1.21\pm 0.19_{\text{stat}}) \cdot 10^{-12} \text{cm}^{-2}\text{s}^{-1}\text{TeV}^{-1}$ entspricht. Damit hat IC310 eines der härtesten je gemessenen VHE Spektren. Im darauffolgenden Jahr ist keine VHE Emission von IC310 nachweisbar. Diese Flussvariabilität schliesst eine Theorie über den Ursprung seiner VHE Emission aus.

In den im Zeitraum 2010/11 genommenen Daten konnte schliesslich VHE Emission von NGC1275 nachgewiesen werden und MAGIC verkündete die Entdeckung im Oktober 2010. Die detaillierte Analyse erwies sich aber als sehr schwierig, da das Signal am unteren Energielimit von MAGIC liegt. Ich rekonstruiere ein exponentielles Spektrum mit einem Index vom $-4.1 \pm 0.4_{\text{stat}}$ und einem Fluss bei 150 GeV von $(6.9 \pm 1.7_{\text{stat}}) \cdot 10^{-12} \text{cm}^{-2}\text{s}^{-1}\text{TeV}^{-1}$. Damit besitzt NGC1275 eines der weichsten Spektren das je bei einer VHE AGN gemessen wurde. Mit IC310 und NGC1275 befinden sich zwei der extremsten VHE AGNs im selben Blickfeld von MAGIC.


In dieser Dissertation wird zunächst der Wissenstand über die die kosmische Strahlung, Beschleunigungsmechanismen und plausibler Quellen erläutert. Anschliessend werden die unterschiedlichen Arten von AGN besprochen und das Auswahlverfahren von NGC1275 beschrieben. Es folgt eine kurze Beschreibung der MAGIC Teleskope und der anderen in der Multiwellenlängenkampagne benutzten Instrumente. Desweiteren wird die Analysemethode von MAGIC dargelegt, sowie der MAGIC Datensatz von NGC1275 und die erhaltenen Resultate besprochen, die anschliessend mit den Ergebnissen der Multiwellenlängen Kampagne zusammengeführt werden. Im letzten Abschnitt werden die Ergebnisse in einen gemeinsamen Kontext gesetzt und interpretiert.
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Chapter 1

Cosmic Rays and Gamma-Rays

A century ago Viktor Hess measured the conductivity of air depending on the height above ground with an electrometer during a balloon flight. In contradiction to the expectation he measured the conductivity to increase with height. Therefore, the ionization of the air could not be induced by radioactivity from the soil but must have its origin somewhere outside of the earth. It was the first indirect measurement of Cosmic Rays [1]. In the following chapter the current knowledge of cosmic rays is presented.

1.1 Nature of Cosmic Rays

Cosmic rays are a stream of particles originating from space consisting mainly of ionized atoms. When they hit the atmosphere of the earth, each induces a particle cascade due to the interaction with atoms in the air. The particles of the cascade interact again with the atoms in the atmosphere generating more cascades that develop into an extended air shower. During the first decades of the 20th century these air showers were the birthplace and playground of particle physics. In 1932 Carl Anderson discovered the positron [2]. Together with Seth Neddermeyer, he also found in 1938 the muon [3] as ingredient of the cosmic ray induced air showers. The measurement of these two new particles formed the basis of a new view of physics.

During the 1950s the first particle accelerators reaching energies comparable to the particles measured in the extended air showers were built [4]. These machines allowed to conduct precision measurements under controlled conditions. From this moment, the accelerators became the main tools for research in particle physics and finally resulted in the highly successful Standard Model of particle physics (SM). But still today the extended air showers induced by cosmic rays are natural laboratories for particle physics. In 1998 the Super Kamiokande Collaboration discovered the
oscillation of neutrino flavors by observing the neutrinos produced in the air showers [5]. It was the proof that neutrinos cannot be massless as was assumed by the SM\textsuperscript{1}. Furthermore, cosmic rays contain few particles with ultra-high energy (UHE) exceeding $20^{20}\text{eV}$ [6], i.e. orders of magnitude more than the reach of the LHC at CERN.

1.2 The Energy Spectrum of Cosmic Rays

The flux of cosmic ray particles is rather isotropic and spans over more than 30 decades covering energies from $\sim 10^8\text{eV}$ up to more than $10^{21}\text{eV}$. At an energy of $10^{12}\text{eV}$ the flux is about 10 particles per square meter and minute, decreasing to one particle per square kilometer and century at an energy of $10^{20}\text{eV}$ (figure 1.1). At energies below $\sim 10^{10}\text{eV}$ the solar wind and magnetic field influences the spectrum of the cosmic rays, depending on the solar activity.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{cosmicray_flux.png}
\caption{The energy spectrum of cosmic rays [7].}
\end{figure}

\textsuperscript{1}Including a neutrino mass does not invalidate the SM, since the zero-mass was not a prediction but a simplification to reduce the amount of free parameters.
1.2. THE ENERGY SPECTRUM OF COSMIC RAYS

The spectrum itself is exceptionally featureless and for energies above $\sim 2 \cdot 10^9$ eV it can be described by a power law:

$$\frac{dN}{dE} \propto E^{-\gamma}$$ (1.1)

with a spectral index $\gamma \approx 2.7$ that changes to 3.1 for energies between $\sim 4 \cdot 10^{15}$ eV and $\sim 4 \cdot 10^{18}$ eV. The change of the index at $\sim 4 \cdot 10^{15}$ eV is called knee. The second change in the index at $\sim 3 \cdot 10^{18}$ eV is called ankle.

The universe is filled with photons of the cosmic microwave background (CMB)\[8],[9]. UHE protons above $6 \cdot 10^{19}$ eV interact with these photons via the processes:

$$p_{\text{UHE}} + \gamma_{\text{CMB}} \rightarrow \Delta^+ \rightarrow p + \pi^0$$ (1.2)

$$p_{\text{UHE}} + \gamma_{\text{CMB}} \rightarrow \Delta^+ \rightarrow n + \pi^+$$ (1.3)

For lower proton energies, this process is energetically forbidden.

The cross section of protons with photons of the CMB depends on the center-of-mass energy and can be measured precisely in the laboratory without the need to produce UHE protons [10]. The density of CMB photons is known as well with high precision [11]. Using these two numbers the mean free path length of protons is calculated to be less than 100 mega-parsec (Mpc). Protons originating from a larger distance likely interact with the CMB resulting in the so-called GZK-cutoff [12] [13].

A general assumption about particle acceleration up to an energy E is, that the local magnetic field must be strong enough to keep the Larmor radius of a charged particle within the extension of the field. Comparing the size of astronomical objects with the strength of their magnetic fields, one can see that none of them is able to accelerate protons to trans-GZK energies (figure 1.2)

Since no feasible accelerator seems to exist within 100 Mpc, the claim from the AGASA collaboration to have measured an excess of protons with energies larger than the GZK limit [14], gained a lot of interest. Assuming the measurement to be correct, the only explanations would be a Lorentz-Invariance violation, i.e. the proton-photon cross section at fixed center-of-mass energy being different for different proton energies, or the existence of a completely new kind of astrophysical accelerator in the vicinity of the Milky Way.

---

21 parsec corresponds to 3.26 lightyears or $30.8 \cdot 10^{15}$ m.

3The enormous magnetic field of special neutron stars, so called magnetars, would be sufficient, but in such an environment the protons would lose their energy immediately by synchrotron radiation. Gamma-ray Bursts (GRB) might also be candidates, but they usually happen at very large distances outside the local cluster.
Figure 1.2: The ‘Hillas plot’ shows the linear size $R$ and the magnetic field $B$ of an acceleration region. The shaded areas present size and field values for the different source classes, while the diagonal lines indicate the minimal $B R$ combination needed to be able to accelerate $p$ or Fe to energies exceeding the value given for each line [15].

New measurements by HiRes [16] and the Pierre-Augier-Observatory [6] do not yet give conclusive results if trans-GZK events exist at all (figure 1.3), but any excess would be significantly smaller than claimed by AGASA. Furthermore, the UHE flux could contain a significant contribution [17].

1.3 Acceleration of Cosmic Rays

As the origin of the cosmic rays cannot be thermal emission there exist basically two scenarios how to produce particles with such high energies. The first possibility would be a top-down mechanism where extremely massive particles or topological defects would decay into all kinds of high energetic particles. These models predict a high photon fraction in the particle flux. Recent results from the Auger Observatory rule out a significant contribution of the top-down scenario at energies above $3 \cdot 10^{18}$ eV [18].
The second, favored option is a bottom-up scenario where particles like protons or electrons are e.g. accelerated in shock fronts or reconnections of magnetic fields.\cite{19} Assuming

- a homogenous distribution and constant flux of cosmic ray particles in our galaxy as shown in figure \ref{fig:fig1}, i.e. an average energy density of $\epsilon \approx 1 \text{eV cm}^{-3}$,
- a typical retention time for cosmic ray particles in our galaxy of $\tau \approx 10^7 \text{years}$ \cite{20},
- the size of our galaxy $V \approx \pi (15 \text{kpc})^2 \times (200 \text{ pc})$,

the total power needed to keep a constant energy density can be estimated as

$$P = V \times \epsilon / \tau \approx 5 \times 10^{40} \text{erg/s} = 5 \times 10^{33} \text{J/s}. \quad (1.4)$$

For photons the conversion between different energy units is

$$1 \text{ GeV} = 1.6022 \cdot 10^{-3} \text{ erg} = 1.6022 \cdot 10^{-10} \text{ J} = 2.418 \cdot 10^{23} \text{ Hz}$$
There exist several astronomical objects that could release the needed amount of energy. Zwicky proposed already 1933 supernovae as possible sources for cosmic rays \[21\]. A type II Supernova\[5\] explosion releases in average \(10^{41}\) erg in terms of kinetic energy of the ejected shell. With the observed rate of 0.03 supernova per year in our galaxy, it would be sufficient to convert 10\% of this energy into particle acceleration to power the cosmic rays \[19\]. In 1949, Fermi proposed a collision-less acceleration mechanism \[22\] that is still considered the most probable acceleration mechanism in supernovae remnants and any other object that involve magnetic fields coupled to e.g. moving clouds.

### 1.3.1 Fermi Acceleration

Assuming a particle with a mass \(m\) and velocity \(v\) scattering at a magnetic cloud having velocity \(u\) with \(|v| \gg |u|\). The particle does not undergo a collision with a single atom in the cloud but scatters elastically with the whole cloud with a very large total mass. For illustration, one can easily calculate the energy gain of a particle in such a collision for the two extreme, non-relativistic cases:

In the first case the cloud is moving towards the particle (\(u\) and \(v\) anti-parallel):

\[
\Delta E_1 = \frac{1}{2}m(v + 2u)^2 - \frac{1}{2}mv^2 = \frac{1}{2}m(4uv + 4u^2) > 0.
\]  

(1.5)

In the second case the cloud is moving in the same direction as the particle (parallel):

\[
\Delta E_2 = \frac{1}{2}m(v - 2u)^2 - \frac{1}{2}mv^2 = \frac{1}{2}m(-4uv + 4u^2) < 0.
\]  

(1.6)

The average of the two extreme cases results in positive energy gain:

\[
\Delta E = \frac{1}{2}(\Delta E_1 + \Delta E_2) = 4mu^2.
\]  

(1.7)

Averaging over all angles between \(u\) and \(v\) and calculate for relativistic velocities, one finds an average energy gain per scattering of \[19\]:

\[
\Delta E \sim \frac{8}{3}u^2.
\]  

(1.8)

This is called 2\textsuperscript{nd} order Fermi acceleration or Fermi-2. If one assumes \(k\) scatters, for example on several magnetic bubbles or matter clumps, the total energy gain

\[5\] A type II supernova is a 'classical' core-collapse supernova at the end of the lifetime of a massive star.
is $k\Delta E$. A particle that travels long enough in a zone with e.g. magnetic bubbles could reach any energy.

At some time the particle escapes the acceleration region. After each scattering the probability of leaving the region is assumed to be $P$. Starting with $N_0$ particles with an energy $E_0$ per particle, after $k$ scatters the energy and the numbers of particles are:

$$E_k = E_0 + k\Delta E,$$

$$N_k = PN_{k-1} = P^kN_0. \tag{1.10}$$

This automatically results in a power law spectrum as measured up to highest energies, even with a very low energy gain per individual scattering. There are two major problems with this model:

- the acceleration process is slow, since the distance between such magnetic bubbles is rather large, resulting in rare scatters,
- the particles need an initial velocity larger than the velocity of the cloud, i.e. the acceleration process does not start if there are only particles with thermal velocities around.

The first problem can be circumvented if a shock wave traveling with velocity $u$ through a plasma induces a magnetic inhomogeneity. In this case the particle will be reflected at the shock front and accelerated. The magnetic field in front of the shock guides the particle back to the same shock, where the next acceleration step happens. This so called 1st order Fermi (or Fermi-1) process results in an average energy gain per reflection of ($v$ being the velocity of the particle):

$$\Delta E = E_2 - E_1 = \frac{1}{2}m(v + 2u)^2 - \frac{1}{2}mv^2 = 2m(uv + u^2) \tag{1.11}$$

If $v >> u$:

$$\Delta E \sim uv >> u^2. \tag{1.12}$$

It is obvious that the Fermi-1 process is faster than Fermi-2, but the maximum reachable energy is limited by the size and strength of the magnetic field (figure 1.2). Because it is known that in young supernova remnants (SNR) usually two spherical shock waves exist, it is also possible that the particles get reflected between the two shock waves. Still this reflection is limited by the strength of the shocked magnetic fields and accelerations to $> 10^{15}$ eV seem impossible. Because of the effective

\footnote{More precise: the particle is reflected by the magnetic field behind the shock front.}
acceleration mechanism together with the huge energy release, young SNRs seem best candidates as the main sources of galactic cosmic rays. But the so far best investigated SNR does not support this assumption \cite{23}.

Another possible acceleration mechanism can happen through magnetic reconnection. As a simplified model one can imagine two magnetic field lines with opposite polarity coming together in a plasma. In that case one can 'cut' the two lines and rearrange the fields in an energetically preferred way. In such a process a large amount of energy stored in the magnetic field can be released and accelerate particles in the plasma. Such processes are observed on the sun \cite{24} and there are indications that similar effects occur within the much larger and stronger magnetic fields in jets of active galactic nuclei \cite{25}.

### 1.3.2 Sources of Cosmic Rays

As cosmic rays are charged and the universe is filled with magnetic fields, the particles lose any directional information during their propagation from their sources to the earth. So the origins of the cosmic rays cannot be resolved directly (with the possible exception of UHE particles with $E > 10^{19}$ eV). The only chance is to look for neutral particles. Neutrons can not easily be accelerated (and anyhow would decay before reaching the earth), while neutrinos are still too hard to detect\footnote{No neutrino signal from a cosmic point source has been found so far \cite{26}}. This leaves high energy photons as the best tracers.

While high energy photons are not assumed to be directly emitted in the acceleration mechanisms, they can easily be produced by higher energetic particles as sketched in figure 1.4.

Whenever a proton interacts with matter, there exists a high probability to produce $\pi^0$'s that immediately decay into two photons ($p$ on target $\rightarrow \pi^0 + X \rightarrow \gamma\gamma + X$). If the proton has a very high energy while the target is at rest, the two photons will automatically reach high energies by a Lorentz-boost. On the other hand, high energy electrons can easily transfer energy to low energy photons by inverse Compton scattering. For this process a dense radiation field providing the low energy photons is needed. Another process is possible if electrons emit synchrotron radiation in a magnetic field. These rather low energetic synchrotron photons can then undergo inverse Compton scattering with the same electron population. If this so called Synchrotron Self Compton (SSC)\footnote{During the rearrangement, the moving magnetic fields induce an electric field that works as perfect accelerator for charged particles.} process takes part, one expects a correlation between X-ray (synchrotron) emission and high-energy gamma-ray emission. So finally the interaction of very high energy cosmic-ray particles with the environment is observed.
1.3. ACCELERATION OF COSMIC RAYS

Figure 1.4: Some gamma-ray production mechanisms [27]. See text for explanation.

- Protons interact with high matter density and produce gamma-rays via $\pi^0$ decay. Therefore, gamma-ray emission should be correlated with local matter density distribution.

- Inverse Compton (IC) scattering from electrons need a strong radiation field (e.g. close to a bright star)

- For the SSC mechanism, strong magnetic fields are needed and a correlation between synchrotron emission (e.g. X-ray) IC emission (e.g. high energy gamma-ray) is expected.

While these processes do not necessarily take place directly in the accelerator, it can be assumed that the density of very high energy particles close to the accelerator is much higher than average, so the gamma-rays should be emitted from the vicinity of the accelerator.

Therefore, the currently best method to search for cosmic accelerators is looking for very high energy gamma-rays with so called Imaging Atmospheric Cherenkov Telescopes (IACT) in combination with the Large Area Telescope LAT on the Fermi satellite, both described in Chapter 4.
1.4 Astrophysics with Gamma-rays

Photons have always been the tool to investigate the universe. Starting with visible light humans explored the celestial objects for millennia with the naked eye. This changed around 1600 when the first astronomers began to use optical telescopes to enhance their observational abilities \cite{29}. The golden age for astronomy was entered in 1933 with the first detection of an extraterrestrial radio source by Jansky \cite{30}. This new energy band under which the universe could be investigated changed the picture of the universe dramatically. Since the atmosphere is only transparent for limited wavelength-bands (as depicted in figure \ref{fig:opacity}), ground based astronomy is basically limited to optical and radio observations. This changed with the advent of first satellites that allowed to perform observations outside the atmosphere. In 1962 the first X-ray satellite observed the sky \cite{31} and in 1967 the first MeV gamma-ray sources were found in the Milky Way by the OSO-3 satellite \cite{32}. Since about twenty years also the multi GeV to TeV band of photons is observable: the Very high energy (VHE) gamma Astronomy started with the first IACT Whipple detecting the Crab Nebula in 1989 \cite{33}. A brief description of this technique that allows for ground based observation despite absorption of the initial gamma-rays is given in Chapter \ref{chap:4}.

![Figure 1.5: Opacity of the atmosphere as a function of wavelength \cite{34}.](image)

While the original goal of VHE astronomy was the quest for the sources of cosmic rays, and only a handful of objects were expected to exist still in 2003. Today more than 140 sources of VHE gamma-rays, their distribution shown in figure \ref{fig:distribution}, were discovered with the latest generation of IACTs. About half of the identified sources are inside our galaxy and they belong to several classes of astrophysical objects like supernova remnants, pulsars and pulsar wind nebulae, gamma-ray binaries...
and several not yet identified objects dubbed 'dark accelerators'. With the exception of two recently detected starburst galaxies [35] [36], all known extragalactic accelerators belong to the class of Active Galactic Nuclei (AGNs), where an active super-massive black hole in the center of a galaxy accretes large amount of matter and huge amounts of energy are released. A more detailed description about AGNs will be given in the next chapter.

