Doctoral Thesis

Observations of Markarian 421 in 2010 and 2011 with the MAGIC telescopes

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Observations of Markarian 421 in 2010 and 2011 with the MAGIC Telescopes

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presented by
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Die Planeten laufen langsam. Aber sie machen ihre Transite.
Und dann ändert sich dein ganzes Leben.
(Judith Hermann)
Abstract

From the first observations of the night sky until the 20th century, all astronomical knowledge was based on visible light, a tiny fraction of the electromagnetic spectrum. As the atmosphere is not transparent to light of most parts of the electromagnetic spectrum, it was not before the era of satellites and the development of new measurement techniques that observations over the whole energy range became possible and allowed a more complete view of the sky and its sources. At the highest energies (∼100 GeV to ∼100 TeV), the sky is observed by Imaging Atmospheric Cherenkov Telescopes (IACTs) that use the atmosphere as a calorimeter, like the MAGIC telescopes located at the Canary island of La Palma.

One class of sources that are active at all energy ranges are blazars. Blazars, belonging to the class of active galactic nuclei, are powered by a supermassive black hole at the center of a host galaxy. As material is transported toward the central black hole, two oppositely directed and relativistic outflows of material are emitted, the so-called jets. Different regions and acceleration processes of the source produce a variety of radiation from low frequency radio to extremely energetic gamma-rays, whereby the overall Spectral Energy Distribution (SED) exhibits a typical two-bump structure. As one of the jets is directly pointed to the Earth in the case of blazars, they allow to observe the highest energetic photons in the universe.

In this thesis, the blazar Markarian 421 (Mrk421) is investigated. Mrk421, located in the constellation Ursa Major, was detected at TeV energies in 1992 by the Whipple telescope as the first extragalactic TeV source. With a redshift of $z=0.030021$, it is one of the closest TeV blazars and also one of the brightest. It has been examined by many different telescopes and in extensive multiwavelength campaigns since, and is today one of the best-investigated TeV blazars. But despite the numerous observations, many questions like the the underlying production mechanism of the radiation still remain debated. It is therefore important to continue observing.

In this work, observations of Mrk421 by the MAGIC telescopes in 2010 and 2011 are presented. Lightcurves have been processed, with a much denser sampling density in 2010 compared to 2011. The flux showed strong variability including some flaring states up to three Crab units (the Crab Nebula is the standard candle in gamma-ray astronomy) in 2010, while the measured flux was generally low in 2011. The lightcurves showed higher variability at higher energy ranges, and the 2010 lightcurve was more variable at shorter time bins. A trend toward increasing hardness for higher flux states was observed in the flux points of individual nights, as well as in the energy spectra of different periods during a flaring episode in May 2010. The search for short intranight variability was performed systematically. Unfortunately, nature didn’t provide us with a very strong flare comparable to the one observed in 2001 in the years investigated in this thesis, but a short time variability could be found in the night from 5 to 6 February 2010.

Of special interest was the combination of the MAGIC data with observations performed by the KVA optical telescope at La Palma and the gamma-ray detector on board the Fermi satellite. The Large Area Telescope (LAT) installed on the Fermi satellite performs observations in the energy range from some tens of MeV up to some tens of GeV, in an energy
range that overlaps with MAGIC. Correlation studies revealed no correlation of MAGIC and KVA lightcurves, but a trend for correlation between MAGIC and Fermi lightcurves was found.

By combining the energy spectra measured by MAGIC and Fermi, the complete high-energy peak of the SED could be produced for different time periods and flux states of Mrk421, and was a power law with exponential cutoff was used to fit the high-energy peak. As a result, the cutoff energy shifted toward higher energies for increasing flux levels, corresponding to a hardening of the spectrum during the period of investigation.
Zusammenfassung

Von den ersten Beobachtungen des Nachthimmels bis ins zwanzigste Jahrhundert basierte das gesamte astronomische Wissen auf sichtbarem Licht, einem kleinen Teil des elektromagnetischen Spektrums. Für weite Bereiche dieses Spektrums ist die Atmosphäre nicht durchlässig, deshalb wurden Beobachtungen über den gesamten Wellenlängenbereich erst im Zeitalter der Satelliten und dank neuer Messtechniken möglich. Dies ergab schließlich ein vollständigeres Bild des Himmels und seiner Quellen. Im Bereich der höchsten Energien (\( \sim 100 \text{ GeV} \) bis \( \sim 100 \text{ TeV} \)) kommen so genannte Luft-Tscherenkov-Teleskope zum Einsatz, welche die Atmosphäre als Kalorimeter verwenden. Dazu gehören zum Beispiel die MAGIC-Teleskope auf der Kanarischen Insel La Palma.


Besonders interessant war die Kombination von MAGIC-Daten mit Beobachtungen,

Durch Kombination von MAGIC- und Fermi-Daten konnte der vollständige Hochenergie-Peak des Energiespektrums für verschiedene Zeiträume und Flusswerte erstellt werden. Das kombinierte Fermi-MAGIC-Spektrum wurde mit einem Potenzgesetz mit exponentiellem Abfall beschrieben. Demzufolge verschob sich im untersuchten Zeitraum die Cutoff-Energie für höhere Flusswerte zu höheren Energien, was einem härteren Energiespektrum entspricht.
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Introduction

One hundred years ago in August 1912, Austrian physicist Victor Franz Hess boarded his hydrogen filled balloon (figure 0.1) with one goal in mind: He wanted to solve the mystery of unexplained atmospheric ionization and thereby answer one of the highly debated questions of his time. With three electrosopes on board, Hess reached an altitude of over 5000 m. Thanks to thick brass walls, Hess’ electroscope was unaffected by decreasing pressure at higher altitudes and therefore, unlike earlier measurements [1] [2], properly calibrated. His results showed a significant increase of ionization with height [3], and after confirmation by Werner Kolhörster [4], the conclusion was clear: Radiation of very high penetrating power is entering the atmosphere from space. Figure 0.2 shows the measurement results of Hess and Kolhörster. But the American experimental physicist Robert Millikan was not convinced until his experiments in high-altitude lakes showed the same results [5]. Certain that the penetrating radiation had to be the most energetic form of electromagnetic radiation, the so-called gamma-rays, he introduced the name “cosmic rays” [6]. The findings Hess made during his balloon flight in August 1912, were rewarded by the Nobel Prize in 1936 for the discovery of cosmic rays.

Figure 0.1: Hess during one of his balloon flights in August 1912. Image credit from American physical society.
The assumption that cosmic rays are a form of electromagnetic radiation had to be reconsidered when Dutch physicist Jacob Clay showed in 1927 that cosmic rays are affected by the earth magnetic field and therefore have to be charged [7]. Other researchers confirmed and improved his results, and experiments with a new version of the Geiger-Müller tube finally allowed to reveal the nature of cosmic rays. The results showed that cosmic rays had a component with energies above 1 GeV, and that most of the cosmic ray particles were protons [8].

Figure 0.2: Cosmic rays: Increase of ionization with height as measured by Hess in 1912 and by Kolhörster in 1913 and 1914. Image credit from Alessandro De Angelis.

In the following twenty years, investigating cosmic rays led to the discovery of many important elementary particles, marking the birth of particle physics. When cosmic rays enter the atmosphere, they interact with a nucleus of oxygen or nitrogen and produce a cascade of secondary particles – many of them were unknown at that time. With cloud chambers and later with stacked plates of photographic emulsion, the trajectories of such charged shower particles could be tracked. Placing the chamber in a magnetic field allowed to learn about the charge and momentum of the unknown particle. In this way, the positron was detected in 1932 by Carl Anderson [9], he shared the Nobel Prize with Hess four years later. The detection of the positron was followed by the discovery of the muon in 1936 by Anderson [10], and of the pion in 1947 by Cecil Powell [11].

Around the year 1950, accelerators like the Bevatron at Lawrence Berkeley National Laboratory, U.S.A. [12] or the Proton Synchrotron (PS) at CERN [13] were built, and replaced cosmic ray induced air showers for the study of the subatomic world. With the development of new experiments like the Whipple gamma-ray telescope [14], the Pierre Auger cosmic ray observatory [15] or the neutrino observatories Super-Kamiokande [16] and IceCube [17], the focus of cosmic ray research shifted from particle physics to astronomy. The main tasks were to identify the composition, the sources and the accelerating mechanism of cosmic ray particles. Since then, cosmic rays were studied in detail. The charged cosmic ray energy spectrum was measured over many orders of magnitude. It’s also known that protons are the dominant cosmic ray particles, followed by helium nuclei and a small fraction of heavier elements and electrons. Uncharged cosmic gamma-rays contribute only with a very small fraction.
The search for the sources of cosmic rays remains however challenging. When charged cosmic ray particles travel from a source to the observer on earth, they are deflected by omnipresent magnetic fields. Their arrival direction is therefore randomized and doesn’t yield any information about the source that produced them. Regions that accelerate charged cosmic rays are assumed to be related to regions that produce gamma-rays [18], [19], [20], [21]. As gamma-rays are uncharged, they travel in a straight line from the source to the observer, and their arrival direction points directly to the source. Being able to produce this most energetic form of light, the possible gamma-ray sources must belong to the most violent and energetic phenomena in our universe. Up to now, more than 140 gamma-ray sources were detected, the source catalog covers a wide variety inside our galaxy and beyond. As the atmosphere is not transparent for gamma-rays, they must be observed either with satellites or, at energies above a few tens of GeV, with so called Cherenkov telescopes like the MAGIC telescopes that are introduced in Chapter 4.