Despite the unexpected richness of the VHE sky (a regularly updated list of VHE sources can be found at [38]), it is still not possible to clearly claim the origin of the cosmic ray particles. Nevertheless, the detection of VHE gamma-ray emissions from so many object classes challenges accepted astrophysical models. Observing the VHE sky is no longer limited to searching for the origins of cosmic rays, but is now also evolving into a new sector of astronomy. This might best be illustrated by the fact that there exist at the moment three VHE observatories: H.E.S.S. [41], MAGIC [42] and VERITAS [43] with a total of 10 telescopes, and a new observatory with more than 100 telescopes is in the design phase: the Cherenkov Telescope Array (CTA) [44].

Today, it is possible to do astronomy over all wavelengths, as e.g. nicely illustrated in figure 1.7. As will be shown later, so called Multi-Wavelength (MWL) observations are crucial for investigating the cosmic accelerators.

\[9\] This unfortunate name should not be mistaken to mean these sources are related to Dark Matter or Dark Energy.

\[10\] As an example: while the first detection of photons from a pulsar with energies above 25 GeV [39] was already a big surprise, there exists now confirmed observation of pulsed emission > 100 GeV [40] in clear contradiction to standard pulsar models.
For completeness it has to be mentioned that VHE gamma-rays can also be used to investigate other astrophysical and fundamental physics effects. The TeV energies together with very large distance sources are used to constrain the amount of extragalactic background light. Short scale variability of a source’s flux can be used as a tool to search for an energy dependent velocity of light \[46\] as predicted by some quantum gravity theories. And while current IACTs might not be sensitive enough, VHE gamma-rays can also be used to search for a signal from potential Dark Matter annihilation. As has recently been pointed out by \[47\], such indirect Dark Matter searches can explore regions of the supersymmetric phase-space that, because of too high neutrino background, are intrinsically not accessible to direct search experiments.
Chapter 2

Active Galactic Nuclei

In 1913 Edward Fath found the first hint that some "spiral nebulae" in the sky are more active than others by observing not only the typical absorption line spectrum but also emission lines from the source NGC1068 [48]. Later it was realized that such nebulae are independent galaxies. 1926 Edwin Hubble found two more objects showing similar features [49]. First measurements proving that some galaxies with emission lines share similar characteristics and form a distinct population were presented by Seyfert in 1943 [50].

2.1 Identification of Active Galactic Nuclei

In general, the compact region in the center of a galaxy with exceptionally high luminosity in some energy regimes is classified as AGN, if it shows emission lines on top of a bright non-thermal continuum, or strong flux variability. It is assumed that an AGN is caused by a super-massive black hole[1] situated in the center of its host galaxy. It is accreting matter in a disc and two strongly collimated relativistic particle outflows called jets are emitted perpendicular to the disc. An instructive image of an AGN is shown in figure 2.1. The accretion disk is obscured by a dust torus, and there exist moving clumps of gas in the vicinity. Depending on their velocity, these clumps are dubbed hot or cold and exhibit wide or narrow emission lines, respectively. This is depicted in figure 2.2. While the jets can be orders of magnitude larger than the whole host galaxy, the inner radius of the dust torus has a size of just a fraction of a parsec [51]. It is generally assumed that magnetic field lines anchored at the rotating accretion disk are responsible for the strong collimation of the jets as depicted in figure 2.3.

[1]There are strong indications that each galaxy hosts a super-massive black hole in its center, having masses from several millions to many billions of solar masses. The formation process for such black holes is not yet understood.
Figure 2.1: Very high resolution image of the AGN NGC4261. On the left image one can see the two huge jets, while zoom in the right image shows the dust torus.

Figure 2.2: Structure of an AGN (based on a figure from [53]).
2.1. IDENTIFICATION OF ACTIVE GALACTIC NUCLEI

Figure 2.3: Magnetic field lines collimate a narrow jet [53].

AGNs are observed to be variable on any time scale (from minutes to decades) and show many different properties that depend on observational constraints as well as intrinsic differences and different interactions with the surrounding medium. A good overview can be found in [54] and references therein. Here I will just summarize the most basic parts.

A conclusive single observable signature to identify AGNs does not exist. For different wavelengths, some characteristic properties are:

- **Radio:** Synchrotron emission from within the jets. With modern instruments the jets can be resolved in various substructures. Additionally, the jets can form so called radio-lobes, a shock front between the head of the jet and the surrounding medium.

- **Optical:**
  - Broad emission lines originating from illumination of the fast moving gas clumps. The emission lines are broadened by Doppler effect because of the rather fast (but non-relativistic) movement of the clumps.
  - Narrow emission lines are less broadened because of slower movement of the clumps farther away from the center.
  - Bright continuum emission originating directly from the nucleus.
• **X-ray:** Similar to optical emissions, there can be emission lines (from heavy elements in the gas clumps) or direct emission from the nucleus.

• **Gamma-ray:** Detection of fast flux variability is a strong indication for emission from an AGN, since other acceleration mechanisms that could induce high-energy emission are assumed to be too slow to allow for fast variability.

### 2.2 Classification of Active Galactic Nuclei

Based on their properties, AGNs are separated into several classes. Since these classifications are usually based on just one energy regime they can be highly contradicting for the same objects observed at different wavelengths. In the past, several attempts were made to combine the classifications. A very complete overview is shown in figure 2.4. The nowadays most often used assumption is the so called "unified model of AGNs" 55. It claims that the different appearance of AGNs can mainly be described as a dependence on the observation angle relative to the orientation of jet, as depicted in figure 2.5. But also this classification scheme is problematic since the measurement of this angle is difficult.

Here I summarize the classes most often found in the literature, following mainly 54.

- Most AGNs can easily be distinguished into well separated **radio loud** and **radio quiet** groups. Typically, the radio loud AGNs show clearly visible radio emission from the core, from at least one of the two jets and from two dominant lobes 2. In radio quiet AGNs, the radio emission is at least a factor $10^3$ suppressed compared to similar radio loud objects. On average, radio loud AGNs also show three times brighter X-ray emission.

- **Seyfert galaxies** (Sy) are the most abundant type of all AGNs discovered so far. Typically they are hosted in a nearby spiral galaxy and show bright emission lines of hydrogen, helium, nitrogen and oxygen and are radio quiet. The subclass Sy1 exhibits broad and narrow emission lines, while Sy2 is lacking the broad lines. It is assumed that in the case of Sy2 the broad lines from hot gas clumps in the inner part are obscured by the dust torus. In the mean time, this class has undergone a diversion in more subclasses between Sy1 and Sy2, containing galaxies sharing features of both classes. Some exceptional Sy galaxies are even radio loud.

- **QSOs** (quasi stellar objects) are typically very far away and show a starlike appearance, as their small core completely outshines the host galaxy. For a

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2Lobes are shock fronts separating the jets from the surrounding medium.
large number of them it is not possible to disentangle any signal from their host galaxy. Most QSOs show AGN emission similar to Sy1. About 10% of all QSOs are radio loud and are sub-classified as Quasars (Quasi stellar radio objects).

- **Blazars** are AGNs where the jet is directly pointing towards the observer. They do typically not show any emission lines and are highly variable. The most prominent subclass are BL Lac objects, named after the role model of this class BL Lacertae. Depending on the energy where the synchrotron spectrum from these objects peaks, they are further sub-classified into: high frequency peaked BL Lac (HBL), intermediate BL Lac (IBL) and low frequency peaked BL Lac (LBL).

- Another important class covers the Flat spectrum radio Quasars (FSRQ) showing a distinguished radio spectrum. While they seem to be a subclass of Quasars, recent observations (especially by the Fermi LAT, but also by
IACTs) imply that they might be a class of distant (or early) Blazars. This interpretation is widely accepted in the VHE community, and I will use it in this work. Recently, MAGIC detected VHE emission from the FSRQs PKS1222+24 [57] and 3C279 [58].

- **Radio Galaxies** are typically hosted by elliptical galaxies, show prominent jet structures and are radio loud. They are divided into the subclasses FR I and FR II that are probably similar to the Sy1 and Sy2 subclasses for spiral galaxies. Among the most prominent members of this class are M87, where the first jet was discovered already 1918 in the optical(!) band [59], and CenA, being the closest radio galaxy and the brightest radio source in the extragalactic sky.

Since the underlying emission mechanism(s) for AGNs are far from being understood, it is clear that these classifications can not be very strict. The identical object can be found in the literature associated to different classes, especially if the classifications were based on observations using different wavelengths. To make it even more complicated, the identical object has often various names, depending on the wavelength. As example, an extended list with names for NGC1275 can be found in table A-1 in the appendix.
2.3 Very High Energy Gamma-Ray Emission from Active Galactic Nuclei

It was quite a surprise when in 1991 the second ever detected source of VHE emission was the HBL Mrk421 [60]. Under the assumption that the emission of VHE gamma-rays is correlated with the relativistic jets of an AGN, it is rather obvious that Blazars are best extra-galactic candidates: if the relativistic jet is pointing towards the observer, any observable is Lorentz boosted to higher energy. Since HBLs seem to be the most powerful Blazars, they are assumed the best candidates to search for VHE emission from extragalactic objects.

In the past twenty years, more than 50 extragalactic VHE emitters have been identified by IACTs [38]. With the exception of two starburst galaxies [36] [35], all of them are AGNs, with a vast majority of Blazars.

One of the best studied AGNs in the VHE regime is Mrk421. The latest multi-wavelength observation campaign on this object [61] reveals the typical double hump structure of the spectral energy distribution shown in figure 2.6. The first hump is assumed to originate from synchrotron emission and is usually dubbed synchrotron peak, while the second hump can be described with inverse compton effect and is called IC-peak.

Figure 2.6: Spectral energy distribution of Mrk421 averaged over all the observations taken during the multi-frequency campaign from 19 January 2009 (MJD 54850) to 1 June 2009 (MJD 54983) [67].

\(^3\)As mentioned before, I adopt the convention to count FSRQs as Blazars.

\(^4\)For photons the conversion between different energy units is

\[1 \text{ GeV} = 1.6022 \times 10^{-3} \text{ erg} = 1.6022 \times 10^{-10} \text{ J} = 2.418 \times 10^{23} \text{ Hz}\]
So far, the only detected VHE emitting AGNs not belonging to the Blazar class are radio galaxies. Already in 2003, a strong hint for VHE emission was found from the radio galaxy M87 [62], but this object was generally explained to be exceptional. It is rather close, very bright and it was not excluded that the innermost part of one bent jet might point towards the observer. Therefore, M87 was sometimes classified as ‘misaligned Blazar’. In 2009, also the radio galaxy CenA in the Coma cluster was detected to emit VHE gamma-rays [63].

As will be described later, in the framework of the observation of the Perseus cluster two more radio galaxies were identified as VHE emitters, namely NGC1275 and IC310.
Chapter 3

The Central Region of the Perseus Cluster

When I joined the MAGIC Collaboration in 2008, the giant radio galaxy M87 was the only known extragalactic VHE emitter not belonging to the Blazar class. Considering that Seyfert galaxies by far outnumber all other types of AGNs it is a logic (but risky) step to search for VHE emission from such galaxies. As the amount of available observation time is small compared to the number of interesting observable objects for IACTs like MAGIC, it is difficult to get many hours granted to spend on a high risk project like searching for a VHE signal from a pure Seyfert galaxy. Therefore, I searched in the literature for an object that has clear characteristics of a Seyfert galaxy, but being radio loud. By far the most interesting object with these features is NGC1275, the central galaxy of the Perseus cluster (figure 3.1).

3.1 The Galaxy NGC1275

The galaxy NGC1275\(^1\) is situated in the constellation of Perseus at the coordinates: Equatorial (J2000.0) longitude: 49.9506671 latitude: 41.5116961 \(^2\). The distance from earth is 72.700±9.402 Mpc \(^6\). Another common name for the same source is 3C84, mainly used by radio astronomers.

NGC1275 is an AGN that does not fit easily into any of the common classes as it is an object with a complex structure and behavior. Therefore, one can find various classifications of this source. The exploration of NGC1275 as AGN started early in the original Seyfert list \(^5\), but it was already there flagged to be unusual because of its complex structure. After the introduction of Sy1 and Sy2 subclasses by

\(^1\)A list of other names for this object can be found in table A-1 in the appendix.
\(^2\)corresponds to RA: 03h19m48.1601s, DEC:+41d30m42.106s.
Khachikian and Weedman [67], NGC1275 was labeled as Sy2. Few years later, Veron proposed it to be a BL Lac [68], but in his catalogue of 2006 NGC1275 is classified as Sy1.5 [69]. The databases NED [66] as well as Simbad [70] classify NGC1275 as FR I radio galaxy. The complex structure of NGC1275, including surrounding filaments as seen in figure 3.2, also leads to a peculiar morphology classification in [66]. Depending on the catalogue one can even find more classes NGC1275 could belong to. Additionally, another galaxy called 'High Velocity System' is moving towards NGC1275 along the line of sight. But recent observations show that a collision between the two galaxies has not started yet [71].

A large scale method like the luminosity ratio of the two jets of NGC1275, leads to an angle of 30-55 degrees relative to the line of sight [72]. Depending on the measurement method of the inclination angle used to define the AGN, the results differ a lot and can result in wrong interpretation of physics processes. According to [73], NGC1275 has an inclination of the jet to the line of sight increasing from
3.1. THE GALAXY NGC1275

Figure 3.2: Hubble image of NGC1275 [65].

an angle of less than 2.7 degrees in the vicinity of the central black hole up to 40-58 degrees at arcsecond scales. During the movement of the jet outward it gets tilted and forms an S-shape, that is best visible in the radio band. The disturbed jets are one of the reasons for the variety of the classes NGC1275 is put in. Another reason is the presence of the filaments showing hydrogen emission lines that could be misinterpreted as originating from the AGN [68]. As such hydrogen lines are crucial for identifying an object as a Seyfert galaxy, NGC1275 might be incorrectly classified as Seyfert.

Measurements of high energy emission by the Fermi satellite [74] and contemporaneous upper VHE limits from a MAGIC campaign [75] in 2008 strongly indicated that the source should be detectable at energies $\approx 100$ GeV, a limit reachable with the new MAGIC stereo system (see chapter 4). It is known that some AGNs show a harder spectrum during flaring state, so monitoring the behavior of the source in the high energy range using the data from Fermi LAT can increase detection probability.

3A value rarely cited in the literature.
4The observation of the center of the Perseus cluster at that time was mainly driven by the hope to find gamma-ray emission produced by intra-cluster cosmic ray interaction and hypothetical dark matter annihilation, as described later.
Additionally NGC 1275 is situated in the center of the Perseus Cluster, which is
the brightest cluster in the X-ray [76]. Any cluster should contain intra-cluster
cosmic rays that are supposed to be a sum of the cosmic ray leakage from the
individual galaxies of the cluster. One key question is the cosmic ray density in
a cluster. Observations in VHE gamma-rays offer the possibility to measure this
value. A more speculative additional possible contribution to the gamma-ray signal
could originate from dark matter annihilation. Depending on the model the highest
density of dark matter can be at the center of the cluster, very close to the position
of NGC1275. Based on this, first MAGIC data had been taken with the mono system
in 2008 [75], assuming that NGC1275 does not emit VHE gamma-rays and disturb
the measurement. All three possible VHE gamma-ray signals are expected to have
different shapes in their spectra, as indicated in figure 3.3. Therefore, it might be
possible to distinguish between them if enough statistics can be gathered. As a first
step for investigating the cosmic ray and dark matter contents of the Cluster the
knowledge about the NGC1275 spectrum is crucial.

Figure 3.3: Possible VHE emissions from the central part of the Perseus region, based on
[74] [75]. The blue contribution from NGC1275 can be variable and the spectral shape could
change. The green contribution from intragalactic cosmic ray interactions is expected, but
the intensity and shape of the spectrum is highly model dependent. Additionally, there is
a lot of Dark Matter concentrated in the central region of the Perseus cluster that might
result in a measurable VHE emission with highly speculative spectrum (red). The blue,
green and red lines are for illustration purpose only and are not based on any specific
model.

As the source turned out to be challenging in physics and analysis, I concentrated
on the AGN and multi-wavelengths part where I acted as Principle Investigator (PI)
in MAGIC from 2009 to 2011, while Fabio Zandanel, a PhD student from Granada,
concentrated on the cosmic ray and Dark Matter related tasks.
3.2 Two Head Tail Radio Galaxies

A Head Tail Radio Galaxy only appears in dense clusters. The attribute of this class are that jets that are strongly bent into the same direction. Typically these galaxies are moving fast relative to the cluster and the friction of the intra-cluster medium with the jet results in a strong bending of the jets \cite{77}, as seen in figure 3.4. This special types of AGNs were never assumed as possible emitters of VHE gamma-rays, but by chance when observing NGC1275, MAGIC had also two galaxies of this class in the field of view, resulting in the serendipity detection of VHE emission from IC310 as described in chapter \ref{7.1.1}.

![Radio image of NGC1265](image)

**Figure 3.4:** Radio image of NGC1265. The red point in the center of the jets corresponds with the position of the host galaxy. Both jets are strongly bent by friction with the intra-cluster medium\cite{78}.

3.2.1 NGC1265

NGC1265 is the role model of the head tail radio galaxy class. It is also a member of the FR I class of radio galaxies. Another common name for the source is 3C083.1B. It is situated in the north of NGC1275 at the equatorial coordi-
The distance to the earth is not exactly known as there are contradicting measurements in [66]. The host galaxy is stated to be of the elliptical class E [70].

In the radio picture 3.4 one can easily see the two heavily bent jets that form the bright head and a fainter tail. While it is a bright radio source, it was never detected in the X-ray nor high energy band.

### 3.2.2 IC310

IC310 is situated in south-west of NGC1275 at the equatorial coordinates (J2000.0) 49.1790729 deg, 41.3249719 deg\(^6\), with a distance of 76.650±0.495 Mpc from earth [66]. The host galaxy is stated to be of the spiral galaxy class S0 [70].

In contrast to NGC1265, there are no bent jets visible in radio images (figure 3.5). IC310 is not only a bright radio source, but was also identified as an X-ray emitter [79]. As will be described in detail later, IC310 was also detected by Fermi [80] and, within the scope of this observation campaign, in the VHE [81] regime at the same time.

![Radio image of IC310](image_url)  
\textit{Figure 3.5: Radio image of IC310. There is no jet bending visible that is comparable to NGC1265. [82]}

\(^5\text{corresponds to RA: 03h18m15.664s, DEC: +41d51m27.88s}\)

\(^6\text{corresponds to RA: 03h16m42.977s, DEC: +41d19m29.90s}\)
Chapter 4

The Instruments

Since AGNs usually show variability, it is important to have contemporary data for the different energy bands to be able to compare measurements. In this chapter I will briefly describe the instruments that were used to observe NGC1275.