Figure 0.3: Cropped Hubble Space Telescope image of blazar Markarian 421. Image credit from NASA/STScI/Roberto Fanti (http://hla.stsci.edu/hlaview.html).

In this thesis I will focus on Markarian 421 (also Mrk421 or Mkn421), a member of the active galactic nuclei (AGN) class with a supermassive black hole in the center of the host galaxy. Subclassified as a blazar, it emits radiation all across the electromagnetic spectrum, as 93 different identifiers in the Simbad Astronomical Database document [22]. It shows strong variability in different timescales and energy ranges. In the TeV energy range, Mrk421 was discovered in 1992 by the Whipple telescope [23] as the first extragalactic TeV source. Being only 400 million lightyears away, Mrk421 is one of the closest TeV blazars and therefore provides an excellent laboratory. In figure 0.3, a Hubble image of Mrk421 is shown.
By now, Mrk421 is one of the most studied extragalactic TeV objects. In extensive multiwavelength campaigns, instruments observing all across the electromagnetic spectrum kept the blazar under close surveillance and allowed a deeper understanding of that extraordinary source. But nevertheless, Mrk421 didn’t reveal all his secrets: Still we cannot distinguish between different emission mechanism, we don’t understand the origin of radiation and the radiation mechanism, nor the reason for the variability.

To complete the picture, we need to continue observing. MAGIC observed Mrk421 since 2004. In this thesis, I will present the data taken by the MAGIC telescopes in 2010 and 2011. Especially in 2010, Markarian 421 was remarkably active and provided us three major flares in January, March and May, of which the May flare will be deeper investigated. The spectral as well as the temporal behavior of the source was studied, and the search for intranight variability was performed systematically. The combinations with results from the Fermi telescope and from the KVA optical telescope give a more complete picture of the source in that period.

This thesis is organized in the following way: An overview of gamma-ray sources is given in Chapter 1, continued by a discussion of active galactic nuclei (AGN), a class of extra-galactic gamma-ray emitter, in Chapter 2. The blazar Markarian 421, belonging to a subclass of AGNs and the main target source of this thesis, is introduced. Chapter 3 explains the development of extended air showers produced when a very high-energy particle strikes the atmosphere. The Imaging Atmospheric Cherenkov technique that detects the very brief flash of Cherenkov radiation generated by these air showers is described. In Chapter 4, a description of the main characteristics and components of the MAGIC experiment is given, followed by a description of the necessary analysis tools used in this thesis in Chapter 5. A method implemented to correct crosstalk in the readout electronics of MAGIC-II is also explained. Chapter 6 finally reports on the results from MAGIC observations of the blazar Markarian 421, performed in January-June 2010 and in January-June 2011, while Chapter 7 combines the MAGIC observations with the results of the Fermi and the KVA telescopes. Chapter 8 finishes with a summary of the work, some concluding remarks and an outlook.
1 The Gamma-Ray Universe

Since their detection in 1912 by Victor Hess, scientists learned a lot about cosmic rays. In this chapter, a short overview about the current knowledge is given.

1.1 Cosmic Rays

Thanks to observations with satellites and huge ground based detectors, we know the energy spectrum of cosmic rays (figure 1.1) that covers a wide energy range of more than 12 orders of magnitude from $10^8$ to $10^{20}$ eV, and a flux range of more than 32 decades. It is described by an almost featureless power law $dN/dE \propto E^{-\alpha}$, resulting in a rapidly falling rate with increasing energy: While at $10^{12}$ eV, one particle per square meter per second bombards the atmosphere, it’s only one particle per square meter per year at $10^{15}$ eV and even only one particle per square kilometer per year at $10^{18}$ eV. The only spectrum characteristics are the so called knee at $\approx 10^{15}$ eV where the spectrum steepens from $\alpha \approx 2.7$ to $\alpha \approx 3$, and the ankle at $\approx 10^{18}$ eV. Below 20 GeV ($20 \, \text{GeV} = 20 \cdot 10^9 \, \text{eV}$), the shielding by the variable solar wind and magnetic field must be taken into account.

The overall dominant cosmic ray particles are protons, followed by helium nuclei and a small fraction of heavier elements and electrons. In figure 1.2, the abundance of elements in cosmic rays as a function of the nuclear charge number at energies around 1 GeV/n is shown. All natural elements of the periodic table are present in cosmic rays, in roughly the same abundance as in the solar system. However, there exist certain differences, especially the light elements lithium, beryllium and boron are much more abundant than in the solar system. They are thought to be produced in spallation processes of the more abundant elements carbon, nitrogen and oxygen on interstellar dust or gas during their journey through the galaxy [25].

1.1.1 Origin of Cosmic Rays

The search for possible sources of cosmic rays is challenging, as charged cosmic ray particles are deflected by omnipresent magnetic fields and therefore don’t point back to the sources where they were produced. The identification of possible sources and acceleration mechanism must explain both the very wide energy range of the cosmic ray spectrum and it’s almost featureless shape.

An acceleration mechanism fulfilling this criteria was proposed in 1949 by Enrico Fermi [26]. In a first version, Fermi described the acceleration due to deflections of charged particles on randomly moving interstellar clouds, that act as magnetic mirrors. Fermi showed that the average energy gain per collision is proportional to $\beta^2 m = \frac{v^2}{c^2}$ with $v_m$ the magnetic mirror velocity, for which reason this process is called second order Fermi acceleration. This process succeeds in producing a power law spectrum, as the number of particles remaining in the acceleration region after n interactions decreases with $N_n = N_0 \cdot (1 - P_{\text{esc}})^n$, with $P_{\text{esc}}$ the escape probability per encounter. However, the Fermi second order mechanism is not very efficient as the energy gain per step is small and the particles have to travel long distances between the reactions. The goal of the first order Fermi acceleration was therefore
1. The Gamma-Ray Universe

Figure 1.1: The energy spectrum for cosmic rays, measured by different instruments. The spectrum follows a power law \( dN/dE \propto E^{-\alpha} \), with \( \alpha \approx 2.7 \) below the so-called knee at \( \approx 10^{15}\text{eV} \), and \( \alpha \approx 3 \) above the knee. Image credit from [24].
1. The Gamma-Ray Universe

Figure 1.2: Abundance of elements in cosmic rays as a function of the nuclear charge number at energies around 1 GeV/n, normalized to Si=100. To compare, the abundance of elements in the solar system is shown. Image credit from [25].

to find a mechanism that would make the acceleration process more efficient. Fermi could show that when a charged particle gains energy by reflection and back-reflection between a shock front and an extended and strong static magnetic field, or similarly between two shock fronts like for example in a Supernova remnant, the energy gain per collision is linear in $\beta = \frac{v_s}{c}$, with $v_s$ the shock front velocity.

When searching for possible cosmic ray sources, the Hillas criterion [27] is very useful. It limits the maximum energy that a particle with charge $q$ can gain in a region with size $R$ and magnetic field $B$ by

$$E_{\text{max}} = qBR$$

This is obtained by requiring the Larmor radius\(^1\) of the particle to be no larger than the size $R$ of the accelerator, as the particle will be unable to gain more energy if it escapes from the acceleration region. Figure 1.3 is an example of a Hillas plot which gives the relation between the magnetic field and the size of an accelerator for a given maximum energy of the accelerated particle. Sources above the top line are able to accelerate protons up to $10^{21}$eV, while sources above the bottom line are able to accelerate iron up to $10^{20}$eV.

At energies up to $\approx Z \cdot 10^{14}$eV, with $Z$ the charge of the cosmic ray particle, the contribution of Supernova remnants is essential [25] to the cosmic ray flux. The upper limit of galactic Supernova remnants is an explanation for the existence of the knee. Another common explanation is the leakage of the cosmic ray particles from the galaxy, which is for protons at an energy of $\approx 10^{15}$ eV. Lower-energetic cosmic ray particles are trapped in our galaxy by the galactic magnetic field [29], when their Larmor radius is smaller than the size of our galaxy.

The origin of cosmic rays between the knee and the ankle is debated [30]. Different models describe a second unknown population of galactic sources that dominates in this energy range, or an extra-galactic component consisting mainly of protons and dominating down to $\approx 10^{18}$eV. In both cases, the extra-galactic components, produced for instance by active galactic nuclei, dominate above the ankle.

\(^1\) $r_L = \frac{p}{|q|B}$, with $p$ the momentum and $q$ the charge of the particle, and $B$ the magnetic field.
Figure 1.3: The Hillas plot showing the linear size $R$ versus the magnetic field $B$ of possible accelerators. Sources above the top line are able to accelerate protons up to $10^{21}\text{eV}$, while sources above the bottom line are able to accelerate iron up to $10^{20}\text{eV}$. See text for more information. Image credit from [28].

For protons above $5 \cdot 10^{19}$, Greisen, Zatsepin and Kuz’min [31] [32] predicted a cutoff (GZK-cutoff) that should be evident in the cosmic ray spectrum. These high energetic protons interact with photons of the cosmic microwave background (CMB) radiation via the reactions

\begin{equation}
\gamma_{\text{CMB}} + p \rightarrow \Delta^+ \rightarrow p + \pi^0
\end{equation}

and

\begin{equation}
\gamma_{\text{CMB}} + p \rightarrow \Delta^+ \rightarrow n + \pi^+
\end{equation}

This process continues, until the energy of the proton falls below the production threshold energy. Taking into account the mean path associated with this reaction, cosmic ray
protons with energies above this threshold and traveling further than some tens of Mpc$^2$
\cite{33} should not be observed on Earth. Recent results by the HiRes \cite{34} \cite{35} experiment
and confirmation through the Pierre Auger Observatory \cite{36} \cite{37} are in accord with the
GZK prediction, although some uncertainties remain. Earlier observations by the AGASA
experiment \cite{38} \cite{39} had previously led to the so-called GZK paradox, as they seemed to
show cosmic rays above the cutoff energy.