The key instruments are the Major Atmospheric Gamma-ray Imaging Cherenkov (MAGIC) telescopes MAGIC, where I acted as PI for the observation of AGNs in the center of the Perseus cluster to search for VHE emission and did a complete analysis of the data during the 2009/10 and 2010/11 observation campaigns. Second is the LAT detector at the Fermi satellite that measures the adjacent high energy range. During the early part of the 2010/11 campaign I did a real-time analysis of the public Fermi data to decide the optimal MAGIC observation strategy in case Fermi LAT sees enhanced emission from NGC1275 at high energies.

Additional information is coming from the following instruments:

- the Chandra X-ray satellite,
- the KVA and NOT optical telescopes,
- the Planck satellite measuring micro waves,
- the VLBA radio telescopes through the MOJAVE program monitoring several AGNs.
4.1 The MAGIC Telescopes

The MAGIC telescopes are ground based IACTs situated at the Roque de los Muchachos Observatory (ORM) on the Canary Island La Palma at 2200 m a.s.l.. The first telescope, MAGIC-I, (shown in figure 4.1) started standard operation in 2004. Since autumn 2009 the second telescope, MAGIC-II, which is a slightly improved version of MAGIC-I, started to take data on a regular basis and enabled stereo observations. The two telescopes are situated in a distance of 85 m to each other (figure 4.2). Each telescope has a segmented mirror of 17m diameter and a camera built of photomultiplier tubes (PMTs) situated in 17 m distance to the reflector. The field of view of both telescopes is 3.5°. MAGIC can only operate during clear sky conditions and (rather) dark nights, since too much ambient light would outshine the Cherenkov flashes. A more technical problem is the fast ageing of PMTs if exposed to too much light, e.g. full moon. This limits the total observation time to about 1000 to 1500 hours per year. Since the MAGIC telescopes are very large, it is not feasible to protect them with a dome. If direct sunlight would hit the mirror, the focal spot would immediately destroy the camera. Therefore, it is crucial that the telescopes are always in the park position well before sunrise.

![Figure 4.1: Photo of the first MAGIC telescope](image)
4.1. THE MAGIC TELESCOPES

Reflector

Both MAGIC reflectors have a parabolic shape which allows to keep the time spread of photons on the camera plane at less than 1 ns. In MAGIC-I the total reflector area is 236 m$^2$ consisting out of 964 square shaped aluminum mirrors of 0.495 x 0.495 m$^2$, mounted in groups of four and arranged in a chessboard structure. MAGIC-II has a mirror area of 241 m$^2$ consisting of segments with the size of 0.985 x 0.985 m$^2$. 60% of the segments are aluminum mirrors and mounted in the inner part of the reflector while the remaining 40% of the segments in the outer rings of the reflector consist of aluminized glass. When pointing to different positions in the sky the mirror dish deforms under its weight. Therefore, each mirror segment is equipped with two actuators that move the mirror back into the correct position. This active mirror control system is the responsibility of our group at ETH Zurich. MAGIC is currently the only IACT using such an active mirror control, but it is widely agreed that active mirror control will be used for CTA telescopes.

Structure

The Structure of both telescopes is made of lightweight carbon fiber tubes. The dish of each of the telescopes weighs only about 65 t. The drive system of each telescope has independent servo motors for azimuth and zenith directions. When pointing to different positions in the sky, sagging of the camera and other effects can degrade
the pointing. Images from stars at different positions in the sky are used to produce a bending model for each telescope to antagonize the structural effects. Using this correction the pointing precision per telescope is better than 0.02° \[85\]. Additionally during data taking, CCD cameras mounted in both telescopes look at the sky and compare it to sky maps. This allows to correct for short time mispointings induced by e.g. wind load on the structure.

**Camera, Trigger and Readout**

One of the main differences between both telescopes is the layout of the camera. The MAGIC-I camera consists out of 577 hexagonal pixels with the size of 0.1° in the inner area and 0.2° in the outer area. The 180 bigger pixels are not connected to the trigger system, which encloses the inner area of 0.95° radius. In MAGIC-II the camera consists of 1039 pixels of 0.1°. The trigger area of this telescope has a radius of 1.25°. The signals from the photomultipliers in both cameras are transformed into light pulses using vertical cavity surface emitting laser diodes. The optical fibers leave the camera and lead the signal to the counting house where the pulses are converted back to electrical signals.

Cherenkov flashes are very dim compared to the ambient light even during dark nights, but all photons arrive within few nanoseconds. Therefore, the electronics has to be fast enough to distinguish these events from the fluctuations of the night sky background. Both telescopes use sampling rates of 2 GHz but the electronics is rather different. While the readout of MAGIC-I is based on time-multiplexed FADCs, MAGIC-II uses the newer analog ring buffer DRS-2 \[85\]. These differences, mainly in the trigger area, reduce the theoretical performance of the system. Therefore, a replacement of the MAGIC-I camera with a clone of the MAGIC-II camera is ongoing, together with an upgrade of the readout to the latest DRS-4 chip for both telescopes.

The Trigger has the function to distinguish between pulses originating from air showers and pulses that originate from uncorrelated fluctuations of the night sky background light. MAGIC uses a multi layer trigger for this purpose. The first level (L0) consists of a discriminator. To avoid exploding individual pixel rates (IPR) if a bright star is in the field of view the threshold is adjusted automatically to keep the pixel rates in an allowed range. The L0 trigger is followed by the topological L1 trigger per telescope. The function of the L1 trigger is to check if the pixels surviving the L0 trigger form a compact group. It has several options out of which two were used during these observation campaigns:

- A four next neighbor trigger 4NN, requesting to have four adjacent pixels in the camera to be above a defined threshold.
A three next neighbor trigger $3\text{NN}$, needing only three adjacent pixels above threshold was used 2010/2011. Since the probability for an accidental trigger is increased, the trigger threshold must be set higher to reach the same total trigger rate.

The stereo trigger called L3 combines the L1 triggers from the two telescopes. If both telescope trigger within an orientation dependent time window, both cameras are read out. Because there the L3 trigger was not yet commissioned during the 2009/2010 campaign, a different trigger setup (described in chapter 6) had to be used, resulting in worse energy threshold than for later observations.

To be able to analyze the signals one has to convert the FADC counts into photoelectrons. Before taking data on a source a dedicated run with calibration events induced by a fast, stable light pulser in the mirror plane of each telescope is taken. Additionally during data taking 25Hz of interleaved calibration events are recorded to be able to correct for drifts in the electronics. The pulses for the calibration events are generated in MAGIC-I by UV LEDs sending out pulses lasting few ns. In MAGIC-II a laser sending out pulses shorter than a nano second is used. From the signal of these pulses the conversion factors from FADC count to photoelectrons are derived.

### 4.1.1 Extended Air Showers

Extended air showers are the result of the interaction of the cosmic ray particles with atoms in the air. There are two basic types depending on the primary particle: hadronic air showers are induced by any kind of nuclei while electrons, positrons and photons induce electromagnetic showers (figure 4.3).

![Development of gamma-ray air showers](image1.png) ![Development of cosmic-ray air showers](image2.png)

**Figure 4.3:** Hadronic and electromagnetic air showers [86]. See text for explanation.
Hadronic air showers consist of different parts. The hadronic part forms the back bone of the shower and transports the main fraction of the energy through the atmosphere. It consists mainly of protons, charged pions and neutrons with a small contribution of other hadrons. If the charged pions have energies above $\approx 10\text{ GeV}$ most of them interact hadronically with the atmospheric atoms adding more hadrons to the shower. Else, they decay into muons and neutrinos, e.g. $\pi^- \rightarrow \mu^- \nu_\mu$. The neutral pion is formed as well in every hadronic interaction. These decay instantaneously into two photons that are developing into electromagnetic cascades. This way the hadronic shower part generates and fuels all the other components.

Muons having energies above $\approx 2\text{ GeV}$ typically reach ground before they decay. If their energy is below $2\text{ GeV}$, most decay by $\mu^- \rightarrow e^- \nu_\mu \nu_e$. On ground one can measure a rate of 100 muons per square meter and second as an overall rate of air shower muons reaching ground.

The electromagnetic part is typically outnumbering the other shower components. Photons originating from outer space or from the decay of neutral pions can do pair production. In the simplified Heitler model [87] these electrons and positrons emit Bremsstrahlung, i.e. create a photon that again undergoes pair production. This way in every generation the number of particles doubles and the energy per particle is divided by about two. The electromagnetic part stops growing when the particles reach the critical energy of $\sim 80\text{ MeV}$ in air, when ionization becomes more efficient than bremsstrahlung. From this point on the atmosphere starts to absorb the electromagnetic shower. Air showers induced by VHE gamma-rays are purely electromagnetic.

To simulate air showers statistically correct, the Monte Carlo program CORSIKA is used [88]. While the electromagnetic part is pure QED and well understood, hadronic interactions are ruled by QCD effects and are far more difficult to describe correctly.

Depending on the energy and the primary particle the air showers have statistically different profiles. The profile of a single shower depends strongly in the first interaction between the primary particle and the air. In general, pure hadronic showers look less regular than electromagnetic ones. This is used to statistically distinguish between showers induced by cosmic rays and gamma-rays.

### 4.1.2 IACT Technique

While very high energetic gamma-rays could in principle directly be measured with satellites, their flux is far too low to be able to collect sufficient statistics, taking into account the typical size of a satellite experiment of $< 1\text{ m}^2$. A more efficient method

\[ ^{1}\text{In particle physics experiments, these so called 'cosmic muons' are often used to check detectors.} \]
to detect VHE gamma-rays is using the atmosphere as a calorimeter and observe the air showers they produce. If a charged particle moves through a medium faster than the speed of light in this medium it emits Cherenkov photons with a maximum in the blue to UV waveband with an emission angle dependent of the velocity and the refractive index. Since the particles in air showers are highly relativistic, they all emit Cherenkov light.

Figure 4.4: Illustration of the IACT technique [89]. See text for explanation.

Since the refractive index of air changes with density and therefore with height, Cherenkov photons from the upper part of a shower arrive under slightly different angles than those from the lower part. Cherenkov photons originating from the same shower but from different altitudes hitting the mirror of an IACT at the same place are reflected to a different part of the camera (figure 4.4). Therefore, the image of a shower in an IACT camera corresponds to a sideway projection of (a fraction) of the shower, forming an ellipse in the camera plane. Since pure electromagnetic showers tend to be more regular than hadronic ones, the shape of the shower image is used to distinguish statistically between hadronic and photon induced showers.

The orientation of the ellipse is correlated with the angle between the telescope axis and the direction of the axis of the shower. If the same shower is recorded by several telescopes, the stereo observation allows for a rather precise reconstruction of the origin of the primary particle (figure 4.5). Gamma-rays from a hypothetical source must all have the same origin, while the much more abundant cosmic ray particles are randomly distributed. This allows to further suppress hadronic background. While the hadron-shower dominated trigger frequency is above 100 Hz in MAGIC, this technique allows to see sources with gamma-ray fluxes lower than 10 mHz (depending on the spectrum of the source).
4.1.3 Performance of MAGIC

This section contains a brief summary of the performance of the MAGIC system. A far more detailed description was just published in [85]. Because of its mirror size the MAGIC system is currently the most sensitive IACT for energies below 200 GeV and has a trigger threshold of $\sim 50$ GeV of a primary photon. The image cleaning and analysis cuts raise the analysis threshold to $\approx 75$ GeV depending on the cuts and the spectrum of the analyzed source.

The integral sensitivity of MAGIC for $N_{\text{excess}}/\sqrt{N_{\text{background}}} = 5$ after 50 h of effective observation time is shown in figure 4.6(a). This defines the minimal apparent flux a source must have to be detectable within 50 h of observation time. Since no procedure to precisely calibrate an IACT exists yet, there can be large systematic effects in the fluxes calculated from the measurements. Therefore it is common in the community to express flux values in units of flux of the well known Crab nebula measured by the same instrument, resulting in cancellation of many systematic uncertainties. At several hundred GeV the sensitivity reaches $\sim 0.8\%$ of the Crab nebula flux and worsens to $\sim 1.5\%$ of the Crab nebula flux at 100 GeV. The differential sensitivity for MAGIC with same setting is shown in figure 4.6(b).

At medium energy of few hundred GeV the energy resolution is as good as 16\%. The angular resolution of the stereo system is shown in figure 4.6(c) being $\sim 0.07$ deg at 300 GeV. These values are dominated by intrinsic fluctuations of the air-showers.

The sensitivity of MAGIC depending on the offset to the camera center is plotted in figure 4.6(d). This is especially important for off-axis sources like IC310.
4.1. THE MAGIC TELESCOPES

Figure 4.6: The four plots show the performance of the MAGIC stereo system [85]. (a) displays the integral sensitivity of MAGIC. The black line represents the achieved sensitivity of the MAGIC stereo system for $N_{\text{excess}}/\sqrt{N_{\text{background}}} = 5$ after 50 h of effective observation time, while the dashed black line stands for the theoretical expectation derived from Monte Carlo simulations. The grey line shows the sensitivity achieved with a single MAGIC telescope. (b) shows the differential sensitivity of the MAGIC stereo system. (c) displays the angular resolution depending on the estimated energy. Since the width of a two-dimensional gauss-fit only contains 39% of data, using the width containing 68% of data is a better measure. (d) shows the sensitivity of MAGIC depending on the offset to the camera center.
4.2 The Fermi Satellite

Contrary to the MAGIC Telescopes that are ground based, Fermi \cite{91} is a satellite measuring directly high energy photons in space.

The Fermi satellite (figure 4.7) was launched on June 11, 2008 and is orbiting around the earth at an altitude of \( \sim 350 \text{ km} \). It consists of two main detectors: the Large Area Telescope (LAT) and a Gamma-ray Burst Monitor (GBM). For this thesis only data obtained with the LAT are relevant. The LAT consists of 16 towers, each having 18 layers of tungsten converter planes and silicon layers for tracking, and a CsI calorimeter. It has a field of view of 2.4 sr that allows to scan the whole sky within two orbits, i.e. every three hours. This provides a constant monitoring of the entire sky and is complementary to the ground based IACTs that are optimized to observe a small fraction of the sky with high sensitivity. On very rare occasions, like the observation of exceptionally strong flaring objects, Fermi can change from the scanning mode to a pointing mode.

LAT uses a conversion technique that turns gamma-rays by pair creation into electron positron pairs. Their direction is measured by the tracker, while the total energy is measured by the calorimeter located behind the tracker. Hadronic events are rejected by an anti-coincidence system: segmented scintillators around the telescope record a signal if a charged particle crosses them. Therefore, LAT is not background limited by hadronic particles as IACTs. LAT has an active area in the order of 1m\(^2\), limiting measurements above \( \sim 50 \text{ GeV} \) to the brightest sources. Furthermore, Fermi has a duty cycle of close to 100\% since it can always point away from the sun.

The LAT delivers data in the energy range of 20 MeV up to 300 GeV depending strongly on the spectrum of the source and the integrated observation time. Depending on the energy the angular resolution is 3 degrees at 200 MeV and improves
to 0.1 degrees above several GeV. For several sources the accessible energy range of LAT and MAGIC overlap, offering a unique possibility to measure spectra from MeV to TeV without any gap in the energy coverage. Typically the latency from measuring the photon until the data is available in the Fermi Science Support Center (FSSC) to the analyzer is less than 72 hours.

After the first year of data taking the LAT data became public. As will be described in chapter 6.3 I did a real-time Fermi LAT monitoring to decide the best observation strategy for MAGIC.

4.3 Additional Instruments used for the Multi-Wavelength Observation of NGC1275

In this section I briefly summarize the instruments that additionally observed NGC1275 to get a wide energy coverage of NGC1275. While most of the data are public, analysis for a difficult source as NGC1275 is left to experts. I made sure that whenever possible contemporary observations of the different instruments were taken.

4.3.1 Chandra

Chandra [93] (figure 4.8) is an X-ray satellite launched with shuttle mission STS-93 on 23 July 1999. Its orbit is very elliptical and reaches an altitude of up to 133'000 km. The field of view has a diameter as small as 30 arcmin. With a resolution of 0.5 arcseconds it is the only X-ray instrument able to resolve NGC1275 against the strong X-ray background originating from the Perseus cluster. It is difficult to get observation time granted since there is huge overbooking. But we knew about an approved NGC1275 observation campaign and ensured best possible overlap of the MAGIC observation schedule during the 2009/10 campaign. Chandra data of that observation are now public and are currently analysed. There was no NGC1275 observation approved during the 2010/11 campaign.

4.3.2 KVA and NOT Telescopes

KVA (Kungliga Vetenskapsakademien) [95] is a 35 cm optical telescope situated at the canary island La Palma and has an extended AGN monitoring program in the R-band. It is often observing AGNs in parallel with MAGIC. Therefore, there is very good coverage of KVA and MAGIC measurements for both NGC1275 campaigns. For monitoring AGNs, KVA is using differential photometry comparing the source brightness to the constant brightness of stars in the observation field. This method
is insensitive to atmospheric disturbances. Key problem in using KVA data is that in the R-band the host galaxy of NGC1275 is very bright and it is difficult to disentangle emission from the host galaxy and from the AGN.

NOT (Nordic Optical Telescope) is an optical telescope with a primary mirror of 2.56 m in diameter also situated at La Palma. The Telescope has a better angular resolution compared to KVA and was used to measure the flux of the host galaxy to try to subtract the value from the KVA measurements.

Figure 4.9 shows a photograph from the Observatorio Roque de los Muchachos (ORM) at La Palma, including KVA and NOT.

Figure 4.8: The Chandra observatory situated in the shuttle bay of the space shuttle before launch.

Figure 4.9: Photograph of part of the ORM at La Palma. In the foreground the KVA building can be seen. The dome of the NOT is situated on the left side, behind the tower of the solar telescope.
4.3.3 Planck Satellite

Planck [97] is a microwave observatory (figure 4.10) launched on Ariane 5 on 14 May 2009. It has a size of 4.20 m x 4.22 m and it follows a so called Lissajous orbit at an average distance of 400'000 km from the so called Lagrange point L2. This orbit has the earth constantly shielding the satellite from the sun to simplify observations. Planck is taking data in 9 different micro-wave frequency bands with a resolution as good as an arcminute for some frequencies. Some detectors are operated at a temperature of 0.1 K [98] [99]. The Planck data for the bright sources of the 2009/10 observational campaign are now public [100] and taken into account in this thesis, while data for the 2010/11 campaign are not yet available.

Figure 4.10: Picture of the Planck observatory before launch [98].