\subsection*{1.1.2 Measurements of Cosmic Rays}

To investigate the whole range of the cosmic ray spectrum, different observation techniques
were developed. At energies below $\approx 10^{15}$ eV, charged cosmic rays can be directly measured
above the atmosphere, using balloon or satellite experiments like BESS \cite{40}, AMS \cite{41} or
PAMELA \cite{42}. Above $10^{13}$ eV, the cosmic ray flux is too small for air or space borne
experiments, as large detection areas are needed. Cosmic rays above $10^{13}$ eV are therefore
investigated with large-area ground based experiments that sample the secondary particles
produced when the cosmic ray particle hits the atmosphere and causes an air shower (air
shower will be described in chapter 3.1). Examples of ground-based experiments are
Kascade-Grande \cite{43} or the Pierre Auger Observatory \cite{15} that covers an area of 3000 km$^2$
and is designed to study the highest energy cosmic rays. It consists of 1600 water Cherenkov
detectors along with four atmospheric fluorescence detectors overseeing the surface array
(figure 1.4).

Figure 1.4: The Pierre Auger Observatory: On the hill is one of the 4 fluorescence detector
buildings and communications tower. In the bottom foreground is one of the 1’600 surface
detectors. Image credit from the AUGER collaboration \cite{15}.

\subsection*{1.2 Gamma-Rays}

Despite the variety of experiments that are investigating cosmic rays, it is difficult to learn
about their sources. As charged particles are isotropically distributed by galactic and
extragalactic magnetic fields while they travel from the source to the earth, their incoming

$^2$The parsec (pc) is a unit of length used in astronomy, corresponding to 3.26 lightyears or $3.09 \cdot 10^{13}$ km.
direction is randomized and doesn’t yield any information about the source. Only the most energetic particles with a larmor radius much larger than the size of our galaxy could give a hint to their sources. Indeed, the AUGER collaboration reported a correlation between the arrival direction of cosmic rays with energies above $6 \cdot 10^{19}$ eV and the positions of active galactic nuclei (AGN) in 2007 [44], but the strength of the correlation has been diminishing since [45].

A more promising possibility is to track neutral particles instead: neutrons, neutrinos or gamma-rays$^3$. As neutrons can’t be accelerated easily and decay quickly, and neutrinos are still too hard to detect, the observation of gamma-rays is the most promising way. The detection of gamma-rays allows to learn also about the cosmic ray sources, as they are almost always produced as secondary products of high-energetic cosmic ray particles, usually by protons in hadronic ([46], overview in [47]) or by electrons in leptonic [48] [49] processes (more details of these processes are given in section 2.3.1). Regions of high gamma-ray density are therefore coupled to regions with a high density of cosmic rays [18], [19], [20], [21], multiplied with the density of the target medium needed to produce them, like interstellar matter used for pion production, the strength of the magnetic field in the case of synchrotron radiation or the density of a low-energetic photon field that is upscattered by Inverse-Compton-Scattering.

### 1.2.1 Measurement of Gamma-Rays

The main advantage of observing gamma-rays, compared to charged cosmic rays, is that gamma-rays are uncharged and therefore not deflected by magnetic fields. Their arrival direction points to the region where they were produced, what allows to learn about the sources. As can be seen in figure 1.5, the atmosphere is not transparent at the high energies and small wavelengths of gamma-rays. Gamma-rays in the MeV to a few GeV range$^4$ are usually measured by ballons or satellites. The main current spacecraft experiments are INTEGRAL [50], AGILE [51] and Fermi [52]. Fermi is described in more detail in chapter 7.1.

Above a few tens of GeV$^5$, the low photon flux requires large detection areas that are not practicable for space-based telescopes. When these Very High Energy (VHE) gamma-rays hit the atmosphere, they produce air showers of secondary particles (air showers will be explained in chapter 3.1). These air showers can be investigated from the ground using the so-called Imaging Cherenkov Technique (IACT), that detects the Cherenkov light emitted by secondary shower particles. Currently, there are three operating IACT systems, as shown in figure 1.6: In the southern hemisphere there is H.E.S.S. [53] in Namibia, and in the northern hemisphere there are MAGIC [54] at the Canary Island of La Palma and VERITAS [55] in Arizona, USA. A new generation Cherenkov experiment is currently in the preparatory phase: The Cherenkov Telescope Array (CTA) [56] will consist of two telescope arrays on the northern and the southern hemisphere respectively. Using tens of Cherenkov telescopes of different sizes, CTA is expected to improve the sensitivity$^6$ by an order of magnitude compared to current IACTs. The Imaging Cherenkov Technique will be described in chapter 3, and the MAGIC Telescopes are presented in chapter 4.

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$^3$Photons with an energy above 100 keV are usually called gamma-rays or gamma-rays.

$^4$Gamma-rays with energies in the MeV to a few GeV range are called High Energy (HE) gamma-rays.

$^5$Gamma-rays with energies above a few tens of GeV are called Very High Energy (VHE) gamma-rays.

$^6$The sensitivity is defined as the flux of a source that results in significance $= 5$ after 50 h of effective observation time.
Figure 1.5: Transparency of the atmosphere for light of the electromagnetic spectrum. Most gamma-rays are absorbed by the atmosphere, and must therefore be observed with satellites or using Cherenkov-Telescopes on the earth. Image credit: NASA.
Figure 1.6: The three operating IACT systems: HESS in Namibia, Veritas in Arizona and MAGIC at the Canary Islands. Image credit from the HESS collaboration (Arnim Balzer), Veritas collaboration and MAGIC collaboration.
1.2.2 Gamma-Ray Sources

Even though scientists like Philip Morrison [57] predicted already in the 1960s that several processes in the universe should lead to gamma-rays, the detection of their sources was not before it was possible to observe the sky from above, using ballons or satellites. The first detection was actually by chance when the Vela satellites, built to detect flashes of gamma-rays from nuclear bombs, recorded bursts of gamma-rays from deep space – the so-called Gamma-ray bursts (GRBs). The first skymap at gamma-ray wavelengths was produced by the satellites SAS-2 (1972) that observed the sky between 20 MeV and 1 GeV and detected the Geminga pulsar, and COS-B (1975-1982) that was sensitive to energies between 30 MeV and 5 GeV [58]. COS-B found around 25 point sources and produced a map of the Milky Way. It was however not possible to identify most of the point sources with known objects in the sky, as the resolution of the instruments was not sufficient.

A large boost of cosmic gamma-ray sources was achieved with the compton gamma-ray satellite (CGRS, 1991-1999) [59]. The EGRET (Energetic Gamma Ray Experiment Telescope) experiment on board of CGRS detected 271 HE sources between 20 MeV and 30 GeV, like pulsars, solar flares, the Large Magellanic cloud or active galactic nuclei [60].

Since 2008, the Fermi telescope (see chapter 7.1) monitors the HE gamma-ray sky between 30 MeV and 300 GeV, detected a multiplicity of point sources and produces sky-maps of great precision (figure 1.7). In this sky survey, the Milky Way shows up as a bright band, indicating the gamma-rays that are produced when cosmic ray particles collide with the interstellar gas. Superimposed with this continuous gamma-ray band are point sources, representing cosmic accelerators like bright pulsars or supermassive black holes. Figure 1.8 presents an overview of sources detected by Fermi above 10 GeV, whereof more than half are AGNs, and more than a third are unidentified sources, having no clearly identified counterpart detected in other parts of the spectrum [61].

Figure 1.7: Fermi’s view of the gamma-ray sky at energies above 1 GeV, including three years of observations by Fermi’s Large Area Telescope (LAT). Brighter colors indicate brighter gamma-ray sources. Image credit: NASA/DOE/Fermi LAT Collaboration.
1. The Gamma-Ray Universe

Above about hundred GeV, space-born telescopes like Fermi run out of gamma-ray statistics. In this VHE range, the sky is observed by IACT telescopes (more details in chapter 3). The first source found in this energy regime was the Crab Nebula, that was detected by the Whipple telescope in 1989 [62]. Until now, 46 extragalactic and 61 galactic sources have been detected (figure 1.9).

Among the VHE gamma-ray sources are extragalactic and galactic sources, the most important ones are presented in the following. Most of the extragalactic sources, and the most important ones for this thesis, are blazars of the type HBL. They belong to the Active Galactic Nuclei (AGN) class that is presented in more detail in chapter 2.
Extragalactic sources:

Active Galactic Nuclei: An Active Galactic Nucleus (AGN) [63] [64] is the compact center of a galaxy that produces much more electromagnetic emission than expected from its stellar content and interstellar medium. AGNs are believed to be powered by a supermassive black hole at the center of the galaxy, which is on the order of $10^6$ to $10^{10}$ solar masses and accelerates material. Material close to the black hole forms a so-called accretion disk, which again can produce jets, very fast and collimated outflows of material that point in opposite directions and perpendicular to the accretion disk. Particle acceleration is likely to take place in small regions of these jets. Due to objects like Mrk421, AGNs are currently among the best-explored VHE gamma-ray sources. Their acceleration mechanism is however still under debate. AGNs are presented in more detail in chapter 2.