4.3.4 MOJAVE-Program using VLBA Radio Telescopes

The Very Long Baseline Array (VLBA) [101] is the largest array of radio telescopes. It consists of 10 antennas of 25 m diameter located between Hawaii over the USA to the Virgin Islands in the Caribbean, a distance of more than 8600 km. With this long baseline, angular resolutions down to milli-arcseconds can be reached. The Monitoring Of Jets in Active galactic nuclei with VLBA Experiments (MOJAVE) [102] program is constantly monitoring a set of bright AGNs in the northern hemisphere at a wavelength of 2 cm. NGC1275 is among this set of AGNs, and there is
reasonably good coverage with MAGIC observations. Figure 4.11 shows a full-sky map based on Fermi LAT data, with an overlay of selected MOJAVE images. Most of these sources, including NGC1275, look pointlike using Fermi LAT and MAGIC resolutions, but show complicated morphology using the very good VLBA angular resolution.

Figure 4.11: Full-sky map of Fermi LAT observations of GeV emissions, overlayed by MOJAVE results at 2 cm wavelength for selected AGNs. Most of these objects look pointlike for Fermi LAT and MAGIC, but show complicated morphologies with the MOJAVE resolution. NGC1275 is at the left side, indicated with its radio name 3C84 [103].
Chapter 5

MAGIC Analysis Chain

For the analysis of MAGIC data a software package called MARS was conceived [104] [85], based on the data analysis framework ROOT [105] developed at CERN.

Figure 5.1 contains a summary of the dataflow and the individual processes needed to analyze MAGIC data. The individual steps will be briefly described in the chapters indicated in the figure 5.1. The full analysis will be demonstrated based on a small sample of data from the Crab nebula, used to cross check the analysis applied to the NGC1275 data in the next chapter.

5.1 Data Processing in the MAGIC Datacenter

Every day, data taken during the past night are copied to the MAGIC datacenter in Barcelona where they are processed.

5.1.1 Calibration

The raw binary data from the camera is first combined with the log files of the different subsystems of the telescopes by the merpp program. Additionally the data are converted to a root format.

The next step is the calibration of the data to correct for e.g. drifts in the electronics. For this task distinct calibration data are needed that are taken in the beginning of the night and the beginning of the observations of each source as well as interleaved with physics data.

The Datacenter provides also higher stages of processed data, but to ensure a consistent analysis chain over several campaigns with one version of MARS, I downloaded
the calibrated data from the datacenter and processed the next steps by myself. The MARS version I am using for the final analysis is M2-4-13.

5.1.2 Monte Carlo Simulations

To simulate air showers and correctly taking into account statistical fluctuations, Monte Carlo (MC) simulations with the program \textit{Mmcs} based on CORSIKA \cite{corsika} are used. CORSIKA simulates the development of gamma-ray induced air showers in the atmosphere and its Cherenkov photon production. The simulation of hadronic primary particles is also possible but is not used very often as the simulation of the
5.2. DATA ANALYSIS

A huge amount of background is very computer time consuming and, since ruled by QCD effects, the underlying physics is difficult to model with the necessary precision. Using the $\text{Mnco}$ output files the program $\text{Reflector}$ is used to simulate the absorption and scattering of the Cherenkov photons in the atmosphere and the reflectivity of the MAGIC mirrors. $\text{Reflector}$ stores the position and arrival time of the photons in the camera plane.

The $\text{Camera}$ program uses output files of $\text{Reflector}$ and simulates the reflectivity of the light guides, the efficiency of the photomultiplier and the digitization of the electronics. Each photon is converted into a (simulated) electronics signal and the overlay of all photons in a given channel converted in a simulated FADC pulse. Electronics noise is added as well as a night sky background (NSB), containing all sorts of ambient light like stars, (partial) moon, airglow, meteorites, as well as man made light pollution. $\text{Camera}$ also simulates the single telescope triggers.

After $\text{Camera}$, the analysis of MC data is basically the same as for physics data described in the next sections.

5.2 Data Analysis

As a general rule in MAGIC, every single analysis, including the parameters used, has to be checked on a sample of data taken under as similar as possible conditions from the Crab nebula. Since this source is assumed to be rather stable, the outcome of the analysis is known in advance and severe mistakes in the analysis would show up. In this chapter, I will use the Crab sample used to cross-check my analysis as example to explain the different steps. Data taken during the 2009/10 campaign are called cycle 5, and those from 2010/11 are called cycle 6.

5.2.1 Image Cleaning and Calculation of Image Parameters

The program $\text{Star}$ uses calibrated data and calculates the so called Hillas parameters of each shower image.

The first step is the image cleaning: pixels with signals above six photo electrons (phe) for MAGIC-I or nine phe for MAGIC-II respectively\footnote{Because of higher photo-detection efficiency but also higher electronics noise in MAGIC-II, the optimum cleaning level was found to be higher than in MAGIC-I \cite{85}. Currently, MAGIC is undergoing an upgrade program towards similar cameras and electronics for both telescopes.} are selected to be so called core pixels if they have at least one adjoining pixel fulfilling the same conditions and their arrival time is within 4.5 nanoseconds around the mean arrival time of all core pixels of that event. In a second step all neighbor pixels of the core pixels
that have signals above three phe for MAGIC-I, or 4.5 phe for MAGIC-II, within 1.5 nanoseconds are selected to be boundary pixels. All signals from pixels not selected as core or boundary pixel are set to zero.

Core and boundary pixels are forming a shower image which is parameterized based on the technique Hillas proposed 1985 [106], resulting in the so-called Hillas parameters:

\[
\begin{align*}
\text{Size} & = \text{sum of all photo electrons that survive image cleaning.} \\
\text{Leakage} & = \text{sum of photo electrons in the outermost ring of PMTs in the camera. From this one calculates a correction value to the size, taking into account the amount of photons that lay outside the camera.} \\
\text{Length} & = \text{semi-major axis of the shower image.} \\
\text{Width} & = \text{semi-minor axis of the shower image.} \\
\text{Disp} & = \text{distance from the center of the shower image to the reconstructed source position. The reconstructed source position is by definition in line with the major axis of the shower ellipse, and the distance } disp \text{ is calculated from the shape and time structure of the shower image, taking into account parameterization from Monte Carlo simulations.} 
\end{align*}
\]

Figure 5.2: Hillas parameters used in this analysis. The Hexagon indicates the camera boundary and the ellipse represents the shower image after image cleaning. The real source position is the projection from the observed source into the camera. See text for explanation of the Hillas parameters.
• Theta - distance between real and reconstructed source position. It is usually not given in mm, but in the corresponding angular projection to the sky. \( \Theta^2 \) is then the squared angular distance between the observed source and the reconstructed origin of the primary particle that produced the individual shower. For single telescopes the uncertainty of the reconstructed origin of each individual shower is dominated by the calculation of the Disp parameter. This can be improved by using several telescopes in in stereo mode, allowing to reconstruct the origin of each shower based on the direction of the major axis of the ellipses reconstructed in each telescope (figure 4.5).

Many other Hillas-parameters extracted from the shower image can be found in the literature, but they are not used in the current MAGIC stereo standard analysis.

5.2.2 Data Check

While some datasets can be rejected from the beginning (e.g. very bad weather conditions or technical problems with the telescopes), additional quality checks are applied after calculation of the Hillas parameters. One major parameter to check is the rate of reconstructed hadronic events, since this number should in first approximation only depend on the zenith angle of the telescopes.

As the Dataset of NGC1275 contains two different trigger settings, some cuts have to be chosen differently for each time period. Therefore, two different Crab checks have to be done. I will demonstrate here briefly the datachecks on the selected 2009/10 and 2010/11 Crab samples. Some additional plots can be found in the appendix. In the plots, blue points represent MAGIC-I and red points MAGIC-II. Dates are usually given in Modified Julian Date (MJD)\(^2\). One major problem for cycle 5 was that very few Crab data with same non-standard trigger setting were taken, so the control dataset is very limited.

Example: Crab

There exist several measures to identify data taken under rather bad observational conditions. Most of the plots for the Crab test samples can be found in the appendix.

The DC current of the camera is a measure for the darkness of the sky: a brighter sky results in more background photons to be measured by the PMT, so they consume more power. For a low-energy source like NGC1275, dark night data was requested,

\(^2\)MJD is a time measurement often used in astronomy, presenting the time in days and fractions of them since 00:00 November 17, 1858.
i.e. a mean DC value, averaged over all PMTs in the camera, below 1500 units. Datasets exceeding this value are rejected.

The additional humidity in clouds does absorb and scatter the Cherenkov light, distorting the measurements. The cloudiness is measured by a radiation pyrometer (mounted on Magic-I) that measures the average temperature of the sky. Since clouds reflect the thermal radiation of the earth, this temperature can be used to estimate the cloudiness. It is common practice in MAGIC to reject datasets with a cloudiness larger than 50%.

A similar approach is using the starguider CCD mounted on each telescope to correct for tracking errors: it is taking pictures of the sky region MAGIC is pointing at and compares the identified stars with a map of this region of the sky. Since this is not the main purpose of the starguider CCDs, they have never been calibrated precisely, and sometimes a lens got replaced. So the absolute measurements have no direct meaning. Nevertheless, for typical regions of the sky, having less than 20 identified stars is an indication of very strong extinction by high altitude clouds in the field of view and such datasets are rejected.

Cloudiness as well as the number of identified stars are very rough estimates and the cuts are only used to reject data taken with very bad atmospheric conditions. Furthermore, the pyrometer as well as the starguider CCD encountered several hardware problems during part of the observation campaigns, so a value of zero could indicate a valid measurement or a malfunction.

The best check for data quality in MAGIC is the rate of reconstructed showers. This rate is always dominated by the hadronic background. Since the flux of hadronic cosmic rays in the energy range of MAGIC is isotropic, the measured rate should only change with the zenith angle dependent energy threshold of the telescopes. One drawback is that the shift crew has instructions to keep the trigger rate as stable as possible. Often this is done by adjusting the trigger threshold. Furthermore there is an individual pixel rate control (IPR) adjusting voltages on photomultipliers for individual pixels to reduce the local effect of fake triggers induced by bright stars in the FoV. Therefore, the reconstructed rate has to be checked against comments from the shift crew about non-standard trigger settings.

Figures 5.3 and 5.4 show the reconstructed rate depending from the zenith angle and the applied cuts for cycle 5 and cycle 6 respectively. There is a major difference between the two datasets because of the completely different trigger setups used. In cycle 5, MAGIC-I used a 4NN trigger with rather tight threshold and MAGIC-II was read out in a slave mode. Since only a fraction of showers that triggered MAGIC-I can be visible in MAGIC-II, it is clear that the rate of event surviving

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3See figure B.1 for the DC currents for the Crab datasets.
4See figure B.2, for the cloudiness for the Crab datasets.
5See figure B.3, for the number of identified stars for the Crab datasets.
5.2. DATA ANALYSIS

![Graphs of reconstructed event rate for MAGIC-I (a) and MAGIC-II (b) as function of the zenith angle of the observation for cycle 5. Due to the non-standard trigger mode used, the expected rates differ for the two telescopes. Datasets showing for any telescope a rate outside the acceptable range marked by red or blue curves are rejected.](image1)

**Figure 5.3:** Reconstructed event rate for MAGIC-I (a) and MAGIC-II (b) as function of the zenith angle of the observation for cycle 5. Due to the non-standard trigger mode used, the expected rates differ for the two telescopes. Datasets showing for any telescope a rate outside the acceptable range marked by red or blue curves are rejected.

![Graphs of reconstructed event rate for MAGIC-I (a) and MAGIC-II (b) as function of the zenith angle of the observation for cycle 6. Due to the standard stereo trigger mode used, the expected rates are similar for the two telescopes. Datasets showing for any telescope a rate outside the acceptable range marked by red or blue curves are rejected.](image2)

**Figure 5.4:** Reconstructed event rate for MAGIC-I (a) and MAGIC-II (b) as function of the zenith angle of the observation for cycle 6. Due to the standard stereo trigger mode used, the expected rates are similar for the two telescopes. Datasets showing for any telescope a rate outside the acceptable range marked by red or blue curves are rejected.
image cleaning is very different. In cycle 6, the full stereo trigger was operational, i.e. both telescopes used an independent 3NN trigger with very low threshold. Both telescopes are read out when both individual triggers are in coincidence. Therefore, the reconstructed rates have to be rather similar, except for the slightly different image cleaning cuts applied.

The measured rates can be normalized with the zenith angle. Plotting the normalized rate vs. time in figure 5.5 shows that, at least for cycle 6, both telescopes usually exhibit a problem at the same time, i.e. the problem is most probably related to atmospheric condition\(^6\).

![Figure 5.5: Normalized reconstructed rate for MAGIC-I (top) and MAGIC-II (bottom) depending on time for cycle 6. See text for explanation.](image)

\(^6\)The same plot for cycle 5 can be found in [3.4] in the appendix. Since all Crab data usable for this task concentrate on few nights, not much can be seen.
5.2.3 Combining the Information of both Telescopes

The program Superstar is running over star files and is combining the data of both telescopes. Only events that survived the image cleaning for both telescopes are processed. From the combined data, a combined reconstructed source position and $\theta^2$ can be calculated per event, improving the angular resolution. Also the energy resolution is improved compared to measurements of a single telescope.

5.2.4 Distinguishing between Gamma and Hadron Showers

As the atmosphere is used as a calorimeter, the original particle direction as well as its energy can be obtained on a statistical basis only. As in each calorimeter, pure electromagnetic showers have a different shape than hadronic showers. These statistical differences can be used to distinguish between the primary particles.

In MARS, a so-called random-forest method \cite{107} is used. The program has to be fed with a set of pure hadronic and pure electromagnetic showers respectively and then automatically searches for statistical differences in the shower parameters. While gamma-ray showers can easily be simulated, this is hardly possible for the orders of magnitude more abundant hadronic showers. Instead one uses physics data from observations not containing a VHE source within the field of view. Since the geomagnetic field affects the charged particles in a shower, the exact shower shape depends (slightly) on the direction of the shower axis vs. the geomagnetic field. Therefore, it would be good to select the purely hadronic sample for the same zenith and azimuth angles as the to be analyzed data sample. Unfortunately, this would need to take dedicated data not containing any potential source and is generally assumed to be a waste of precious observation time. Operating a telescope long enough, many datasets without a signal from a hypothetical source do pile up and can be used for the task. I checked all existing MAGIC stereo data but could not find any agreeing to my dataset. In such cases, a standard random forest shall be used.

Based on these training samples, the random forest later on calculates for every event a so-called hadroness parameter. The hadroness gives the probability the shower was induced by a hadron or gamma-ray, i.e. a small hadroness indicates a high probability the shower to be gamma-ray like.

Energy of the Primary Particle

The program Melibea is running over superstar files and calculates the radius and the photon density of each shower’s lightpool. Usually for the energy assignment, look-up tables are generated using Monte Carlo simulations of gamma-ray showers.
The look-up tables are binned in size and impact parameter divided by radius of the Cherenkov light pool. For each bin the photon density per size is calculated. The energy of the primary particle is then assigned according to the parameters of the measured showers. Melibea is also calculating the hadroness for each event.

5.2.5 High Level Analysis

After all individual showers are analyzed, the next step is trying to extract an enhanced gamma-ray signal from a potential source.

Signal Plot

The program Odie uses Melibea files to calculate the signal of a potential gamma-ray emitter. Since gamma-rays from a potential (pointlike) source must all have the same origin, enhanced flux from one point is a good indicator. But the key problem is to estimate the remaining hadronic background. This background is best measured by observing under similar conditions another region in the sky (without a gamma-ray source in it) and then subtract the two measurements. This on-off method has two major drawbacks: it is wasting precious observation time and, because of inhomogeneities in the cameras, it is almost impossible to do the off-observations under identical conditions. The so-called ‘wobble observations’ partially overcome these problems: the source is not pointed at directly, but at an offset of 0.4° away. Typically every 20 minutes, the pointing is changed to the mirror point, and the hadronic background can be estimated using the flux originating from the mirror-source point. Using this method allows to collect data from the source all the time. Since during the observation the source as well as the mirror-source follows a circle around the center of the camera, many inhomogeneities cancel. A drawback is that at an offset of 0.4°, the sensitivity and energy threshold of the telescope is slightly worse than in the center of the camera, but this is compensated by the additional observation time available for the source.

One of the advantages of taking data in wobble mode is that in principle the camera can be split along a circle around the center of the camera into one region with possible signal and in several non-overlapping regions where no signal is expected and can be used as off data. For the signal plot one calculates the Θ² parameter for the source position and for the off region(s).

The Θ² distribution of the source and the background is plotted in figure 5.6 using 4.5 hours of Crab Nebula and the mirror-source as only off region. The filled grey histogram represents the background, while the potential signal is overlayed
as points with errors. As gamma-rays originating from the hypothetical source have small $\theta^2$ values only the 'signal region' left to the dashed line is used for calculating the significance of the gamma-ray emission. The cut on $\theta^2$ depends on the energy dependent angular resolution of the system and is optimized on a large sample of Crab data. I usually used the MAGIC standard cuts. The amount of off data within the signal region corresponds to the irreducible background of the measurement. Subtracting this background from the signal results in the amount of excess events.

\[
S = \sqrt{2} \sqrt{N_{\text{on}} \ln \left( \frac{1 + \alpha}{\alpha} \left( \frac{N_{\text{on}}}{N_{\text{on}} + N_{\text{off}}} \right) \right) + N_{\text{off}} \ln \left( 1 + \alpha \left( \frac{N_{\text{off}}}{N_{\text{on}} + N_{\text{off}}} \right) \right)}
\]

(5.1)

taking correctly into account unprecise knowledge about the background. $\alpha$ is a normalization to be applied when the effective observation time for $N_{\text{on}}$ and $N_{\text{off}}$ differ, e.g. if more than one off region was used in the wobble data.

A gamma-ray emitter is found if the significance is larger than $5 \sigma$ and $N_{\text{on}} - N_{\text{off}} > 0.1 \cdot N_{\text{off}}$, i.e. the number of excess events must exceed 10% of the amount of

Figure 5.6: Crab cycle 6 analysis with one off region. The solid gray histogram corresponds to the measured background, while the points with error are the signal. A signal excess is expected below the $\theta^2$ cut indicated by the dashed line.

Since the amount of background events does also contain an error, the significance can not be calculated by the simple formula $S = (N_{\text{on}} - N_{\text{off}})/\sqrt{N_{\text{off}}}$ with $N_{\text{on}}$ the signal, $N_{\text{off}}$ the background events and $S$ the significance of the result. Instead one has to use the more complicated so called 'Li & Ma' formula [108]:

$S = \sqrt{2} \sqrt{N_{\text{on}} \ln \left( \frac{1 + \alpha}{\alpha} \left( \frac{N_{\text{on}}}{N_{\text{on}} + N_{\text{off}}} \right) \right) + N_{\text{off}} \ln \left( 1 + \alpha \left( \frac{N_{\text{off}}}{N_{\text{on}} + N_{\text{off}}} \right) \right)}$

(5.1)

The corresponding plot for cycle 5 is B.5 in the appendix.
background events. For extended or low-energy sources, the $\Theta^2$ for expected emission is enlarged, making a detection of a dim source even more difficult.

Using more than one off positions produces more background statistics. This reduces the uncertainty of the background and improves the significance. But it has to be taken with care. Figure 5.7 shows Crab data using three off regions. As can be seen at $\Theta^2 \approx 0.3$, there is a disagreement between the signal and the off data. Since at such large $\Theta^2$ all the ‘signal’ data should also be hadrons, both values should be identical. But in the case of bright sources like Crab, the amount of badly reconstructed gamma-ray signals that leak into an off region is not negligible, resulting in overestimating the off signal at large $\Theta^2$. This could be overcome by using a larger wobble angle to better separate the regions, but this is not feasible because of the small trigger area of the current MAGIC-I camera. This effect is negligible in case of dim sources, so the official standard procedure in MAGIC was to use three (or even five) off regions for ‘not too bright’ sources.

![Graph showing Crab cycle 6 analysis with three off region.](image)

**Figure 5.7:** Crab cycle 6 analysis with three off region. The solid gray histogram corresponds to the measured background, while the points with error are the signal. A signal excess is expected below the $\Theta^2$ cut indicated by the dashed line. The disagreement between signal and off data at $\Theta^2 \approx 0.3$ indicate a severe problem.

While analyzing NGC1275 data I realized, that this standard procedure of using several off regions is very dangerous for dim and low energetic sources measured with two wobble positions, as it can result in fake detections (see chapter 6.4). Therefore, after a detailed study by experts, the MAGIC software board now officially discourages the usage of several off regions for low energy objects using two wobble

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8The corresponding plot for cycle 5 is B.6 in the appendix.
positions. Instead one should restrict to one off region, or organize the observation to use four wobble positions.

**Off from Wobble Partner**

While testing the effect of fake signals from dim sources, an alternative method to assign the off region from which the background is extracted was developed. Using ‘Off from Wobble Partner’ (OfWP) does not use the mirror source in the same dataset, but instead the off region from the partner wobble dataset. This means that for each set the off region is exactly the same region in the camera as the on region, resulting in better compensation of inhomogeneities in the camera. But it has the disadvantage that it demands for similar observation times for each wobble position. Small mismatches in observation time can be corrected by normalization. Applying OfWP (figure 5.8) to Crab gives the same result as with standard one-off analysis (5.6), so at least for bright sources both methods are equivalent. Currently, the OfWP method is encouraged for analyzing off-axis sources, i.e. sources that were not directly pointed at by the telescope (modulo wobble position).

![Figure 5.8](image.png)

**Figure 5.8:** Crab cycle 6 analysis with one OfWP region. The solid gray histogram corresponds to the measured background, while the points with error are the signal. A signal excess is expected below the $\theta^2$ cut indicated by the dashed line.

9The corresponding plot for cycle 5 is B.7 in the appendix.
Skymap

The Caspar program uses Melibea files of reconstructed data and produces sky-maps of excess in Right Ascension and Declination coordinates, i.e. projecting the reconstructed origin of the showers to the sky. The shower origins are smeared with the angular resolution of the telescopes, the so-called Point Spread Function (PSF). The results are given in test statistics (TS) values derived from [108] equation 17, using a smoothed and modeled background estimation. In general the null hypothesis distribution resembles a Gaussian function and width of one. In this case, the TS value corresponds to significance. But often, the background distribution shows a slightly different shape or width, resulting in TS values differing from the significance obtained in signal plots.

Figure 5.9 shows a skymap of the Crab Nebula. The Signal is centered at the black cross representing the coordinates of the astrophysical object\textsuperscript{10}. Within the point spread function of MAGIC, the object looks point like.

Figure 5.9: Skymap of the Crab Nebula Cycle 6. The black cross in the middle of the plot represents the position of the Crab Nebula. The Excess found is nicely centered to this position and is point like for MAGIC. The PSF circle indicates the angular resolution assumed to produce the skymap.

\textsuperscript{10}The corresponding plot for cycle 5 is B.8 in the appendix.
Flux and Lightcurve

To calculate a preliminary spectrum and the lightcurve (i.e. flux dependent on time), the program Fluxlc needs Melibea files of data as well as gamma-ray MC. After cuts in hadroness and $\Theta^2$, the excess events in bins of estimated energies are calculated. An example of Crab data is shown in figure 5.10\textsuperscript{11}. In this particular case the data is divided in 28 logarithmic bins from 5 GeV to 50 TeV. At the low and high energy ends of the spectrum there are bins which are below the actual threshold of MAGIC or contain not enough events to be significant. These bins are taken care of during the unfolding process.

![Differential Gamma Energy Spectrum](image)

**Figure 5.10:** Measured spectrum of the Crab Nebula cycle 6 using logarithmic bins in estimated energies before unfolding.

In case no signal is detected from a hypothetical source, Fluxlc can also calculate integral or differential upper limits.

Because of the limited energy resolution, a significant amount of events are counted in the wrong energy bin. Especially for very step spectra, it can happen that all events counted in energy bin $E_i$ are just leakage from bin $E_{i-1}$. Additionally the effective area (including the detection efficiency) of the system is highly energy dependent (figure 5.11). This makes a complicated unfolding necessary, taking also into account that the shape of the spectrum is different for the gamma-ray source and the irreducible hadron background. Fluxlc calculates the effective observation time and the effective area for the particular observation as well as the migration

\textsuperscript{11}The corresponding plot for cycle 5 is B.9 in the appendix.
matrix between estimated and real energy, which are needed for unfolding spectra. The unfolding procedure uses information about shape of the spectrum, so several possibilities have to be checked.

![Effective area dependent on Energy for MAGIC stereo observations.](image)

**Figure 5.11:** Effective area dependent on Energy for MAGIC stereo observations. The effective area includes trigger and reconstruction efficiencies, as well as gamma/hadron separation. It depends on the zenith angle of the observation and the energy. It is calculated from Monte Carlo gamma-rays and the hadronic background sample. Above 3 TeV, the effective area shrinks due to the small size of the camera.

**Unfolding of the Spectrum**

The program *CombUnfold* uses the output of *Fluxle* to unfold the spectrum using four different methods described in detail in [109]. During the unfolding process, the estimated energy is converted to real energy and the flux per energy bin is calculated based on the following equation:

\[
Y_i = \sum M_{ij} S_j
\]

where \(Y_i\) corresponds to the measured value in bin \(i\) in estimated energy, \(S_j\), is the true value in bin \(j\) in true energy, \(M_{ij}\) the migration matrix.

Since the migration matrix depends on the (unknown) shape of the spectrum, a direct unfolding is not possible. One has to use an a priori function to be applied, but then the unfolding procedure (especially with small statistics) tends to produce an unfolded spectrum that perfectly agrees with the initial function.
From high statistics analysis of the Crab sample [85], it is known that the spectrum follows a curved power law

\[
\frac{dF}{dE} = F_0 \cdot \left( \frac{E}{r} \right)^{\alpha + b \log_{10}(E/r)}
\]  

(5.3)

The parameters calculated are flux in cm$^{-2}$s$^{-1}$TeV$^{-1}$ ($F$), energy in GeV ($E$), normalization in TeV ($r$), index ($\alpha$) and curvature ($b$). The parameters corresponding to the unfolded spectra in figure 5.12 are shown in table 5-1. In addition to the parameter values the lower (low) and upper (high) limits of the energy band are given.

Figure 5.12 shows the four unfolding methods giving similar results while the flux is 10% enhanced compared to the MAGIC stereo values taken from [85]. As a cross-check I produced a different random forest to produce figure 5.13 which shows the same enhanced flux as can also be seen in table 5-2. One major uncertainty in the reconstruction of a spectrum is the precise energy estimation. Atmospheric variations affect the shower development as well as the transmission for Cherenkov photons. For a rather feature-less power law spectrum it is not possible to disentangle flux variation from a systematical shift in energy. Since the Crab control datasets used are rather small, it is not expected that atmospheric variations cancel out, so a flux deviation on the 10% level is acceptable as long as the spectral shape agrees with the published values. So these checks do not indicate a problem with my analysis.

The Bertero method of unfolding is the one usually used in papers of MAGIC, so I preferably used this method for the rest of my analysis.

---

12 The corresponding plot and table for cycle 5 are B.10 and B-1 in the appendix.

13 The corresponding plot and table for cycle 5 are B.11 and B-2 in the appendix.
Figure 5.12: Spectrum of Crab Nebula cycle 6 test sample using different unfolding methods, compared with published values. Unfolded parameters are given in table 5-1.

Table 5-1: Table of parameter values for different unfolding methods for Crab Nebula cycle 6. For the explanation of parameters see text.

<table>
<thead>
<tr>
<th>Unfolding Method</th>
<th>Energy [GeV]</th>
<th>$F_0$</th>
<th>$F_0$ Error</th>
<th>$\alpha$</th>
<th>$\alpha$ Error</th>
<th>$b$</th>
<th>$b$ Error</th>
<th>$r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bertero</td>
<td>79-5000</td>
<td>6.6e-10</td>
<td>1.6e-11</td>
<td>-2.31</td>
<td>0.030</td>
<td>-0.09</td>
<td>0.057</td>
<td>0.3</td>
</tr>
<tr>
<td>Forward</td>
<td>79-5000</td>
<td>6.8e-10</td>
<td>1.7e-11</td>
<td>-2.28</td>
<td>0.028</td>
<td>-0.18</td>
<td>0.058</td>
<td>0.3</td>
</tr>
<tr>
<td>Schmelling</td>
<td>79-5000</td>
<td>6.6e-10</td>
<td>1.0e-11</td>
<td>-2.34</td>
<td>0.023</td>
<td>-0.07</td>
<td>0.044</td>
<td>0.3</td>
</tr>
<tr>
<td>Tikhonov</td>
<td>79-5000</td>
<td>6.8e-10</td>
<td>1.4e-11</td>
<td>-2.29</td>
<td>0.032</td>
<td>-0.16</td>
<td>0.062</td>
<td>0.3</td>
</tr>
</tbody>
</table>
**Figure 5.13:** Spectrum of Crab Nebula test sample cycle 6 using different unfolding methods, compared with literature values. The plot is using a different random forest. Unfolded parameters are given in table 5-2.

<table>
<thead>
<tr>
<th>Method</th>
<th>Energy [GeV]</th>
<th>$F_0$</th>
<th>$F_0$ error</th>
<th>$\alpha$</th>
<th>$\alpha$ error</th>
<th>$b$</th>
<th>$b$ error</th>
<th>$r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bertero</td>
<td>79</td>
<td>5000</td>
<td>6.5e-10</td>
<td>1.6e-11</td>
<td>-2.32</td>
<td>0.030</td>
<td>-0.044</td>
<td>0.055</td>
</tr>
<tr>
<td>Forward</td>
<td>79</td>
<td>5000</td>
<td>6.7e-10</td>
<td>1.7e-11</td>
<td>-2.29</td>
<td>0.029</td>
<td>-0.129</td>
<td>0.057</td>
</tr>
<tr>
<td>Schmelling</td>
<td>79</td>
<td>5000</td>
<td>6.5e-10</td>
<td>1.0e-11</td>
<td>-2.35</td>
<td>0.022</td>
<td>-0.026</td>
<td>0.043</td>
</tr>
<tr>
<td>Tikhonov</td>
<td>79</td>
<td>5000</td>
<td>6.7e-10</td>
<td>1.4e-11</td>
<td>-2.30</td>
<td>0.031</td>
<td>-0.112</td>
<td>0.060</td>
</tr>
</tbody>
</table>

**Table 5-2:** Table of parameter values for different unfolding methods for Crab Nebula cycle 6 using a second random forest. For the explanation of parameters see text.
Chapter 6

MAGIC Observations of NGC1275

NGC1275 was known before the start of the stereo observation campaign to be a weak and, in the context of MAGIC, low energy source resulting out of the Fermi LAT spectrum \cite{74} and the MAGIC upper-limits from 2008 mono observations \cite{75}. Therefore, I asked for observation time during dark nights and lowest possible zenith angle. The darker the night and the smaller the zenith angle, the lower are the accessible energies. During two years I submitted a proposal to the time allocation committee (TAC): in 2009/10 for 50 hours and 2010/11 for 60h observation time that were granted both times. To search for intra-cluster cosmic rays and hypothetical dark matter annihilation signals from the central region of the Perseus cluster, another proposal using the same field of view but with relaxed observational requirements was submitted by Fabio Zandanel in both years. Only his 2009/10 proposal was granted dedicated observation time. Joining together all granted observation time for the center region of the Perseus cluster sum up to 210h, so far the most observation time ever granted by MAGIC for a single AGN, not including the observations already done before with the MAGIC mono system.

During the 3 years observation campaign on NGC1275 three different hardware setups of the telescopes were used. The 2008 data using only the single telescope are not part of this thesis. During summer 2009 the second telescope was finished and commissioning of the stereo system was completed in December 2009. Since the NGC1275 observation campaign started during commissioning of MAGIC-II, before the stereo trigger was fully operational, a non-standard trigger setup was used. Instead of using 3NN stereo trigger (see Chapter \ref{chapter:4.1}), a 4NN trigger was used in MAGIC-I only, but both telescopes read in case of a trigger signal. This allows to simulate stereo trigger later in the analysis, but the energy threshold is higher than in the standard 3NN stereo trigger used for the 2010/11 campaign.
6.1 Cycle 5 - Season 2009/10

The first year of the stereo campaign on the central region of the Perseus cluster started during the commissioning phase of the second MAGIC telescope and the stereo system. Due to a lot of technical problems in the data we have to exclude the first ten nights of data taking completely, so the first useful data were taken 2009/10/19. Table C-1 in the appendix contains a list of all remaining datasets, including additional technical problems found.

From the total 50h of data on NGC1275 plus additional 100h granted for dark matter and cosmic rays of the Perseus cluster, only 45h effective observation time were finally accumulated because of long periods of bad weather and technical problems, but also because of observations of other sources during the same observation window received higher priority.

Officially, the commissioning of the stereo system ended on 1 January 2010. From then on, it was recommended to observe with the standard stereo trigger. But to keep the full dataset with similar hardware condition and because there were still minor unsolved problems with the standard trigger, we decided to continue with the special trigger setup for the remainder of the NGC1275 observations. For the whole period, we did take data using two wobble positions at a distance of 0.4° at angles 000 and +180 around NGC1275 (see figure 6.1). This is the standard operation mode in MAGIC for sources without an exceptionally bright star within the trigger region.

Multi-wavelength Data Cycle 5

To be able to have a nice spectral energy distribution I organized with help from other MAGIC members a multi-wavelengths campaign. Including Radio data from the MOJAVE telescopes, optical data from the KVA that usually works closely together with MAGIC, X-ray from Chandra (where we contacted the PIs from an already granted proposal), high energy gamma-ray from Fermi LAT data that became public at that time, and Planck microwave data.
6.1. CYCLE 5 - SEASON 2009/10

Figure 6.1: Skymap of the central region of the Perseus cluster (produced with Xephem [110]). The position of the interesting AGNs are marked in colors. The white and gray boxes indicate the wobble positions used during the 2009/10 and 2010/11 observation campaigns respectively.
6.2 Cycle 6 - Season 2010/11

For the observation campaign 2010/11, two major changes were applied to the observational setup: we used the standard 3NN stereo trigger to reach a lower energy threshold and four instead of two wobble positions for a better coverage of the central region of the Perseus cluster. The wobble positions used are 0.4° distance from NGC1275 at the angles +058, +157, +238, +337 as indicated in figure 6.1. During this season 53.5h of effective observation time were accumulated reaching almost the granted number of 60h.

While the emission from NGC1275 was rather stable during cycle 5, Fermi reported on 14 July 2010 an observation of a very bright flare from NGC1275 in the ATel #2916 [111]. At that time, the source would only have been observable for MAGIC under a very large zenith angle, resulting in an energy threshold of $\approx 400$ GeV, far too high for any reasonable observation. But to be prepared for another flare with better observational conditions, I concluded a daily check of the public Fermi data is crucially needed. A dedicated group within MAGIC was created at that time to provide monitoring activities of selected AGN based on the public Fermi LAT data. The group provided a new point for the lightcurve every three days which implied the danger to miss a short flare, so I did a daily monitoring of Fermi LAT data for NGC1275 myself (described in the next section). During August, I found again an indication for enhanced activity in Fermi LAT data. By that time, NGC1275 was observable for about an hour per night under a zenith angle of $<37^\circ$. While this is worse than the $<25^\circ$ requested, the collaboration agreed that the opportunity to catch a flare does compensate the slightly worse energy threshold, and the observation schedule was changed immediately to take data from NGC1275 whenever there is a hint of enhanced activity in the Fermi LAT data.

The useful datasets for the 2010/11 campaign are listed in table C-2 the appendix

Multi-wavelength Data Cycle 6

During Cycle 6, data from the MOJAVE in radio, the KVA in optical and the Fermi LAT for high energy gamma-rays are available. The Planck data from this season is not yet public, so it was decided not to use them yet\(^1\). In X-ray, NGC1275 is a difficult target as the cluster is so bright that only Chandra can distinguish between the AGN emission and the background of the cluster, and no Chandra observation on NGC1275 was scheduled during that observation period.

\(^1\)To get early access to these Planck data would need to add the whole Planck Collaboration to the author list.
6.3 Monitoring of NGC1275 using Fermi Data

The Data from the Fermi LAT is available online publicly \[112\]. The Fermi Collaboration provides also the needed tools \[113\] for a basic analysis. There is a web form one can get datasets for particular sources or weekly files including all the data recorded \[112\]. The data comes in two filetypes which are needed for the basic analysis. Photon files (*PH*.fits) contains all information connected to individual photons like relative direction and energy. Spacecraft files (*SC*.fits) contain the information of the Satellite like pointing direction. Additionally one can download Extended data files (*EV*.fits) which are used for a deeper analysis.

First one uses the program *gtselect* to preselect the data sample in terms of quality, time, energy and the radius of search region in the photon files. Followed by *gtmktime* to do quality cuts on the information stored in the Spacecraft files.

The next step is to generate an exposure map. Starting with *gtltcube* that uses photon and spacecraft files to produce a live time cube. This is a table including the integrated observation time as a function of inclination to the z-axis of the LAT. The output file of *gtltcube*, the spacecraft file and the output of *gtmktime* is needed by *gtexpmap* to calculate the exposure map. As Fermi has a large field of view and its angular resolution at 200 MeV energies is in the order of \(3^\circ\), one has to include all known gamma-ray sources in the field of view in a source model file to be able to extract the photons of the source one is interested in. Typically one uses the list of sources published in the Fermi catalogue. The last step provided in the public analysis tools put together the output files of *gtmktime*, *gtltcube*, *gtexpmap*, the source model file and the space craft file. With this information *gtlike* optimizes the variables and assigns fractions of the total photon contents to every source. The output of *gtlike* can be used out of the box when one is only interested in relative activity behavior of the source, or it can be normalized to absolute flux values, but there exists no official tool for the normalization. Since I was only interested in the relative flux to be able to identify enhanced activities, I did not need to apply any normalization.