Illustration credit: NASA.

Starburst Galaxies: Starburst Galaxies are characterized by a very high star formation rate. As a result, both the rate of Supernovae and the plasma wind merging from the galaxy are higher than in normal galaxies. As both processes are expected to produce gamma-rays, Starburst Galaxies are gamma-ray candidates.

Illustration credit: NASA.

Gamma-Ray Bursts: These very short and violent outbursts of gamma-rays are supposed to be very energetic explosions in distant galaxies. They can occur at any time anywhere at the sky, and last from milliseconds to several minutes [65]. The initial outburst in the X-ray and gamma-rays is usually followed by an afterglow at longer wavelengths. So far, no Gamma-ray burst has been detected in the VHE gamma-rays. The Fermi telescope captured gamma-ray bursts in the energy range between 8 keV and 30 MeV.

Illustration credit: NASA/Swift/Mary Pat Hrybyk-Keith and John Jones.
Galactic sources:

**Supernova Remnants:** When a massive star at the end of its lifetime runs out of fuel to provide the fusion, it collapses inward under the force of its own gravity. Depending on its mass, the inner part of the star will form a black hole or a neutron star, while the outer layers are violently expelled and form a spherically shaped nebula, the so-called Supernova remnant. When this material flows into the interstellar medium, it forms energetic shock waves that can efficiently accelerate particles through Fermi acceleration. Supernova remnants are actually considered to be the main source of galactic cosmic rays. Gamma-rays are then produced through synchrotron emission and Inverse-Compton-Scattering.

**Pulsars:** A fast rotating neutron star, left over after a Supernova explosion, is called a neutron star. As the magnetic axis spins along with the rotation of the neutron star, the movement of the very strong magnetic field produces an electric field, that again accelerates charged particles.

**Pulsar Wind Nebulae:** A pulsar wind nebula is a nebula that is powered by the relativistic particle wind emitted by the pulsar. In this stationary shock, the gamma-rays are produced. For young pulsars, the pulsar wind nebula is often placed inside the shells of the supernova remnants, while for older pulsars the supernova shells have disappeared. The best-known member of this class is the Crab nebula (picture on the right), with its strong and steady emission the standard candle of VHE gamma-ray astronomy.

**Binary Systems:** In a binary system, a compact object like a neutron star or a black hole of a few solar masses accretes material from a massive companion star. Binary systems including a black hole share many characteristics with Active Galactic Nuclei, like the accretion disk surrounding the central massive black hole, but on a smaller scale. In a so-called micro-quasar, a relativistic jet is formed.
2 Active Galactic Nuclei

Most of the extragalactic VHE gamma-ray sources are blazars. They belong to the class of Active Galactic Nuclei that is presented in the following. Markarian 421, a blazar of the type HBL and the most important source for this thesis, is introduced.

2.1 History

First indications for Active Galactic Nuclei (AGN, see for example [63] [64] and image 2.1) were found early in the 20th century, when Edward A. Fath [66], as part of his dissertation work in 1909, undertook a series of observations at Lick Observatory in order to clarify the nature of the “spiral nebulae”, now known to be galaxies. It was an open question at that time, if these objects were nearby gaseous objects or if they were distant accumulations of unresolved stars. Fath found that the very most of these objects showed starlike absorption-line spectra, composed of the light of stars of so-called “star clusters”. However when Fath measured the optical spectrum of NGC 1068, he noted the presence of strong and broad emission lines, similar to those seen in planetary nebulae. The bright emission lines of NGC 1068 were later confirmed by V.M. Slipher [67] with spectra taken at Lowell Observatory.

![Core of Galaxy NGC 4261](image)

Figure 2.1: A Hubble Space Telescope (HST) image of the gas and dust disk in the active galactic nucleus of NGC 4261 as observed in the optical and radio regime. Image credit: HST/NASA/ESA.

The first systematic study of galaxies with nuclear emission lines was carried out by Carl Seyfert in 1942 [68]. Seyfert selected a group of galaxies with high central surface brightness, i.e. nearly stellar nuclei, and found that their spectra are dominated by high-excitation nuclear emission lines. The large widths of the lines corresponded to high velocities of up to 8500 km s$^{-1}$. Galaxies characterized by high-excitation nuclear emission lines and a bright, small and quasi-stellar appearance nucleus are now called “Seyfert galaxies”. They
are the most common type of nearby AGNs [69].

After Second World War, advances in radio astronomy allowed to identify the radio sources with known optical counterparts. In 1951, the radio source Cygnus A was identified with a distant galaxy with redshift $z=0.056$ [70]. Other detections followed quickly, and these sources were subsequently called “radio galaxies”. Similar to Seyfert galaxies, they have luminous cores and show bright emission lines, but Seyfert galaxies are mostly radio quiet.

While most of the optical counterparts of radio sources were galaxies, some were stellar-appearing sources. For example, the radio source 3C 48 was found to have a magnitude 16 star as optical counterpart [71]. The optical spectra of these quasi-stellar radio sources (QSRs), or “quasars” were very confusing, as they showed strong emission lines at unknown wavelengths. The extragalactic origin of quasars was revealed in 1963, when Marteen Schmidt [72] investigated the source 3C 273 and found that the unknown emission lines in its spectrum were actually the hydrogen Balmer-series emission lines at the large redshift $z=0.158$. This is an order of magnitude larger than for original Seyfert galaxies, and was among the largest distances ever measured at that time. After this detection, the identification of other quasars followed quickly. More disturbing than the large distances of these quasi-stellar objects was the enormous luminosities implied, that could not be explained by the stellar contributions. 3C 273 is around 100 times more luminous than bright spiral galaxies like the Milky Way. These high luminosities implied that very extreme physical processes must be involved. Soon after, the idea of energy production from accretion onto a supermassive black hole appeared ([73] and others).

Blazars, the most important AGN type for this thesis, were first observed as irregular variable stars that showed variability in brightness on timescales of days or years, but with no pattern. In 1968, the variable star BL Lacertae was identified with the strong radio source VRO 42.22.01 [74]. BL Lacertae showed many quasar-like characteristics, but its optical spectrum showed just continuum emission without spectral lines. In 1974, signs of an underlying host galaxy could be found, showing that BL Lacertae was of extragalactic origin and not a star. More of such sources were found later and grouped together in a class called “BL Lacertae” or just “BL Lac” objects.

### 2.2 AGN Taxonomy

AGNs are broadly divided in two classes: radio loud and radio quiet ones. The further taxonomy of AGNs is complicated and ambiguous, as it is mainly based on historical classifications and observational characteristics. An example for a galaxy classification scheme is shown in figure 2.2. On the radioquiet side, it includes among others Seyfert galaxies and radioquiet quasars, and as radioloud objects radio galaxies, radioloud quasars, blazars and many more. The class of blazars is defined by rapid variability and a high degree of linear polarization at visible wavelengths. Their subclass of BL Lac objects are nearly devoid of emission lines, and about 90% of the BL Lac objects that have been resolved were found in elliptical galaxies (see [69] for an overview of blazars and BL Lacs). Most extragalactic sources detected at TeV energies are so-called high-energy peak BL Lacs (HBL) or X-ray selected BL Lacs, as they were originally detected at X-ray frequencies [76]. HBLs are marked in the lower right hand corner of the scheme, making clear how rare these sources are among all galaxies. Only a small minority (7%) of all galaxies are classified as active, and only a very small fraction (0.005%) of these active galaxies are classified as radio-loud. The radio-loud class further divides into radio galaxies, radio-loud quasars and the blazar class, that again contains HBLs as a subset.
2.3 Standard Model of AGNs and the Blazar Subclass

Today, the various subclasses of AGNs are assumed to be explained by unification models (see Antonucci [77] and Urry and Padovani [78] for detailed explanation). Thereby, a supermassive black hole (with a mass between $10^6$ and $10^{10}$ times that of the sun) at the center is the engine of the system. Such supermassive black holes are believed to be found at the center of most massive galaxies. In AGNs, material close to the black hole forms a so-called accretion disk (image 2.3). As material is transported toward the black hole and angular momentum is transported outward, gravitational energy is transformed into radiation. The accretion disk heats up and radiates, mainly in the optical-ultraviolet range. A hot corona above the accretion disk may also scatter the photons up to the hard X-ray regime [78]. Radiation from the accretion disk excites atoms in rapidly moving clouds close to the central black hole, or in slightly slower clouds a bit further away from the central region. Thereby, the broad and narrow emission lines that can be observed in the optical spectra of AGNs are produced. Part of the central region is sometimes hidden by an optically thick dust torus, that again produces radiation itself, mainly in the infrared region.

It is further known that at least some of these accretion disks form jets, highly collimated and very fast outflows of material, tightly bound by the magnetic field lines (figure 2.4). These jets point perpendicular away from the accretion disk and can extend far from the black hole (kpc to Mpc scale). Inside the jet, energetic particles and photons interact with each other and the strong magnetic field, causing radiation in all wavelengths from radio to gamma-rays. The best resolution is obtained in the radio regime thanks to Very-Long-Baseline Interferometry (VLBI). Image 2.5 presents detailed radio and optical views on the center of the misaligned blazar M87, about 50 million light-years away. Several blobs can be observed that travel with different velocities along the jet axis. The production mechanism of these jets remains however unclear.
Active Galactic Nuclei

According to the unification model, all AGN types can be explained by a different viewing angle (image 2.6). Depending on this angle, different parts of the central region are obscured by the dusty torus, and additionally the contribution of the jet to the radiation depends on the viewing angle. Blazars are thereby the most powerful objects, as one of their jets is pointed to the line of sight of the observer. This special orientation explains the main observed characteristics, as relativistic effects amplify the luminosity and the variability. If the jet doesn’t point directly but at a small angle toward the observer, apparent superluminal features along the jet can be observed (see Appendix A for explanation). This is the case for example for the misaligned blazar M87.

Figure 2.3: Radio-loud AGN model. Image credit from C.M. Urry and P. Padovani.

Figure 2.4: Artist’s concept of the jet formation region of an AGN. An accretion disk (red-yellow) surrounds the black hole, and its magnetic field lines twist tightly to channel the outpouring subatomic particles into a narrow jet. Image credit: NASA/ESA and Ann Feild (Space Telescope Science Institute).
Figure 2.5: Close-up Look at a jet near a black hole in the galaxy M87 (Hubble and Ground-Based View). Image credit: National Radio Astronomy Observatory, STScI (http://www.spacetelescope.org/images/opo9943a/).

Figure 2.6: Model showing the main features of a unified model for AGN as reviewed by [78]. The classification according to the viewing angle is illustrated. Blazars are AGNs with a relativistic jet pointing in the direction of the Earth.
2.3.1 Acceleration Mechanism of Blazars

The observed spectral energy distribution (SED \(^1\)) of blazars is characterized by a two peak shape, as shown in figure 2.7 for the SED of Mrk421 in 2009. According to the production mechanism that is explained below, the first bump is commonly referred to as Synchrotron peak, and the second bump as Inverse Compton (IC) peak. There are basically two different competing emission models that can explain the double-peak shape of the SED, which differ in the type of seed particle. These two models are briefly discussed in the following.

![Figure 2.7: Spectral energy distribution of Mrk421 taken during a multiwavelength campaign in 2009. Image credit from [79].](image)

- **Leptonic models**
  
  In leptonic models (figure 2.8), the main particles accelerated in the jet of the blazar are relativistic electrons. The high energy bump of the SED is explained by inverse Compton-scattering of optical to X-ray photons. In the case of the external radiation Compton (ERC) scenario, these low-energetic photons were produced outside the jet by the accretion disk or the torus. In the so-called **Synchrotron Self-Compton** (SSC) model [48] [49], the photons were produced by the same population of electrons via synchrotron radiation in a homogeneous, randomly-oriented magnetic field. Homogeneous one-zone SSC-models, the most simple models, assume that the relativistic electrons are injected in a single spherical zone in the jet. As a result of this model, correlation between the X-ray and the VHE photons is expected.

\(^1\)The SED is the spectrum multiplied by \(E^2\)
• Hadronic models

According to these models (figure 2.9) ([46], overview in [47]) a component of high-energetic protons is accelerated together with the electrons in the jet. The acceleration of protons is more efficient than for electrons, as protons suffer less synchrotron radiation. The low-energy component is then explained due to electron synchrotron radiation, while the VHE gamma-rays are produced by the relativistic protons, due to interaction with matter, low energetic synchrotron photons or magnetic fields. In the following proton-induced cascade, neutral pions decay in two gamma-rays via

$$\pi^0 \rightarrow \gamma\gamma$$  \hspace{1cm} (2.1)

Charged pions decay in muons, that finally decay in electrons and positrons respectively. These electrons and positrons again produce synchrotron radiation.

In this model, the emission of neutrinos is expected, as they should be produced in the decay of the charged pions in the proton-induced cascade. Their detection would be a clear indication for a hadronic model.

For some sources, the multifrequency SED has been studied in great detail in multiwavelength campaigns, as this can lead to a deeper understanding of the underlying emission mechanism. The large number of free variables, limited sampling and simultaneity as well as the different sensitivities of the instrument makes it however difficult to exclude emission models. For Mrk421, an extensive multiwavelength campaign was performed in 2009 [79], when the source was generally in a quiet state showing some variability, but no significant flaring. Both frameworks, the leptonic and the hadronic emission model, were able to describe the observed SED in this case (figure 2.10).
2. Active Galactic Nuclei

Figure 2.10: (a): SED of Mrk421 in 2009 with SSC model fit: The two lines are obtained for different minimum variability timescales (red curve: 1 day, green curve: 1 hour). (b): SED of Mrk421 in 2009 with hadronic model fit: The dotted and dashed lines show the contributions of different cascades, and the solid black line shows the sum of all emission components. Both frameworks are able to describe the observed SED. Image credit from [79].
2.3.2 Markarian 421

The High-frequency peaked BL Lac (HBL) source Markarian 421 (or Mrk421, also Mkn421) is one of the brightest sources in the TeV sky, and is investigated in this thesis. In the following, a brief survey of historical and recent observations covering energies from radio to TeV gamma-rays is given.

2.3.2.1 A brief History

Starting in 1963, the Armenian astronomer Benjamin Markarian drew attention to a special class of galaxies that showed an ultraviolet excess compared to other galaxies. These galaxies had a non-thermal spectrum and most of them produced strong emission lines. In 1965, Markarian started an excessive search, the “Byurakan Survey”, using the Schmidt telescope at the Byurakan Astrophysical Observatory. Between 1967 and 1981, he compiled a catalog including in total 1515 galaxies [80]. The objects were simply listed from Mrk1 to Mrk1515 with name, coordinates, spectral type, visible size and morphological type. Mrk421, located in the constellation Ursa Major, appeared in volume 5 of this catalog [81]. The corresponding photographic plate is presented in figure 2.11. Next to Mrk421, its companion galaxy Mrk421-5 can be recognized. For comparison, an optical image with better resolution is presented in figure 2.12, obtained with the Nordic Optical Telescope that is located on the Canary Island of La Palma.

Figure 2.11: Identification charts including Mrk421. Image credit from [81].

Already one year later, Mrk421 was identified with the radio source 1101+38 in the second Bologna survey [82]. Ulrich et al. [83] identified Mrk421 as a BL Lac object in 1975, and measured its redshift $z=0.0308$. This makes Mrk421, together with Mrk501, one of the closest TeV blazars to the earth, and with a magnitude\(^2\) around 14 mag also one of the brightest in the optical. A historical look at the optical behavior of Mrk421 is given by Liu et al. [84]. They compiled data from 22 publications and produced a long-term lightcurve dating back to 1900 and found that the brightness varied from 11.6 mag to more than 16 mag (figure 2.13).

\(^2\)Magnitude is the logarithmic measure of the optical brightness of an object. The brighter the star, the smaller the magnitude.
2. Active Galactic Nuclei

Figure 2.12: Optical image of Mrk421 and its companion galaxy 421-5. Image credit from Aimo Sillanpaa/Nordic Optical Telescope.

Figure 2.13: The long-term lightcurve of Mrk421 from 1900 to 1991. The discontinuity of the light curve between 2435000 and 2439000 is due to lack of observations. The brightness varies from 11.6 mag to more than 16 mag. Image credit from [84].

The identification with the X-Ray source 1102+384 followed in 1978 by Cooke et al. [85]. The 2A catalog they presented is the result of 10'000 orbits of observation by the Sky Survey Instrument on the Ariel 5 satellite [86]. In 1992, Mrk421 was also detected as J1104+3813 above 100 MeV by the EGRET telescope [87].
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2.3.2.2 Mrk421 at TeV Energies

In 1991, the Whipple gamma-ray telescope at the Fred Lawrence Whipple Observatory [14] in Southern Arizona started to observe sources that had been previously observed by EGRET. The detection of Mrk421 above 350 GeV followed in 1992 [23], making Mrk421 the second source detected at TeV energies, and the first extragalactic TeV source. This was confirmed in 1996 by the first two HEGRA Cherenkov telescopes that reported the observation of Mrk421 in 1996 [88]. In the following, the source was observed extensively by most TeV experiments, including H.E.S.S. [47], MAGIC [89] and VERITAS [90]. A long-term TeV lightcurve of Mrk421 including the years 1992 to 2008 is presented in [91] (figure 2.14). A period of very strong activity was reported in 2000/2001. Additionally, the extensive observations allowed for a number of discoveries. Rapid flux variability with doubling times ≤ 15 minutes were already reported in 1996 by the Whipple group (image 2.15) [92] [93].

![Figure 2.14: Long-term lightcurve of Mrk421 (day-wise integral flux) at energies above 1 TeV in Crab units (C.U.) (Crab is a unit of the flux observed from the Crab Nebula, the standard candle in gamma-ray astronomy.). Image credit from [91].](image)

The violent flaring episode in the period 2000/2001 allowed to obtain deeper insights into the spectral behaviors of Mrk421. Both the Whipple collaboration [94] and the HEGRA collaboration [95] reported a hardening of the TeV energy spectrum with increasing flux. The Whipple collaboration observed Mrk421 between 28 November 2000 and 13 April 2001 and obtained the energy spectra for eight different subsets of different flux levels (image 2.16). The spectra were found to be well described by a power law with a fixed exponential cutoff, and the spectral index varied with the flux state in a tight correlation, with harder spectra for higher flux levels. The HEGRA collaboration collected data from December 1999 until May 2001. They found clear evidence for variations of the spectral shape, getting harder with increasing flux level, as displayed in figure 2.17 that presents the energy spectra for three different flux bins (high, medium and low) and the corresponding flux ratios. Even for short intranight flares with doubling times of less than 1 hr, spectral hardening well correlated with the increase of the flux was reported.