As NGC1275 is not among the brightest sources in the Fermi LAT sky it needs a minimum integration time to be visible. I found an integration time of three days to be sufficient to accumulate a decent amount of photons in the energy range \(> 2\text{ GeV}\). To be able to have an activity measure on every single day I used a running window of 72 h lengths that is shifted by 24 h every day. This is sufficient to send an alert to the MAGIC scheduler and the shift crew in case of a strong flaring activity.

Unfortunately, there was some strange correlation found: whenever enhanced activity was found in Fermi LAT data, the source was not observable for MAGIC because of too bright moonlight, bad weather or technical problems (figure 6.2).
Figure 6.2: The plots show the Fermi LAT lightcurve of NGC1275 during cycle 5 (a,b) and part of cycle 6 (c,d), for all data above 200 MeV (a,c) and limited data above 2 GeV (b,d). The x-axis is given in Fermi Mission Time, i.e. seconds since 1 January 2001, 00:00 UTC. The black triangles represent my analysis with a three day sliding window, while the blue points show the analysis from the MAGIC group that monitors Fermi LAT data using three day bins. The red lines represent nights when MAGIC observations took part. After September 2010, we no longer monitored the Fermi data, because it was clear that from then on MAGIC has to observe NGC1275 whenever it is visible under low zenith angle to accumulate all the granted observation time.
Obtaining spectra out of Fermi data is much more complicated than doing lightcurves and needs quite some experience. In accordance with an agreement between the Fermi and MAGIC Collaborations, we asked experts from Fermi LAT to calculate the needed spectra for the upcoming publication of the full NGC1275 multi-wavelength campaign.

6.4 Features in the MAGIC Data of NGC1275

The data-selection for MAGIC data is highly non standardized and differs from analyzer to analyzer, from source to source and it differs as well depending on the physics one wants to address. In the case of NGC1275, having a weak and low energy source just at the limit of the MAGIC performance, there are two contradicting issues. On one hand, to be able to see a significant signal over background, one wishes to include as much data as possible, while on the other hand to extract a reliable spectrum needs very stringent cuts to ensure correct flux and energy calculations.

Because lowest energies are most sensitive to problems in the very early calibration of raw data, whenever an improved calibration existed, a complete re-analysis starting from raw data had to be done\(^2\). But not only re-calibrations were needed several times, analyzing NGC1275 uncovered several problems in the MAGIC analysis that went undetected for brighter and/or higher energetic sources.

Technical Problems with the Calibration Box

While there was no indication in the online displays for the shift crew, it was discovered during analysis that for several data sets in January and February 2011 the raw level calibration was completely screwed up. The problem was traced back to a sporadic malfunctioning of the calibration box that should illuminate the camera with constant light pulses. It was not clear if these data sets (among them a significant fraction of all NGC1275 data) could ever be recovered. But finally the calibration experts found a way how to treat these cases, and applying a non-standard calibration finally allows to use the data for normal analysis.

\(^2\)It is not possible to calibrate IACTs in a testbeam or similar. Not even the operation conditions for PMTs can reasonably well be emulated in the laboratory. The only possibility is to try to find correlations among individual pixels of the camera, and at a higher level compare the reconstructed shower parameters with MC predictions. Since the MAGIC-II camera and electronics were new, several iterations with improved calibrations as well as bug fixes were needed.
Jumping Source Position in Camera

When observing in wobble mode the source position travels around the camera center with a radius accordingly to the wobble offset, usually $0.4^\circ$. One can see in figure 6.3 that occasionally the source position is not where it is supposed to be, but jumping to some far away points and back again. These jumps can screw up the reconstructed parameters of the hypothetical source.

![Figure 6.3: Plots showing the pointing quality of the MAGIC-I (a) and MAGIC-II (b) telescopes for the 2010/11 observation campaign of NGC1275 after applying pointing correction. The trajectories should follow a circle around the camera center. The large jumps of individual events indicate a not yet understood problem in applying higher order pointing corrections.](image)

The origin of these jumps is not yet fully understood. I checked the drive system logfiles of these data sets and had several discussions with the drive system experts, and we came to the conclusion that it can not be a problem of the drive system, but a feature of the pointing correction applied afterwards to correct for small mispointings of the telescopes. Comparing the data before and after pointing correction and further discussions with the pointing correction experts, it is agreed to be a software problem. But the experts have not yet found and corrected this bug. Since only a very small fraction of the events in the individual data sets are affected, the advise from the MAGIC Software Board for the time being is to simply cut out those individual events exhibiting such strange jumps.

Fake Signal with Standard Analysis

It was known that the standard random forest set originally recommended at that time to be used for analysis of stereo data had a minor bug, since it was missing the so called leakage correction\footnote{Very large shower images or showers at the edge of the camera might not be fully contained. The missing part can be estimated and be corrected for.}. But the experts were sure fixing this bug has not
highest priority, since it should only affect the very rare highest energy gamma-rays and can be neglected, especially for a low energy source like NGC1275.

Analyzing the NGC1275 data of cycle 5, I suddenly found a clear $>5\sigma$ excess in one single night (figure 6.4). But doing several cross checks it became evident this excess can not be real. Finally I could show the fake signal to be a combination of the missing leakage correction and using too many off positions. This triggered extensive studies by the different experts, resulting in a new standard random forest including the leakage correction, and the strong recommendation that for low energy sources one shall not use more wobble off regions than wobble positions were used during the observation. By chance the NGC1275 observations of cycle 6 were using four wobble positions to better cover the interesting central part of the Perseus cluster. This was the only existing data with four wobble positions and so the only testbed to investigate the effect of different wobble combinations.

Finally, while we are restricted to use only one off region for the cycle 5 analysis, we still can use three off regions for cycle 6.

6.5 Data Preparation

The calibration of the raw data is done at the MAGIC datacenter in Barcelona. Since there was a learning curve needed in calibrating data for the new stereo system, recalibrations of older datasets had to be done whenever a new feature was found. Re-calibrating the full MAGIC dataset affected can take several months. Correct calibration is crucial for dim and low-energy sources, so the NGC1275 analysis had to be redone whenever a new calibration became available. One can also download processed star files, but these are not regularly redone when a new version of the analysis software is available. Since modifications and bug-fixes in the underlying software can be crucial for weak sources like NGC1275 I decided to run the complete datasample myself, the final analysis of the full dataset was done with software version Mars_V2-4-13.

6.6 Data Selection

Data selection is a highly non standardized process as described in chapter 5. In the following section the datacheck of the NGC1275 campaign is shown. In all plots values of MAGIC-I are represented by blue points and MAGIC-II values are shown using red points. Whenever feasible, the same cuts had been applied to the Crab control sample.
Figure 6.4: Example for a fake signal at low energies using three off regions: (a) is the average signal, (b-d) are the signal using off regions at 180, 90 and 270 degrees in the camera respectively. All three should contribute equally to the average signal, but in this case the result is dominated by the 'fake off' regions 90 and 180 degrees.

6.6.1 Cycle 5

A low energy source like NGC1275 has to be observed during dark time to allow lowest energy threshold, so a DC value of less than 1500 units was requested. The cloudiness measured by the radiation pyrometer was cut to be less than 50%, and the number of identified stars must be larger than 20. All data quality control plots for cycle 5 are in figure 6.5.
Figure 6.5: Data quality plots for NGC1275 cycle 5 depending on time in MJD. The top plot shows the average DC current indicating amount of ambient background light. The middle plot shows the cloudiness value estimated by the radiation pyrometer. The lower plot shows the amount of identified stars as measured by the starguider CCD. Since these CCDs had never been calibrated, the absolute values for both telescopes can differ. Measurements for MAGIC-I are blue while those for MAGIC-II are in red. If a dataset for one of the telescopes exceeds 1500 units for DC, 50% for cloudiness or less than 20 identified stars, the dataset is rejected. Measured values of zero often indicate hardware problems of the auxiliary device and need to be treated specially.
The reconstructed event rate after image cleaning is dominated by hadronic events and is considered to be a good tool for removing problematic data. During cycle 5 MAGIC was operated with a soft stereo trigger where MAGIC-I was triggering and MAGIC-II was readout as a slave. Therefore, the expected event rate after image cleaning is very different. Figure 6.6 shows the normalized event rate for both telescopes. Datasets laying outside the indicated band in one of the telescopes are rejected. There exists no clear definition for ‘good rates’, so the limits applied are a mixture of experience and educated guess.

Usually, the rates are outside the accepted band for both telescopes, indicating days with bad weather.

Figure 6.6: Normalized event rate for NGC1275 cycle 5 depending on time in MJD. The top plot corresponds to MAGIC-I, the lower one to MAGIC-II. Since MAGIC-II was triggered in slave mode, the expected event rates differ a lot. Datasets laying outside the marked band in one of the telescopes are rejected.
6.6.2 Cycle 6

For cycle 6, the same data quality checks were applied as in cycle 5. The plots for cycle 6 data are shown in 6.7.

![Data Quality Plots for NGC1275 Cycle 6](image)

**Figure 6.7:** Data quality plots for NGC1275 cycle 6 depending on time in MJD. The top plot shows the average DC current indicating amount of ambient background light. The middle plot shows the cloudiness value estimated by the radiation pyrometer. The lower plot shows the amount of identified stars as measured by the starguider CCD. Since these CCDs had never been calibrated, the absolute values for both telescopes can differ. Measurements for MAGIC-I are blue while those for MAGIC-II are in red. If a dataset for one of the telescopes exceeds 1500 units for DC, 50% for cloudiness or less than 20 identified stars, the dataset is rejected. Measured values of zero often indicate hardware problems of the auxiliary device and need to be treated specially.
Since in cycle 6 the final stereo-trigger mode was used where both telescopes are only read out if both trigger within a narrow time window, the reconstructed event rate should be the same, except for minor differences in the image cleaning. Figure 6.8 shows the normalized event rate for both telescopes.

Figure 6.8: Normalized event rate for NGC1275 cycle 6 depending on time in MJD. The top plot corresponds to MAGIC-I, the lower one to MAGIC-II. Since the standard stereo trigger was used in cycle 6, the expected event rate is identical for both telescopes. The measured event rate can differ because of small differences in the image cleaning for both telescopes. Datasets laying outside the marked band in one of the telescopes are rejected.
Summary

Table 6-1 summarizes the amount of MAGIC data for NGC1275 for both data taking cycles. The granted observation time in cycle 5 includes 100 h requested for search for signal from intra-cluster cosmic ray interaction and dark matter annihilation, but of course it was always forseen to use the combined data.

<table>
<thead>
<tr>
<th>observation time</th>
<th>cycle 5</th>
<th>cycle 6</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>granted</td>
<td>150.0 h</td>
<td>60.0 h</td>
<td>210.0 h</td>
</tr>
<tr>
<td>taken</td>
<td>45.0 h</td>
<td>53.5 h</td>
<td>98.5 h</td>
</tr>
<tr>
<td>after cut</td>
<td>38.7 h</td>
<td>44.5 h</td>
<td>83.2 h</td>
</tr>
</tbody>
</table>

Table 6-1: Summary of MAGIC data taken observing NGC1275. The first line is the amount of time granted by the Time Allocation Committee, the second line the amount of time data were taken, and the third line the amount of data that survived the quality cuts and were used for high level analysis.
Chapter 7

Results of the MAGIC Analysis

In this chapter the high level analysis results from the MAGIC observations of the galaxies IC310, NGC1265 and NGC1275 in the Perseus Cluster are presented. All three galaxies are in the same field of view and the results are based on the same datasets. The interpretation of the results is given in the next chapter.

7.1 Head Tail Radio Galaxies in the Perseus Cluster

As described in chapter 3 Head Tail Radio galaxies were never considered to be potential sources of VHE gamma-ray emission. Therefore, it was a big surprise when several gamma-rays with energies exceeding 30 GeV were found in the Fermi LAT data [80]. VHE gamma-ray emission from that source was so unexpected, that in this paper a peculiar VHE emission process based on bow shocks was proposed. By chance, IC310 was in the field of view of MAGIC for the ongoing observation of NGC1275, where I acted as PI.

7.1.1 The Galaxy IC310

IC310 is situated ~0.6 degrees south-east to NGC1275 (see figure 6.1). Therefore, only one of the two wobble positions used in the 2009/10 campaign had IC310 in the field of view. For the 2010/11 campaign, this was the main reason to use four wobble positions, so that IC310 was in the field of view for two of them.
Analysis of 2009/10

When taking these data, the MAGIC stereo system was still under commissioning and the stereo analyze software under test. Furthermore, the source was off-axis, i.e. the position was not where the telescope pointed at (modulo wobble position), and only one of the two wobble positions could be used for the analysis. Therefore, a task-force of software and analysis experts was formed and with non-standard software the source was found in the MAGIC data and published as the first source detected with the MAGIC stereo system [81].

In the mean time, the understanding of MAGIC and the analysis software has improved, and I reanalyzed the data again with the latest software.

To calculate the significance of the IC310 signal its off axis position has to be taken into account. I used the off from wobble partner method (OffWP) using one of the two wobble positions (+180) as on data and the second wobble position as off sample. As the source shows signal exceeding several hundred GeV the signal plot was done using standard full-energy range cuts for cycle 5. Using such high size-cuts there is no need to take special care about the non-standard soft-stereo trigger mode used, since at these energies the trigger efficiencies of both methods are the same. Due to improved angular resolution at high energies, the $\Theta^2$ cut can be made much tighter than it is needed for low energy analysis.

Figure 7.1 shows the result of odie with a clear signal excess of 8.9 sigma, while figure 7.2 shows the skymap of cycle 5 data above 600 GeV estimated energy. Left to the center there is a pointlike gamma-ray source visible consistent with the position of IC310.

Since no indication for a curvature is seen in the spectrum, I unfolded with a pure power law spectrum:

$$\frac{dF}{dE} = F_0 \cdot \left( \frac{E}{r} \right)^\alpha$$

(7.1)

with the parameters flux in cm$^{-2}$s$^{-1}$TeV$^{-1}$ ($F_0$), energy in GeV ($E$), normalization in TeV ($r$) and index ($\alpha$). I have chosen 22 bins from 9 GeV to 62 TeV for the spectrum of IC310, further labeled as 'Binning 4'. Using the Bertero unfolding, I get:

$$\frac{dF}{dE} = (1.21 \cdot 10^{-12} \pm 1.9 \cdot 10^{-13}) \text{cm}^{-2}\text{s}^{-1}\text{TeV}^{-1} \cdot \left( \frac{E}{1 \text{TeV}} \right)^{-2.0\pm0.3}$$

(7.2)

with statistical errors only. The spectral index of $\sim -2$ up to such high energies is one of the hardest VHE spectra ever measured for an AGN.

$^1$size1>150, size2>190, fEnergy>250, hadronness<0.2 , $\Theta^2$<0.01.
Figure 7.1: IC310 cycle 5 analysis with OfWP method. The solid gray histogram corresponds to the measured background, while the points with error are the signal. A signal excess is seen below the $\Theta^2$ cut indicated by the dashed line.

Figure 7.2: Skymap of IC310 cycle 5 for energies above 600 GeV estimated energy. The excess found on the right side is compatible with the position of IC310. At the position of NGC1275, marked with a white cross in the center of the plot, no hint for a signal at these high energies is found.
To investigate the effect of different binnings, I applied several other logarithmic binnings labeled Binning '1' to '3'. The unfolded spectra using the Bertero method is shown in figure 7.3. As a reference the lines show the Crab Nebula spectra and the published MAGIC IC310 spectrum. The values of the parameters to the corresponding spectra are given in table 7-1. While the unfolded parameters seem to agree within the errors, it has to be remembered that these methods used exactly the same data, so the deviations are an indication for systematic differences originating from binning effects.

![Figure 7.3: Spectrum of IC310 using the Bertero unfolding method with a simple power law and different binnings. As a reference the lines show the Crab Nebula spectra and the published MAGIC IC310 spectrum. See text for explanation.](image)

<table>
<thead>
<tr>
<th>Binning</th>
<th># Bins</th>
<th>Energy [GeV]</th>
<th>F$_0$</th>
<th>F$_0$ error</th>
<th>$\alpha$</th>
<th>$\alpha$ error</th>
<th>r</th>
</tr>
</thead>
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<td>1.2e-12</td>
<td>2.3e-13</td>
<td>-1.5</td>
<td>0.4</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>128 - 3581</td>
<td>1.1e-12</td>
<td>2.1e-13</td>
<td>-2.0</td>
<td>0.3</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>126 - 3155</td>
<td>1.0e-12</td>
<td>1.9e-13</td>
<td>-1.8</td>
<td>0.3</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>186 - 4309</td>
<td>1.2e-12</td>
<td>1.9e-13</td>
<td>-2.0</td>
<td>0.3</td>
<td>1</td>
</tr>
</tbody>
</table>

*Table 7-1: Parameter values for different binnings for IC310 cycle 5. For the explanation of parameters see text.*
Analysis of 2010/11

During the campaign of 2010/11 the number of wobble positions was increased to four, including two wobble positions suitable to investigate IC310 (figure 6.1).

The source was analyzed using the standard full-energy range cuts for cycle 6. Despite the lower energy threshold in 2010/11, better coverage by using more wobble positions and more observation time, no clear excess signal is found in this dataset (figure 7.4). The statistically insignificant excess of $2.37\sigma$ seems even to be enhanced by a negative background fluctuation in the first $\Theta^2$ bin. Fluxlc calculates an upper limit of $4.77 \cdot 10^{-12} \text{ph cm}^{-2}\text{s}^{-1}$ above 200 GeV estimated energy. Since the bow-shock acceleration model predicts steady emission on a timescale of centuries, this clear flux change within a year does exclude this model.

![Figure 7.4: IC310 cycle 6 analysis with OFWP method. The solid gray histogram corresponds to the measured background, while the points with error are the signal. No significant excess below the $\Theta^2$ cut indicated by the dashed line is visible.](image)

$\Theta > 125$, size $> 125$, fEnergy $> 250$, hadronness $< 0.16$, theta $< 0.01$. 
7.1.2 The Galaxy NGC1265

NGC1265 is the role model of the head tail radio galaxy class. As IC310 is emitting gamma-rays and belongs to the same class of AGNs, it is a logical target to be investigated, especially since it is in the field of view of NGC1275 and therefore, no dedicated observation time is needed.

Analysis of 2009/10

NGC1265 is situated north-west to NGC1275 and both wobble positions can be used for this analysis (figure 6.1). Figure 7.5 shows a signal plot of the position of NGC1265 using standard cycle 5 full-energy range cuts and OfWP method. There is no hint for any excess, and \( \text{fluxlc} \) calculates an upper limit of \( 4.29 \cdot 10^{-13} \text{ ph cm}^{-2} \text{s}^{-1} \) above 200 GeV estimated energy.