Fossati et al. [96] presented simultaneous optical, X-ray and TeV gamma-ray (including Whipple and HEGRA data) observations for the period of 18-25 March 2001. They found
strong and highly correlated variations in both the X-ray and the gamma-ray band. Both the X-ray and the TeV spectra significantly hardened over the course of the week-long campaign, accompanying a gradual brightness increase. The spectral indices for a power law fit with exponential cutoff shifted from 2.3 to 1.8, suggesting that the IC peak moved to higher energies, from below to within the bandpass observed by the Whipple telescope. The obtained multiwavelength SED is shown in figure 2.18 for a high flare state and a low (pre-flare state), with the simulatenous 2001 data shown in blue. The TeV-spectrum is significantly harder for the high-flare state.

Figure 2.16: Mrk421 spectra at different flux levels averaged over the 2000/2001 season, observed with the Whipple Observatory 10 m gamma-ray telescope. The spectra have been fitted by a power with a fixed cutoff at 4.3 TeV. Spectral hardening with increasing flux level can be observed. Image credit from [94].
2. Active Galactic Nuclei

Figure 2.17: Energy spectra for three different flux intervals observed with the HEGRA system of Cherenkov telescopes. In the image below, the flux ratios have been calculated. The energy spectra get considerably softer with decreasing average flux. The cut-off energy remains unchanged within the statistical error. Image credit from [95].

Extensive multiwavelength campaigns proved as a powerful tool to learn about the SED and the spectral correlations of Mrk421, and were performed regularly (for example [97] [98] [99]). The results showed positive but complex correlation between X-rays and gamma-rays, that challenge both the simple one-zone SSC and hadronic models. Also modeling of data taken during different states indicated that the one-zone SSC model is insufficient to describe the observations [98]. Alternative models include more complex geometries that lead to a larger number of free variables [99] [100].

With the launch of the Fermi satellite in 2008 (see chapter 7.1), the observational gap at energies between $\approx 0.1$ MeV and 0.3 TeV was filled. This gap had partially been filled by EGRET before, but its moderate sensitivity and limited observation time didn’t allow for detailed correlation or spectral studies. Additionally, the current generation of IACTs with low energy thresholds at some tens of GeV didn’t start operating before 2004, and this was after EGRET had stopped operating. Results from data collected between 5 August 2008 and 12 March 2010 with the Fermi-LAT instrument are reported in [79]. The flux measured by Fermi LAT was found to be comparable to the flux measured by EGRET, and a statistically significant flux variability was found. In contrast to the TeV energy range, the photon index was compatible with being constant. Additionally, no obvious relation between flux and index was found. The Fermi spectrum of Mrk421 during the period from 5 August 2008 to 20 February 2010 is presented in figure 2.19.
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Figure 2.18: Spectral energy distributions for two epochs (left: high flare state, right: low (pre-flare) state) during the March 2001 campaign performed by Fossati et al. Simultaneous 2001 data are shown in blue. Other colors mark reference data points, the orange symbols mark the highest state observed in 1996. The solid red lines represent fits with a simple one-zone homogenous SSC model. The TeV-spectrum is significantly harder for the high flare state. Image credit from [96] and references therein.

Figure 2.19: Energy spectrum of Mrk421 during the period from 5 August 2008 to 20 February 2010, observed with the Fermi gamma-ray space telescope. Black line is the likelihood power law fit, red contour is the 68% uncertainty of the fit and the black data points show the energy fluxes computed on differential energy ranges. Image credit: [79].

Today, with Fermi constantly delivering data and the new generation and low energy threshold IACTs like the MAGIC stereo system, we have the best conditions ever to perform comprehensive observation over the entire energy spectrum, and thereby gain a more complete view of the behavior of Mrk421. Especially the covering of the high-energy peak of the SED with data collected by Fermi and MAGIC provides new insights into its spectral behavior, as will be shown in chapter 7.


# 3 Imaging Cherenkov Telescopes

The following chapter is dedicated to the Imaging Air Cherenkov technique used to indirectly measure cosmic gamma-rays. After a short description of gamma- and hadron-induced air showers and the Cherenkov light they produce, the technique used to record and parameterize these airshowers is presented.

## 3.1 Air Showers

When cosmic ray particles like protons or gamma-rays above an energy of several GeV enter the atmosphere, they produce an extensive cascade of secondary particles. The existence of these Extensive Air Showers (EAS) was discovered in 1938 by Pierre Auger [101]. When investigating cosmic rays, he found that the cosmic radiation events were coincident in time, meaning that they were associated with a single event. The development of the shower is different for gamma- and hadron-induced showers. A short overview is given in the following, more detailed explanations can be found for example in [33] or [102].

- **Electromagnetic shower**: An electromagnetic shower (figure 3.1(a)) consists of photons, electrons and positrons. Their development is characterized by an exponential increase in the number of particles in the beginning, and then an even faster decrease after the maximum has been reached. The shower starts with an electron-positron pair production by the primary gamma-ray. This is followed by bremsstrahlung of the secondary electron and positron pair, whereby approximately half of their energy is transferred to the photon. Thereby, the number of particles doubles in each interaction, while the energy of the individual particles is halved. New particles are produced, until they reach a certain critical energy which is around $\approx 83\,\text{MeV}/Z$ for a particle with charge $Z$. Below this value, ionization losses dominate over the bremsstrahlung process. For photons, the critical energy is around $\approx 5\,\text{MeV}$, when the Compton radiation starts to dominate over the pair production process. Once the critical energy is reached, no new particles are produced and multiplication comes to an end. The shower particles gradually lose their energy until the shower extinguishes. Electromagnetic showers can be described by analytic approximation like the Rossi & Greisen approximation [103], or computed as Monte Carlo (MC) simulations. Examples of such shower simulations are shown in figure 3.2, left side, for two different energies.

- **Hadronic shower**: The development of hadronic showers (figure 3.1(b)) is more complex, as they are composed of different components. In the first interaction, pions are produced, in more rare cases also kaons and baryons. While the hadronic component builds the core of the shower, the neutral pions decay in two gammas that again produce electromagnetic subshowers. Further shower particles are muons. Having a half-life of $2.2\,\mu\text{s}$ in their own reference frame [104], many of them arrive at the ground before decaying. Compared to electromagnetic showers, hadronic showers are less regular, have larger fluctuations and show a larger lateral distribution, as significant transverse momentum is transferred in hadronic interactions (figure 3.2,
right side). As hadronic interactions cannot directly be obtained from QCD (quantum chromodynamics) calculations, hadronic interaction models are needed (e.g. [105]).

### 3.2 Cherenkov Radiation

Most of the particles produced in air showers are highly relativistic. Charged particles with velocities $v_{\text{particle}}$ faster than the speed of light in the atmosphere $c_n = \frac{c}{n}$, with $n$ the refraction index of the medium, produce so-called Cherenkov light [108]. This Cherenkov light is produced by the polarization of the medium that the charged particle propagates through. The polarized atoms emit electromagnetic waves that interfere constructively if the charged particle is faster than the speed of light in the medium (figure 3.3). This again leads to an emission cone in front of the particle as explained by Huygens principle, with a thickness of only a few ns\(^1\). The angle $\Theta$ between the particle track and the emission direction of the Cherenkov light can be calculated as

$$\cos(\Theta) = \frac{1}{\beta n} \quad (3.1)$$

with $\beta = \frac{v_{\text{particle}}}{c}$ the relative particle velocity.

\(^1\)1 ns = $10^{-9}$ s
3. Imaging Cherenkov Telescopes

Figure 3.2: Simulations of a gamma-ray and a proton induced air shower for energies of 100 GeV and 1 TeV and 0° zenith angle. The particle type is encoded in track color: red for electrons, positrons, gammas, green for muons and blue for hadrons. The gamma-ray induced shower is more compact than the proton induced shower, and its lateral distribution is smaller. Image credit from [107].
3. IMAGING CHERENKOV TELESCOPES

Figure 3.3: Cherenkov radiation emitted by a charged particle traveling faster than the speed of light in that medium. According to Huygens principle, electromagnetic waves emitted by the polarized atoms along the path interfere constructively and emit light under the angle $\Theta$.

In the case of an air shower, the density and therefore also the refraction index of the atmosphere depends on the height via

$$n(h) \approx 1 + (1 - n_0) \cdot e^{-h/h_0}$$  \hspace{1cm} (3.2)

with $n_0 \approx 1.00029$ [109] and $h_0 = \frac{kT}{Mg}$ [110] with $k$ the Boltzmann constant, $T$ the temperature, $M$ the molecular mass and $g$ the standard gravity, and $h_0 \approx 7.1$ km for $T = -30^\circ C$. According to equation 3.1, the Cherenkov angle is smaller the higher the radiating particle is. For an air shower, the Cherenkov light emitted by many charged particles at different heights finally superimposes at ground level, producing a light pool with a radius of $\approx 100$ m around the shower core.

3.3 IACTs Detection Technique

Cherenkov flashes from air showers can be detected on ground level by Imaging Atmospheric Cherenkov Telescopes (IACTs). These telescopes use a large mirror to reflect and focus the Cherenkov light onto a fast camera consisting of light detectors like Photomultiplier Tubes (PMTs). In doing so, IACTs don’t measure the distribution of Cherenkov photons on the ground, but rather gain information about the total shower development. A sketch of the IACT technique is shown in figure 3.4. The image of the shower has an elliptical shape with the main axis pointing to the camera center for particles that cross the atmosphere parallel to the telescope axis. Due to the smaller Cherenkov angle, Cherenkov photons produced at higher altitudes forming the “head” of the shower, are imaged closer to the camera center [111]. As the Cherenkov flashes are very short, only 2-3 ns, the trigger electronics has to be very fast.

Thanks to the information about the whole shower development, this technique allows good rejection of the much more abundant hadronic background showers. IACTs typically have collection areas of $\approx 10^5$ $m^2$, as they can detect an air shower whenever positioned in the Cherenkov light pool emitted by an airshower. Other advantages of IACTs are the rather low energy threshold, which lies for MAGIC as the IACT with the currently lowest energy threshold at $\approx 55$ GeV [113], and a good pointing capability. Disadvantages are the small Field of View (FoV) and the short duty cycles, as IACTs can only operate under good atmospheric conditions.
3. Imaging Cherenkov Telescopes

Figure 3.4: Schematics of the imaging technique. An image of the extended air shower is recorded by measuring the emitted Cherenkov light with an IACT. Image credit from [112].

If two or more telescopes are operated in stereoscopic mode, each shower is seen under different viewing angles. The three-dimensional reconstruction of the air shower in the atmosphere allows better energy and angular resolution and also better background rejection.

3.3.1 Image Parameterization

As shown in figure 3.2 proton and gamma-ray induced showers develop in a different way in the atmosphere. In average, proton-induced showers are wider and less compact than electromagnetic showers. Therefore, also the shower images recorded by the IACT camera look statistically different for different shower types. This is shown in figure 3.5.

The air shower images are parameterized using different image parameters like the Hillas parameter [115] but also additional timing and stereo parameters [113]. These parameters allow to distinguish on a statistical basis between proton and gamma-ray induced showers, to reconstruct the energy and the arrival direction of the incoming particle, as will be explained in chapter 5. Some of the most important image parameters used for stereo observations are described below and shown in figure 3.6.
Figure 3.5: Example of three different types of shower images recorded by the MAGIC-I camera: Left: gamma-like shower, center: hadronic shower, right: single muon. Image credit from [114].

Figure 3.6: Definition of simple Hillas parameters, calculated for a gamma-ray image, which may be approximated as an ellipse. Adapted from [116].

- **Size**: the total number of photo-electrons (pe) collected in the air shower. This parameter is directly related to the energy of the primary particle.

- **Length**: the half length of the major axis of the shower ellipse. It is a measure of the longitudinal development of the shower.

- **Width**: the half length of the minor axis of the shower ellipse. It is a measure of the transversal development of the shower. This parameter is important for background-rejection, as hadronic showers have a larger transversal momentum than electromagnetic showers.

- **LeakageN**: the fraction between the number of photoelectrons contained in the N outermost rings of the camera and the total charge of the image (size). Images with a high leakage value are likely to be truncated, which must be taken into account in the estimation of the primary gamma-ray energy.
• **Dist:** the angular distance between the ellipse center of gravity and the expected source position. It is correlated with the impact parameter\(^2\). This parameter is important for the energy estimation of the primary particle.

• **\(\Theta\):** the angular distance between the nominal and the reconstructed source position. The \(\Theta\)-parameter is very powerful for the signal-to-background separation, as gamma events originating from the source peak have small \(\Theta\) values, hadronic events are uniformly distributed in \(\Theta\).

• To reconstruct the a priori unknown source position, the so-called **DISP method** is used. Thereby, the **DISP parameter** describing the angular distance between the ellipse center of gravity and the unknown source position, is estimated for both telescopes separately. To do so, multidimensional decision trees using geometrical and additionally timing information are used [117]. The final stereo reconstructed position is then calculated as a weighted average of the two DISP positions and the crossing points of the ellipse main axis, or, if the two DISP positions don’t agree within a certain range, the event is rejected. This is done by an algorithm that takes also care of the left-right ambiguity that the DISP parameter is susceptible to, i.e. if the source position is placed on the wrong side of the ellipse center.

• By geometrically combining the single image parameterizations, further image parameters which refer to the stereoscopic view of the shower are calculated. Stereo parameters include the **Impact** parameter that describes the orthogonal distance of the shower axis to the telescopes, and the **Max Height** parameter that gives the height of the shower maximum. **Max Height** is a powerful stereo parameter for gamma-hadron separation at low energies [113].

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\(^2\)The impact parameter is the distance between the telescope’s position and the penetration point of the incident gamma-ray direction with the horizontal telescope plane.
4 The MAGIC Telescopes

The MAGIC telescopes (image 4.1) are a system of two 17 m-diameter IACTs, located on the Roque de los Muchachos Observatory (ORM) on the island of La Palma in the Canary Islands, at about 2200 m above sea level. They are optimized to measure VHE gamma-rays between approximately 50 GeV and a few tens of TeV.

The first MAGIC telescope, MAGIC-I (MI), was built in 2004 and operated as a stand-alone system until autumn 2009, when the construction and commissioning of MAGIC-II (MII) finished. MII, placed at a distance of 85 m from MI, was basically built as an improved clone of MI. While the design concept and most of the components were identical for both telescopes, the camera, the readout system and the mirrors were different at the time of their construction. Between summer 2011 and summer 2012, an upgrade of the MI camera and the readout electronics of both cameras took place, making the two telescopes more similar. Regular data taking with the upgraded system started in November 2012.

As the data analyzed in this thesis was taken between January 2010 and June 2011, the hardware setup is described as it was in the period before the upgrade. If not specifically mentioned, the descriptions are valid for both telescopes.

4.1 Frame, Drive and Reflector

As the MAGIC telescopes are a pointing system with a special focus on fast repositioning i.e. in the case of GRB alerts, particular attention has been drawn to keep the total weight of the telescopes as low as possible. Therefore, a lightweight but nevertheless steady structure was especially important. This was achieved by building the frame as a three-layer structure made of fiber epoxy composite tubes, joined by aluminum knots. The camera is held on a distance of 17 m from the reflector by a single aluminum arc supported by steel cables that are connected to the main structure. The frame and the arc holding the camera are shown in figure 4.2.

The instrument is mounted on a circular rail in alt-azimuth configuration, with the azimuth motion being controlled by two motors and the zenith motion by one. The total telescope weight of 72 tons [119] allows a half-turn of 180° in azimuth in just 20 s [119].

The reflectors of both telescopes consist of a 17 m diameter parabolic dish, which focuses
4. The MAGIC Telescopes

Figure 4.2: Picture of the MAGIC telescopes where the frame support structure and the mast holding the camera are visible. Image credit from [118], Robert Wagner.

the Cherenkov light from air showers on the pixelized camera. The large mirror surface is the main feature allowing the low energy threshold. Additionally, the parabolic shape allows to minimize the time spread of the Cherenkov flashes, and thereby preserves the timing information of the arriving photons. In the case of MI, the reflector with a total area of 236 $m^2$ consists of 964 aluminum mirror elements of 49.5 cm x 49.5 cm each, four per moving panel each. MII has a mirror area of 241 $m^2$, as larger mirrors with 1 $m^2$ area were used. 143 of the 247 MII mirrors are made of aluminum, while the remaining 104 outer mirrors are made of glass [120]. In figure 4.3, the mirror and the rails of MI are shown.

Figure 4.3: Picture of MI. Well visible are the reflecting surface, the rails and the camera. Image credit from [118], Robert Wagner.

As the carbon-fiber cell structure is strong but not very rigid, the telescope will deform under its own weight while repositioning, and the mirror segments will defocus. Therefore
a so-called Active Mirror Control (AMC) is needed that readjusts the individual mirror segments. While this was done with a laser system in the beginning, it could be shown that using a database with mirror positions for each zenith angle is much faster and more reliable. The focussing is thereby measured in terms of the Point Spread Function (PSF), and a PSF smaller than the size of 1 pixel can be achieved when using the AMC [121].

The pointing of the telescope is monitored by the so-called starguider CCD camera that is mounted at the center of the reflector and sees both the camera and part of the sky. The starguider system compares the observed star positions with a catalog of stars and measures the mispointing. This setup is also useful when performing the data quality check, as the number of identified stars seen by the starguider system yields information about the atmospheric transparency (see chapter 6.1.1).

4.2 The Cameras

The performance of the camera is critical for the sensitivity of IACTs, as a very fast response is required. In the case of the MAGIC telescopes, this was achieved through the use of photomultiplier tubes (PMTs) of high quantum efficiency as individual pixels, protected behind a plexiglass window (figure 4.4). The PMTs are run at a relatively low gain to prevent high anode currents during moderate moonlight observations. The field of view (FOV) covers approximately 3.5° for both MAGIC cameras. Apart from that, the two MAGIC cameras differed in the period before the upgrade and are described independently.

The MI camera has a hexagonal shape and a diameter of 1.5 m. It is equipped with 576 PMTs ET9116 [122] that have a quantum efficiency of nearly 25%, further enhanced by and extended to the UV by a special coating. In order to minimize the light loss due to the dead space between the round PMTs, hexagonal-to-round light-guiding Winston cones are used. The 397 PMTs occupying the inner region of the hexagon are smaller with a FOV of 0.1°, while the 180 outer ones have a larger FOV of 0.2°. The decision to use PMTs of different size was due to economic reasons. It does however not affect much the sensitivity of the instrument, as small and low-energetic showers are imaged close to the camera center. Only the inner pixels are included in the trigger area, including a trigger

\[1\] The Point Spread Function (PSF) describes the defocussing of a point-like source.
area of $\approx 2^\circ$ diameter FOV [113].