Since the bow-shock model predicts in first approximation a isotropic emission of VHE gamma-rays, the non-detection of NGC1265 did already disfavor that model at that time.
7.1. HEAD TAIL RADIO GALAXIES IN THE PERSEUS CLUSTER

Analysis of 2010/11

For completeness, the same analysis was repeated for the 2010/11 dataset, using OfWP method using the two wobble positions closest to NGC1265 (figure 6.1) and standard full-energy range cuts for cycle 6 were applied. Figure 7.6 again shows no indication for any excess signal is found, and fluxlc calculates an upper limit of $5.7 \cdot 10^{-13} \text{ph cm}^{-2} \text{s}^{-1}$ above 200 GeV estimated energy.

![Graph showing data analysis results](image)

**Figure 7.6:** NGC1265 cycle 6 analysis with OfWP method. The solid gray histogram corresponds to the measured background, while the points with error are the signal. No hint for an excess below the $\Theta^2$ cut indicated by the dashed line is visible.

Combined 2009/10 and 2010/11 Analysis

Since there is no hint for any signal visible in any of the two datasets, it is possible to combine them to reach a better upper limit for the flux. For the combined analysis the same cuts must be applied to both samples, so I applied the cycle 5 full-energy range standard cuts. Figure 7.7 exhibits no hint of a signal, and the combined upper limit for VHE gamma-ray emission above 200 GeV estimated energy is calculated to be $2.5 \cdot 10^{-13} \text{ph cm}^{-2} \text{s}^{-1}$. 
7.2 NGC1275: The Central Galaxy of the Perseus Cluster

NGC1275 is a galaxy with a complex structure and its classification is very disputed, as described in chapter 3. It had been detected by Fermi up to 10 GeV with a rather hard spectrum [74], while MAGIC mono observations did put stringent upper limits for the flux above $\approx 150$ GeV [75]. From this it was clear it will be a very low energy source for MAGIC, asking for very careful analysis.

7.2.1 Analysis of 2009/10 Data

During the first season NGC1275 was observed with two wobble positions (figure 6.1) as it was standard for MAGIC data taking. Figure 7.8 shows the signal plot using standard cycle 5 low-energy $^3$ cuts with OfWP method with one off position and the skymap in figure 7.9 indicates the excess to be in excellent spacial agreement with the position of NGC1275. Unfortunately, the amount of data was not sufficient to reach $5\sigma$ significance and it was not possible to claim a detection based on these data.

$^3$size1$>$58, size2$>$73, hadronness$<$0.28 , theta$<$0.02.
Figure 7.8: NGC1275 cycle 5 analysis with OfWP method. The solid gray histogram corresponds to the measured background, while the points with error are the signal. There is a strong hint for an excess below the $\Theta^2$ cut indicated by the dashed line is visible.

Figure 7.9: Skymap of NGC1275 cycle 5 for low energies. The excess found agrees very well with the position of NGC1275, marked with a cross in the center of the plot. IC310 was also active at that time in the same field of view, but it is not visible at low energies.
Another problem with cycle 5 low energy data is that due to the non-standard trigger used, it was not possible to reach agreement between Monte Carlo simulations and low energy data. This prevents to correctly calculate the effective area at low energies, and therefore, no flux value can be deduced. So it was needed to introduce another cut size > 150, reducing the signal. Nevertheless, limited spectral information can be extracted above 120 GeV. Having very few bins, unfolding can be done only using the most simple power law. For the NGC1275 spectrum in cycle 5 I chose 33 logarithmic bins between 8 GeV and 79 TeV called 'Binning 2'. The result from unfolding with Bertero method is:

$$\frac{dF}{dE} = (2.3 \cdot 10^{-10} \pm 6.7 \cdot 10^{-11}) \text{cm}^{-2}\text{s}^{-1}\text{TeV}^{-1} \cdot \left(\frac{E}{0.15\text{TeV}}\right)^{-5.6\pm1.6}$$

with statistical errors only. The unfolded spectrum using Bertero method with four different binnings is shown in figure 7.10 together with the published Crab spectrum and the NGC1275 spectrum deduced from the cycle 6 dataset. Taking into account the very limited statistics, there is no indication for a significant deviation from the published spectrum. Table 7-2 summarizes the outcome of the unfolding for the different binnings. It is a feature of the MAGIC standard analysis that the energy bins cannot easily be adjusted; they must be logarithmic and the lowest and highest energy must lay within a narrow window. Then, a subrange of these bins can be used in the analysis, resulting in the very strange binnings that had to be used here.

<table>
<thead>
<tr>
<th>Binning</th>
<th># Bins</th>
<th>Energy [GeV]</th>
<th>F0</th>
<th>F0 error</th>
<th>α</th>
<th>α error</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Low</td>
<td>High</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>126</td>
<td>500</td>
<td>1.7e-10</td>
<td>4.9e-11</td>
<td>-4.7</td>
<td>1.1</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>132</td>
<td>437</td>
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<td>120</td>
<td>509</td>
<td>1.2e-10</td>
<td>4.6e-11</td>
<td>-3.8</td>
<td>0.9</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>136</td>
<td>566</td>
<td>1.2e-10</td>
<td>4.4e-11</td>
<td>-3.7</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table 7-2: Power law parameter values for different binnings for NGC1275 cycle 5 data. See text for explanations.

It is instructive to have a direct look at the extracted data used to extract the unfolded spectrum. Figure 7.11 shows the amount of excess-event dependent on estimated energy for the four different binnings. Estimated energies below $\sim 120\text{GeV}$ typically do not survive the applied size cut. But there is no one-to-one correlation between size and estimated energy, so few events at low energies survive the cut. The distributions look very different and it is no surprise they result in diverging unfolded spectra, especially remembering the energy resolution for very low energies to be $O(20\%)$. This systematic uncertainty is much larger than the statistical error
7.2. NGC1275: THE CENTRAL GALAXY OF THE PERSEUS CLUSTER

Figure 7.10: Spectrum of NGC1275 cycle 5, using the Bertero unfolding method with a simple power law and different binnings. For comparison, also the published Crab spectrum and the published NGC1275 spectrum deduced from cycle 6 data is included. Within the very limited statistics, cycle 5 does not significantly differ from the published spectrum. See text for explanation.

bars of the individual points shown in figure 7.10 calculated by CombUnfold. Despite the large uncertainty, all unfoldings agree with a very soft spectrum of $\sim -4$ and a low flux at 150 GeV of $\sim 1.5 \times 10^{-10} \text{cm}^{-2}\text{s}^{-1}\text{TeV}^{-1}$, a strong indication for a very soft spectrum.

7.2.2 Analysis of 2010/11 Data

In August 2010 the second year of stereo observations on NGC1275 was started earlier than planned due to a high state seen in the Fermi data. After 14h of observation the famous significance of 5 was reached and the detection of NGC1275 was announced on 10 October 2010 in ATel #2916 [114]. According to the granted proposal of mine the observation was continued as the measurement of the spectrum is crucial for a better understanding of this complex galaxy. Main difference to the cycle 5 observations was the usage of standard stereo trigger to reach lower energy threshold and the usage of four wobble positions. When the observation was done, it was not yet clear that for dim low energy sources it is not allowed to use three off regions in the camera with two wobble position, since this can result in a fake signal (see chapter 6.4). Using four wobble positions (done to get better coverage of...
Figure 7.11: Calculated amount of excess events in the NGC1275 cycle 5 data for the four different binnings. Events below $\approx 120$ GeV are mainly removed by the size cut applied. See text for discussion.

the central part of the Perseus cluster) resulted in the added value of being able to use three off regions.

The result of odie is shown in figure 7.12 with a signal of 7.8 sigma and a signal to background ratio of 11.6%. The skymap in figure 7.13 shows that the excess is in good agreement with the spacial position of NGC1275 marked with the cross. The weak signal on the right side is not in coincidence with IC310, but is most probably a background fluctuation at low energies, since a $\Theta^2$ plot for that coordinate does not indicate a hint of a signal.
Figure 7.12: NGC1275 cycle 6 analysis with OfWP method and three off regions. The solid gray histogram corresponds to the measured background, while the points with error are the signal. There is a clear signal visible below the $\Theta^2$ cut indicated by the dashed line.

Figure 7.13: Skymap of NGC1275 cycle 6 for all energies. The excess found agrees very well with the position of NGC1275, marked with a cross in the center of the plot, but is more extended than expected from the PSF. The excess on the left side does not coincide with IC310 and is most probably a statistical fluctuation at low energy.
As can be seen in the skymap, the source NGC1275 looks somewhat extended. One reason could be the not well understood angular resolution of MAGIC at such low energies, resulting in an underestimated PSF. But in that case one would expect a symmetric extension and not an elliptical distribution. Another possibility could be a mispointing of the telescope for part of the observation. To investigate further, I re-did the analysis using an additional cut size $>100$ to exclude the lowest energies. The resulting signal is shown in figure 7.14. As can be seen, the excess is reduced to $6\sigma$. In the skymap of figure 7.15 no hint is left for an extension of the source. This excludes the possibility of mispointing, since this would affect higher energy data the same way as low energy ones. There exists not enough statistics to decide if the source is really extended at the lowest energies, or if the full-energy skymap just shows a statistical fluctuation.

**Figure 7.14:** NGC1275 cycle 6 analysis with OfWP method and three off regions and additional cut size $>100$. The solid gray histogram corresponds to the measured background, while the points with error are the signal. There is a clear signal visible below the $\Theta^2$ cut, but it is is significantly smaller than without the size cut.

Since cycle 5 and cycle 6 datasets had different trigger conditions, the energy threshold is different. As described in the previous section, for cycle 5 data it is not possible to calculate a reasonable effective area for lower energies and to extract a flux. To be able to compare the cycle 5 and cycle 6 data, I applied also a cut size $>150$ to the cycle 6 data. As can be seen in figure 7.16, the signal for cycle 6 drops below $4\sigma$. This is a strong indication that the detection of NGC1275 during cycle 6 was mainly due to the improved energy threshold and not due to higher flux from the source.
Figure 7.15: Skymap of NGC1275 cycle 6 with size cut >100. The excess found agrees very well with the position of NGC1275 without any hint for an extension.

Figure 7.16: NGC1275 cycle 6 analysis with OfWP method for size >150. The solid gray histogram corresponds to the measured background, while the points with error are the signal. The signal below the $\Theta^2$ cut drops below $4\sigma$. 
Figure 7.17 shows the spectrum of NGC1275 for cycle 6 data after unfolding with a pure power law spectrum (see equation 7.1) using the Bertero method and different binnings.

For NGC1275 in particular it is very difficult to find an appropriate binning as the analysis package limits the binning to be logarithmic. Changing this would be a major intervention in the software by the experts and as the spectral behavior of NGC1275 is very unusual we have to solve the problem in a different way. For very soft spectra like NGC1275 with a spectral index of $\sim -4$ the main signal is contained in the lowest energy bin. So there are two methods to bin this spectrum. To cover the whole energy range NGC1275 shows a signal, one has to choose large bins to have enough events per bin above 150 GeV. For this task I use 20 logarithmic bins from 5 GeV to 50 TeV called 'Binning 2'. The result of the unfolding with Bertero method and statistical errors only is:

$$\frac{dF}{dE} = (6.9 \cdot 10^{-11} \pm 1.7 \cdot 10^{-11}) \text{cm}^{-2}\text{s}^{-1}\text{TeV}^{-1} \cdot \left(\frac{E}{0.15 \text{ TeV}}\right)^{-4.1 \pm 0.4}.$$  

(7.4)

The other possibility is to choose small bins to take advantage of the strong signal around 100 GeV for the price of not being able to treat the signal above 150 GeV properly. I applied such narrow bins to be able to better check the connection to the high energy end of the Fermi LAT spectrum in the multi-wavelength part. As
7.2. NGC1275: THE CENTRAL GALAXY OF THE PERSEUS CLUSTER

bins have to be much smaller for this I chose 55 logarithmic bins between 6.5 GeV and 50.8 TeV called ‘Binning 4’, resulting in

$$\frac{dF}{dE} = (7.9 \cdot 10^{-11} \pm 3.3 \cdot 10^{-11}) \text{cm}^{-2} \text{s}^{-1} \text{TeV}^{-1} \cdot \left(\frac{E}{0.15 \text{ TeV}}\right)^{-3.7\pm1.0}.$$  (7.5)

for the Bertero unfolding method. The larger error in the spectral index is due to the shorter lever arm of the spectrum.

Either way important information is lost, so I will use one spectrum of each binning type in the further discussion. As can easily be seen in table 7-3 comparing results using Binnings ‘1’ and ‘4’, variations in the selection of bins can drastically change the errors, but one has to keep in mind that $F_0$ and $\alpha$ are correlated. The spectral index is $\approx -4$, making NGC1275 one of the VHE emitters with the softest spectrum found, and MAGIC is currently the only instrument able to observe the high energy end of the spectrum. Due to the steep spectrum the signal of NGC1275 is no longer visible for MAGIC above $\sim 500$ GeV.

<table>
<thead>
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<th>Binning</th>
<th># Bins</th>
<th>Energy [GeV]</th>
<th>$F_0$</th>
<th>$F_0$ error</th>
<th>$\alpha$</th>
<th>$\alpha$ error</th>
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<td>3.3e-11</td>
<td>-3.7</td>
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<td>0.15</td>
</tr>
</tbody>
</table>

Table 7-3: Parameter values for different binnings for NGC1275 cycle 6 after unfolding with a power law using Bertero method. See text for explanation.

Also in this case it is interesting to look into the plot with excess events vs. estimated energy (figure 7.18). Since no cut size > 150 had to be applied, more events at lower energies survive. A not understood feature in the dataset is the clear lack of events at $\sim 20$ GeV. For the narrow binnings ‘1’ and ‘4’, the bin width becomes comparable to the energy resolution. Even with the much better statistics compared to cycle 5, it is difficult to extract a precise description of the (power law) spectrum. Comparing tables 7-3 and 7-2 one gets the impression that the flux during cycle 6 was reduced, but the systematic uncertainties between the two campaigns are too large to claim variability.
Figure 7.18: Calculated amount of excess events in the NGC1275 cycle 6 data for the four different binnings. See text for discussion.
7.2.3 Multi-wavelength Data on NGC1275

In this section some results of the multi-wavelength data from the two years of the campaign on NGC1275 are presented. All Instruments used had briefly been described in chapter 4. Unfortunatly, it recently became clear that at least for energies below $\approx$MeV it is very difficult to correctly subtract the foreground emission originating from the host galaxy. Therefore, for some wavelength only upper limit exists yet, while for other energies no results at all are ready to be shown yet.

KVA and NOT - Optical

The optical lightcurves for NGC1275 were usually measured with the KVA simultaneous to the MAGIC data taking. Within the 5 arcsec apperture of KVA, one measures the sum of the emission from the AGN as well as a contribution from the host galaxy. It soon became evident that KVA data alone are not sufficient to disentangle the emission from the AGN and the host galaxy. Therefore, a dedicated observation of NGC1275 with the NOT telescope was carried out in November 2011. But there are ongoing discussions if the foreground can be correctly subtracted. Therefore, I show here the results from KVA only as an upper limit for the emission from the AGN. Due to its sensitivity, KVA was able to measure a daily light-curve (figures 7.19, 7.20). Since the emission from the host galaxy is expected to be constant, all variabilities must originate from the AGN.

Contact persons to the KVA and NOT are

E. Lindfors, K. Nilsson, R. Rekola, Tuorla Observatory, Piikkiö, Finland.

Planck - Microwaves

In the Planck early release compact source catalogue 100, NGC1275 is included with the two pointings from 29 August to 4 September 2009 and 10 February to 19 February 2010. Data from later observations are not yet available. Unfortunately, the angular resolution of Planck does not allow to disentangle the emission from the AGN and the host galaxy. Therefore, these data can only serve as an upper limit.

To find the correct data, I received help from

J. Rachen, MPA Garching, Germany

MOJAVE - Radio

Interesting data contemporaneous to both MAGIC observations cycles are analyzed, but I am not allowed to show them here. They will be included in the multi-wavelength paper in preparation.
Chandra - X-rays

Since the Perseus cluster itself is a very bright X-ray source, only the instrument with best angular resolution can be used to observe NGC1275. The public Chandra data contain several pointings on the central region of the Perseus Cluster from 10 October to 7 December 2009. Experts are still working on the correct treatment of the foreground signal from cluster and host galaxy, so no data can be shown here.

Fermi - gamma-rays

The Fermi satellite is constantly monitoring the sky. Since no emission from the host galaxy is expected in the energy range 100 MeV (and hypothetical contributions from intra-cluster cosmic rays and Dark Matter would also be small), there is no need for a foreground handling different than for any other source in Fermi LAT.

I did the Fermi LAT analysis using the standard procedure described in chapter 6.3, using the latest version v9r27p1 from [113]. The sensitivity of Fermi LAT allowed me to produce a weekly light-curve (figures 7.19b, 7.20b).

For the publication of the full multi-wavelength NGC1275 campaign, an improved analysis is worked on by the experts

Y. Takahasi\textsuperscript{a}, J. Kataoka\textsuperscript{b}, C. C. Cheung\textsuperscript{c,b}, D. L. Wood\textsuperscript{c}

\textsuperscript{a}Research Institute for Science and Engineering, Waseda University, Tokyo, Japan.  
\textsuperscript{b}Space Science Division, Naval Research Laboratory, Washington DC, USA.  
\textsuperscript{c}National Research Council Research Associate.

Multi-wavelength Lightcurves

Figures 7.19 and 7.20 show the lightcurves from MAGIC, Fermi LAT and KVA for NGC1275 and the cycles 5 and 6 respectively. Due to the higher threshold of MAGIC during cycle 5, only lightcurves above 150 GeV estimated energy are feasible for the comparison of the fluxes. As NGC1275 has a very soft VHE spectrum, there is not much signal left to build a lightcurve, drastically reducing the significance of the MAGIC measurement. For cycle 6, KVA as well as Fermi LAT measured a significantly higher flux than during cycle 5, while there is no indication for increased flux measured by MAGIC above 150 GeV. KVA and Fermi also see clear source variability within cycle 6, but there exists no clear correlation between the two wavebands. MAGIC measurements in cycle 6 are compatible with constant flux.
Figure 7.19: NGC1275 lightcurves for cycle 5 from MAGIC > 150 GeV (a), Fermi > 100 MeV (b) and KVA R-band (c). For KVA, an unknown constant flux from the host galaxy is included. There is no indication for strong flux variability in any energy band.
Figure 7.20: NGC1275 lightcurves for cycle 6 from MAGIC >150 GeV (purple) and all data (black) (a), Fermi >100 MeV (b) and KVA R-band (c). For KVA, an unknown constant flux from the host galaxy is included. KVA as well as Fermi report higher average flux than in cycle 5 and also flux variability within cycle 6. MAGIC >150 GeV shows a flux compatible to cycle 5 and no significant indication for flux variability.
Spectral Energy Distribution

The Spectral Energy Distribution (SED) is defined as the spectrum multiplied by the energy squared. Figures 7.21 and 7.22 show the SED of NGC1275 for the cycles 5 and 6, respectively. SEDs are always given in the units erg and Hz, which are preferred by astronomers. As a guideline to the plots: the optical measurements is in the eV regime ($\approx 10^{15}$ Hz), X-ray covers keV ($\approx 10^{18}$ Hz) and MAGIC is situated near the mark of $2.4 \times 10^{25}$ Hz which corresponds to 100 GeV. The upper limits from KVA are the averaged value of the data from the light-curves.

Figure 7.21: Spectral Energy Distribution for NGC1275, cycle 5, including upper limits from Planck (microwave - orange squares) and KVA (optical - green triangle), as well as points from Fermi - (gamma-ray - blue squares) and MAGIC (VHE - purple circles).
For cycle 5 (figure 7.21) the points measured by MAGIC (purple) are only marginally significant, but compared to Fermi LAT (blue) they clearly show that the flux is decreasing fast at energies $>$150 GeV.

For cycle 6 (figure 7.22), due to the lowered energy threshold of MAGIC the 'IC-peak' is better constrained at the highest energies, and it is absolutely clear that MAGIC has measured the high-energy end of the emission from NGC1275. The black points are based on the same data as the purple points from MAGIC, but using a binning better suited to low energies.

Figure 7.22: Spectral Energy Distribution for NGC1275, cycle 6, including upper limit from KVA (optical - green triangle), as well as points from Fermi (gamma-ray - blue circles) and MAGIC (VHE - purple and black). The lowered energy threshold of MAGIC gives an excellent constraint on high energy end of the 'IC-peak'.
Figure 7.23 shows the SED restricted to the measurements from Fermi LAT and MAGIC, for cycle 5 (blue) and cycle 6 (red and black). While the flux measured by Fermi LAT increased by about a factor of two, there is no strong indication for a change of flux or spectral shape in the MAGIC results. As a comparison the flux measured in the optical R-band by KVA increased by $\approx 20\%$ in cycle 6, but since KVA data include an unknown constant flux contribution from the host galaxy an absolute value cannot be given yet.

**Figure 7.23:** Spectral Energy Density for the IC-peak of NGC1275 for cycle 5 (blue) and cycle 6 (red and black) for Fermi LAT (below $\approx 10^{25}$ Hz) and MAGIC (above $\approx 10^{25}$ Hz). While the flux measured by Fermi LAT increased by about a factor of two, there is no evidence for changed flux or spectral shape in the MAGIC data.
Due to its uniqueness among the VHE gamma-ray emitting AGNs, M87 was often considered to be a peculiarly misaligned Blazar. With the detection of CenA this consideration was challenged, and together with the newly detected two radio galaxies NGC1275 and IC310 (figure 8.1) discussed in this thesis, radio galaxies could indeed be a major class of extragalactic VHE gamma-ray emitters.

Figure 8.1: Skymap of the central region of the Perseus cluster seen with MAGIC using stereo data from October 2009 till February 2011 above 150 GeV estimated energy. There are two point like emission regions visible. The central emission is at a position consistent with NGC1275, the emission east to it is consistent with the position of IC310. Interestingly, within this field of view from MAGIC are not only two out of four known VHE radio galaxies, but they also have one of the hardest respectively the weakest VHE spectrum measured so far.
The rather short distances of the VHE radio galaxies make them ideal candidates to investigate the nature and origin of the VHE emission, since at least in X-ray and radio observations the morphology of the objects can be explored. In this chapter NGC1275 and IC310 are set in context to the radio galaxies M87, CenA and NGC1265.

8.1 VHE Gamma-ray Emission from IC310

Fermi LAT and MAGIC results show that the head-tail radio galaxy IC310 exhibits variable VHE emission on at least a year scale. This variability rules out the possible bow shock mechanism that was proposed in [80] to be the origin of the VHE emission, and favors a AGN-like emission from IC310.

During this enhanced state IC310 showed a remarkably hard spectrum with a spectral index of -2.0 in VHE (one of the hardest VHE spectra ever measured so far), while it could not be seen a year later during a less active state. The very limited statistics of one period of enhanced activity in VHE does not give much room for detailed interpretation of IC310, but including information from all energy bands can give some hint.

Comparing the high resolution radio images of the two head-tail radio galaxies IC310 and NGC1265, they look very different. NGC1265 shows two nicely bent jets (see figure 3.4) but no emission in X-ray or gamma-ray has ever been reported. In contrast IC310 is detected in X-ray, and shows variable activity in Fermi LAT and MAGIC, but the radio image does not show the bent jets (figure 3.5).

I interpret these completely different radio images from 'officially' similar objects to be caused by a different angle between the line of sight and the plane formed by the bent jets. While for NGC1265, the line of sight is perpendicular to this plane, for IC310 the line of sight might lay within the plane. Possibly we are looking from the side on one of the bent jets, so part of this jet could be pointing directly to the observer, which is the definition of a Blazar. This agrees very well with the observed VHE variability. So the VHE gamma-ray emission from IC310 can be explained by assuming that part of the jet hosting the powerful accelerator is pointing to us, i.e. regarding VHE gamma-ray emission, IC310 would be similar to normal Blazars.

8.2 VHE Gamma-ray Emission from NGC1275

Unfortunately the high energy end of the spectrum from NGC1275 is just at the edge of the Fermi LAT and MAGIC sensitivities. Because of the unfolding difficulties for such a soft and low energetic spectrum in MAGIC, the data do not allow to define the shape of the 'IC-peak' with high precision, while difficulties in disentangling the
signal from the host galaxy does not yet allow to describe the ‘synchrotron peak’.

The statistics of only two campaigns with the actual sensitivity of MAGIC is not sufficient, but it would be interesting to check with further observations if the high energy end of the spectrum is independent from the average flux in the ‘IC-peak’ measured by Fermi. A constant maximum reachable energy for the AGN would be very important information to understand the emission mechanism as well as the underlying acceleration of the charged particles that finally emit the gamma-rays. Furthermore, knowing the highest possible energy emitted from NGC1275 allows to define the lower energy limit to be used when searching for effects from intra-cluster cosmic ray interactions or dark matter annihilation, as briefly described in chapter 3.

While the MAGIC data are not sufficient to declare source variability, flares on a weekly scale have been detected by Fermi [111] and can be seen in figure 6.2. Combining this information with the claim of a very small angle (<2.7 degrees) between line of sight and the jet close to black hole [73], also NGC1275 could reasonably be classified as Blazar.

8.3 Large Scale Jet Structures of NGC1275, M87 and CenA

M87 is one of the dominant galaxies in the Virgo galaxy cluster at a distance of 16 Mpc from earth. NGC1275 (see chapter 2) is in many ways a peculiar cousin of M87. Both are large cluster galaxies hosting an AGN with disturbed jets and are observed to emit photons with energies from radio to VHE gamma-rays.

Figure 8.2 shows the jets of M87 and NGC1275 in arcminute scales. One can easily see that jet structures are bent when moving to larger distances from the central black hole. So, the angle between the jet and the line of sight that is assumed to define the class and appearance of an AGN depend on which part of the jet the observer is looking at. For CenA, the angle of the jet is highly disputed, at least one measurement claiming it to be as small as 15 degrees [117].

Due to the intrinsically poor resolution of IACTs like MAGIC of 0.1 degree\(^1\) large scale structures of the jets cannot be resolved. As a comparison, the size of the complete M87 image 8.2(a) corresponds to \(\approx 0.23\) degrees, while the NGC1275 image 8.2(b) has a size of \(\approx 0.06\) degrees. Therefore, it is clear that IACTs are not able to identify the precise emission region of VHE gamma-rays in AGNs. While X-ray and radio observations can have sufficient resolution to resolve jet features, there is no established correlation between VHE and lower energetic emission. The currently most promising method used to search for the emission region of VHE

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\(^{1}\)The angular resolution is dominated by statistical fluctuations of the shower development in the atmosphere.
gamma-rays is to look for time correlated flux variabilities in different wavebands. This approach only makes sense assuming the underlying acceleration mechanism results in simultaneous emission in different energy ranges. The only VHE radio galaxy with extended multi-wavelength observations for several years to check this hypothesis is M87.

### 8.4 M87: The Best Studied Radio Galaxy

The jet of M87 can be resolved in radio and X-rays into substructures like knots and diffuse emission. Having continuous high resolution observations for several years the movement of knots was measured. In the inner jet of M87 the apparent velocity is measured to be up to six times the velocity of light. This implies a beaming effect and results in an upper limit of the jet angle to the line of sight of at most 19 degrees. Figure 8.3 shows the structure of the jets in two radio wavebands, in which several knots can be seen.
A peculiar feature of one M87 jet is the so-called knot HST-1 which is found to have substructures apparently moving superluminal. HST-1 additionally exhibits day scale flares in the X-ray as well as emitting new knots (see [120] and references therein). Since M87 is the first detected and brightest radio galaxy emitting VHE gamma-rays, it is the best studied. In figure 8.4 a multi-waveband lightcurve from radio to VHE covering ten years from 2001 to 2011 is shown. The grey vertical lines mark high flux levels in the VHE gamma-rays [120].

H.E.S.S. observed a first flaring activity during 2005 while the HST-1 knot measured simultaneously in radio showed high activity as well [121]. Monitoring M87 in the VHE during 2008 in a joint campaign of MAGIC, H.E.S.S. and VERITAS, another flare was found, while HST-1 showed no increased flux but the region at the very vicinity of the black hole was more active in the radio and X-ray [122]. In 2010 during another joint campaign a third enhanced activity resulting in the highest VHE flux ever measured from M87 was seen. Again the core showed increased activity in X-ray while radio showed no flux increase.

These three flares indicate that the emission of VHE gamma-rays takes place close to the black hole, but the exact mechanisms and locations are not understood and might be different for every flare [120]. Nevertheless, the day scale flares in the X-ray and VHE gamma-rays point to a Blazar like behavior of the inner jet and core of M87. Since the angle between inner part of the jet and the line of sight is assumed to be less than 19 degrees, it cannot be excluded that fraction of the inner part of the jet is directly pointing towards us. If this part of the jet is hosting an accelerator, regarding to VHE gamma-ray emission also M87 would be a Blazar, similar to IC310 and NGC1275.
Figure 8.4: M87 lightcurve from 2001 to 2011 in wavebands from VHE to radio. The VHE gamma-ray flux shown in the first panel was calculated above 350 GeV. Separate fluxes for the core and the knot HST-1 are shown in cases where the two components can be separated. The increased VHE gamma-ray activities in 2005, 2008 and 2010 are marked with vertical grey bands [120].
8.5 Conclusion

The vast majority of AGNs detected by IACTs are Blazars with the few exceptions of extreme radio galaxies. The detection of NGC1275 and IC310 doubles the amount of known VHE gamma-ray emitting radio galaxies from two to four. A key question is if these VHE emitting radio galaxies form a special sub-class, or if they are just the tip of the iceberg and much more VHE radio galaxies can be found with better sensitivity.

M87 is the best studied radio galaxy in the VHE regime and was often considered to be a misaligned Blazar especially as it was observed to undergo flux variability on day scale. There are indications that the VHE emission region is close to the black hole and it cannot be excluded that some part of the jet in that region has small inclination to the line of sight \[120\].

The information on CenA in the VHE is limited as the flux is so low \[63\] that detecting even yearly variability is not reasonable with current instruments, except the flux would increase dramatically during a huge flare.

IC310 was detected during one period of enhanced activity in VHE \[81\]. The very hard spectrum in the VHE and the comet like shape in the radio imply that the inner part of a jet could point towards earth.

Interestingly NGC1275 is the only VHE radio galaxy having a very soft VHE spectrum that prevents the observation in TeV regions. There are measurements that the angle of the jet to the line of sight close to the black hole is near zero \[73\]. Additionally the AGN showed fast flaring activity in Fermi LAT \[111\].

All radio galaxies that are so far found to be VHE gamma-ray emitters seem to have jets that are bent and change the angle relative to the line of sight. Depending on which part of the jet is observed with different instruments the classification and interpretation can vary.

Combining the information on the four sources M87, CenA, IC310 and NGC1275 it is likely that IACTs detect a distinct subclass of radio galaxies having small angles between the line of sight and the jet close to the black hole driving the AGN. From this I conclude the hypothesis, that the VHE emission of radio galaxies is probably pure Blazar like, i.e that the part of the jet hosting the accelerator is pointing towards earth.
Chapter 9

Outlook

With the detection of NGC1275 and IC310 in the VHE gamma-rays, new laboratories to investigate the emission regions of VHE gamma-rays in AGNs are unlocked.

The multi-wavelengths monitoring program of M87 has already proven to be very successful. The continuation of combined efforts to investigate this AGN is very desirable and has the potential to reveal the mechanisms of VHE gamma-ray emission of AGNs.

CenA is difficult to study with the current generation of IACTs due to its low flux. In case CenA undergoes a massive flaring activity e.g. in the Fermi energy range it is certainly very important to trigger multi-wavelengths observations from radio to VHE. For CTA-south, the proposed next generation VHE instrument situated in the southern hemisphere, CenA is a very interesting object to observe.

For IC310, high resolution observations in radio and X-ray for further investigation of the jet structure are crucial. A better resolution could unveil a double jet structure or substantiate the visibility of one jet with a Blazar like structure. During the enhanced activity of IC310 in winter 2009/10 few photons above 100GeV were detected with the Fermi LAT. Detecting such photons by Fermi again can be a good indicator for enhanced activity and should be used to trigger MAGIC and multi-wavelengths observations. Only one flaring activity of IC310 was detected with one of the hardest VHE spectra so far observed, while its quiescent state is below detection limit in Fermi and MAGIC. To measure the spectrum of IC310 a second time during a flaring activity is obviously very interesting.

Due to the soft spectrum NGC1275 is at the edge of detectability of MAGIC. Nevertheless the central region of the Perseus cluster can serve as unique playground for many physics tasks. NGC1275 is a highly interesting target for a longterm multi-wavelengths campaign similar to the program on M87, but due to its dim and soft spectrum, much longer VHE observation windows than for M87 are needed. A next
generation CTA-north observatory with much lower energy threshold and an order of magnitude improved sensitivity will have the ability to study short time variability of NGC1275. Furthermore, IACT observations of NGC1275 deliver a free monitoring of IC310. As a fringe benefit, deep exposure of this region allows to search for intra-cluster cosmic ray effects as well as hypothetical dark matter annihilation.
Appendix A

Other Names for NGC1275

This table contains all the names found in the NED-database [66] for objects that have a position spatially consistent with NGC1275.
<table>
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<th>Object Names</th>
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Table A-1: List of all Names of Objects spatially consistent with NGC1275 found in the NED database [66].
Appendix B

Crab Tests

In this appendix there are some plots showed for completeness. They are usually described and referenced in the text or footnotes in the text.
Figure B.1: Mean DC current for Crab cycle 5 (a) and cycle 6 (b) vs. time in MJD. Blue is for MAGIC-I and red for MAGIC-II. The DC currents are an indication about the background light during the observation and should always be kept below a limit assumed to be acceptable for a given source (higher DC results in higher energy threshold for the observation). Blue points represent MAGIC-I and red points MAGIC-II data. If any of the telescopes reaches a value above 1500 units, the corresponding data set is rejected.
Figure B.2: Cloudiness for Crab cycle 5 (top) and cycle 6 (bottom). Blue is MAGIC-I and red MAGIC-II. Cloudiness is an indication about the existence of high altitude clouds that could absorb fraction of the Cherenkov photons, resulting in wrong rate and energy estimates. Datasets exceeding 50% for any telescope are rejected.
Figure B.3: Number of Identified Stars Crab cycle 5 (top) and cycle 6 (bottom). Blue is for MAGIC-I and red for MAGIC-II. The number of rather bright stars in the field of view is known for every observable object. These stars are checked by a CCD camera coupled to the MAGIC telescopes. A too low number is another indication for high altitude clouds. Datasets having less than 20 in any telescope are rejected.
Figure B.4: Normalized reconstructed event rate for MAGIC-I (top) and MAGIC-II (bottom) for time for cycle 5. See chapter 7 for explanation.
Figure B.5: Crab cycle 5 analysis with one off region. The solid gray histogram corresponds to the measured background, while the points with error are the signal. A signal excess is expected below the $\Theta^2$ cut indicated by the dashed line.

Figure B.6: Crab cycle 5 analysis with three off region. The solid gray histogram corresponds to the measured background, while the points with error are the signal. A signal excess is expected below the $\Theta^2$ cut indicated by the dashed line. The disagreement between signal and off data at $\Theta^2 \approx 0.3$ is typical for strong sources. For the explanation of the feature see chapter [5].
Figure B.7: Crab cycle 5 analysis with one OfWP region. The solid gray histogram corresponds to the measured background, while the points with error are the signal. A signal excess is expected below the $\Theta^2$ cut indicated by the dashed line.

Figure B.8: Skymap of the Crab Nebula Cycle 5. The black cross in the middle of the plot represents the position of the Crab Nebula. The Excess found is nicely centered to this position and is point like for MAGIC. The PSF circle indicates the angular resolution assumed to produce the skymap.
Figure B.9: Measured spectrum of the Crab Nebula cycle 5 using logarithmic bins in estimated energies before unfolding.
Figure B.10: Unfolded Spectrum of Crab Nebula cycle 5 test sample, compared with published values. Unfolded parameters are given in Table B-1.

Table B-1: Table of parameter values for different unfolding methods for Crab Nebula cycle 5 as plotted in figure B.10.
Figure B.11: Spectrum of Crab Nebula test sample cycle 5 using different unfolding methods, compared with literature values. The plot is using a different random forest. Unfolded parameters are given in table B-2.

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Table B-2: Table of parameter values for different unfolding methods for Crab Nebula cycle 5 using a second random forest as plotted in figure B.11.
Appendix C

Dataset of the NGC1275 Campaign

Here are the lists of all MAGIC NGC1275 datasets used for cycle 5 and cycle 6 analysis respectively.
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Table C-1: List of usable data-sets for NGC1275 observations with MAGIC cycle 5 (2009/2010 campaign). The Date is given in the form year-month-day. For data-sets marked as 'Starguider broken' no pointing correction can be applied. Experience from other data-sets shows that this correction is small anyhow so this is no major problem.
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**Table C-2:** List of usable data-sets for NGC1275 observations with MAGIC cycle 6 (2010/2011 campaign). The Date is given in the form year-month-day. For data-sets marked as 'DRS2 Calib problem' the standard calibration can not be used. A special calibration procedure has to be applied to overcome the problem.
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