Instead, the MII camera [123] (and also the new MI camera) has a circular shape and a diameter of 1.462 m. To achieve a more uniform response, it is homogeneous and consists of 1039 hexagonal pixels and Winston cones. New PMTs from Hamamatsu of increased peak quantum efficiency of around 32\% and $0.1^\circ$ FOV are used. The camera has a modular design with the PMTs grouped in 169 clusters of seven PMTs each, of which the 95 clusters located in the inner area of $2.5^\circ$ diameter FOV define the trigger region [113].

![PMT module](image.png)

Figure 4.5: Assembled PMT module used in the MII camera. Image credit from [123].

The analog PMT signals are pre-amplified, and in the transmitter board within the camera housing they are translated into optical signals by means of a Vertical Cavity Surface Emitting Laser (VCSEL), as can be seen in figure 4.5. The optical signals are transmitted via optical fibres to the counting house, where they are converted back to electrical signals by a photodiode and split in two branches in the so-called receiver boards. While the first branch is coupled to the trigger system (see section 4.3), the signal in the second branch is delayed (in order to wait for the trigger decision) and goes to the data acquisition system (DAQ) (see section 4.4). If the signal passes the trigger requirements, it is digitized and stored for the subsequent analysis. Figure 4.6 gives an overview of the MI readout system.

### 4.3 The Trigger System

As it is not possible to digitize all information from all pixels sampled at 2 GHz, a preselection of air shower images is needed. This is done by the Trigger system [124] [113]. The MAGIC standard trigger consists of three levels:

- **Level 0 Trigger (LT0):** checks if the signal from a PMT is greater than a fixed discriminator threshold (DT) that is set via software. If this happens, a logical signal is produced. The DTs are programmable from the central control so that the rate is stable under different light conditions.

- **Level 1 Trigger (LT1):** evaluates the compactness of the digital signals from LT0, as gamma-ray signals normally have a compact shape. Only signals having $x$ next neighboring ($x$NN, $x$ can be selected as 2, 3 or 4) lighted pixels within a given short time interval of $\approx 3$ ns are selected. While in mono observations a 4NN topology was used, stereo observations require a 3NN condition\(^2\). If at least one such group is detected, the LT1 is fired.

  For special observations aiming for the lowest possible energies, the so-called **SUM-trigger** can be used as an alternative to the LT1 [125].

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\(^2\)3NN/4NN: 3/4 next neighboring pixels needed to fire the LT1. See also section 6.4 for more details.
4. The MAGIC Telescopes

- **Level 2 Trigger (LT2):** bases on different topological criteria, is not used for standard data taking.

- **Level 3 Trigger or Stereo Trigger (LT3):** seeks for coincidence of L1 triggers on both telescopes and rejects events triggered by only one telescope.

![MI readout system](image.png)

Figure 4.6: MI readout system. Image credit from [126].

4.4 Data Acquisition

As the gamma-ray signals are very short, a fast readout electronics is needed. Both MAGIC telescopes sample the signals at a speed of 2 GHz, but the digitizing hardware is different for the two telescopes. Since 2007, MI digitizes the signals with a Multiplexed (MUX) FADC (Flash Analog to Digital Converter) system that increased the sampling frequency from 300 MHz to 2 GHz [126]. For MII, the almost double number of pixels requires a more compact, lower-cost setup, based upon the low power analog sampler chip called Domino Ring Sampler version 2 (DRS2) developed at PSI [127] [128] [129] (see also chapter 5.9).

4.5 The Calibration System

The ADC counts recorded by the data acquisition have to be reconverted into the number of Cherenkov photons that hit the mirrors. For this purpose, a calibration system is needed, that provides controlled light-pulses of different wavelengths and intensities. These light-pulses uniformly illuminate the camera and the response of the system is measured. The calibration system consists of a set of LEDs in the case of MI [130] and of a frequency tripled Neodym YAG microchip laser and a set of attenuation filters in the case of MII. The calibration box is situated in the center of the mirror dish. The system allows a relative calibration between the pixels of the camera, by adjusting the individual high-voltage so that their gain is uniform within the camera. Additionally, the camera is flashed with calibration signals with a rate of 25 Hz, in order to control the response of the system while datataking.

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3After the upgrade, both telescopes have been equipped with the DRS4 chip.
4.6 Performance of the MAGIC Stereo System

In order to evaluate the performance of the MAGIC stereo system, a data sample from the Crab Nebula\(^4\) taken in November 2009 and January 2012 under small zenith angles, was analyzed [113]. After the data selection, 9h of good data remained that was analyzed using the standard software package called MARS (see chapter 5). For the analysis, a low zenith angle Monte Carlo (MC) sample consisting of gamma-rays with energies between 30 GeV and 30 TeV was used. Some of the results obtained are:

- **Energy resolution:** The performance of the energy reconstruction was estimated using gamma MC events with true energy \(E_{\text{true}}\) and reconstructed energy \(E_{\text{rec}}\). The energy resolution can be calculated as the standard deviation of the distribution \((E_{\text{rec}} - E_{\text{true}})/E_{\text{true}}\). The mean value of this distribution describes the bias introduced by the method. The energy resolution and the bias are shown as a function of true energy in figure 4.7. In the medium energy range at few hundred GeV, the energy resolution is as good as 16%.

- **Angular resolution:** The angular resolution is defined as the standard deviation of the 2-dimensional Gaussian fitted to the distribution of the reconstructed event direction of the gamma-ray excess. It is shown as a function of the estimated energy in figure 4.8, obtained with the Crab Nebula data set and calculated with MC simulations. For an energy of 300 GeV, the angular resolution is as good as \(\approx 0.07^{\circ}\). For completeness, also the 68\% containment radius was calculated and is also shown in figure 5.8.

- **Integral sensitivity:** The sensitivity is the flux of a source giving a significance of approximately \(N_{\text{excess}}/\sqrt{N_{\text{bgd}}} = 5\) after 50 h of effective observation time, where \(N_{\text{excess}}\) is the number of excess events, and \(N_{\text{bgd}}\) the estimation of the background. The integral sensitivity of the MAGIC stereo system is presented in figure 4.9. It is as good as \((0.76 \pm 0.03)\) of the Crab Nebula flux above 290 GeV.

- **Trigger threshold:** From the MC simulations, an energy threshold\(^5\) of 50 GeV was obtained for sources with a differential spectral index -2.6. After image cleaning and analysis cuts, this value increases to \(\approx 75\) GeV, depending on the cuts used in the analysis and the spectrum of the analyzed source. This makes MAGIC the IACT with the currently lowest energy threshold, allowing an overlap with observations performed by the LAT instrument on board the Fermi satellite.

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\(^4\)The Crab Nebula is the standard candle in gamma-ray astronomy.

\(^5\)The energy threshold is the maximum of the distribution of triggered gamma-ray events.
4. The MAGIC Telescopes

Figure 4.7: Energy resolution (solid line) and the bias (dashed) obtained with the MC simulations of gamma-rays. Image credit from [113].

Figure 4.8: Angular resolution as a function of the estimate $N_{\text{phot}}$ obtained with the Crab Nebula data sample (points) and compared with the MC simulations (lines) for the 2D Gaussian fit (solid line, full circles) and the 68% containment radius (dashed line, empty triangles). Image credit from [113].
Figure 4.9: Integral sensitivity of the MAGIC Stereo System, i.e. the flux of a source above a given energy for which $\frac{N_{\text{excess}}}{\sqrt{N_{\text{bgd}}}} = 5$ after 50 h of effective observation time. For MAGIC Stereo (black, solid - data, dashed - MCs) compared with the MAGIC-I telescope (solid gray line). For comparison, fractions of the integral Crab Nebula spectrum are plotted with the thin, dashed, gray lines. Above a few hundred GeV, the MAGIC Stereo sensitivity is a factor of 2 better than the one of the MAGIC-I telescope. Image credit from [113].
5 MAGIC Analysis Chain

The data recorded with the MAGIC telescopes is analyzed using MARS (MAGIC Analysis and Reconstruction Software, [131]), the standard analysis package developed by the MAGIC collaboration. MARS is a ROOT-based [132] software package written in C++ consisting of several individual programs, each taking as an input the output of the previous one. An overview about the standard analysis chain for stereo data is given in figure 5.1 [133], the individual analysis steps will be shortly discussed in the chapters marked in the figure.

Figure 5.1: Summary of the analysis steps for MAGIC stereo analysis. The individual analysis steps are discussed in the chapters marked in the figure. Modified from [133].

As a general rule in MAGIC, every analysis chain has to be cross-checked with a sample of Crab Nebula data processed with the identical analysis chain. As the Crab Nebula is a strong and stable TeV point-source, it is used as a standard candle [113]. Since the outcome of the analysis is known a priori, the analysis chain including cuts and parameters can be tested. The Crab Nebula sample should correspond with the analyzed data set as closely as possible in terms of the observation period, the hardware setup or the trigger.
configuration. For this work, four different Crab Nebula samples were studied: A sample with data taken in 2009/10, from now on called cycle 5, a second sample with data taken in 2010/11, from now on called cycle 6, in addition a data set with data taken under a special trigger configuration (L1-4NN, see chapter 6.4) and a sample with data taken under moderate moonlight conditions (see chapter 6.4). In the following, results from the analysis of the cycle 5 dataset will be used to illustrate the different analysis steps. Results for the three additional Crab Nebula samples, as well as some general remarks concerning the performed analysis, can be found in Appendix F.

5.1 Data Taking

There are three different types of data needed for the MAGIC analysis:

- **Data runs:** Since the MAGIC system consists of two telescopes, the standard observation procedure is the so-called **stereoscopic mode**. This means that both telescopes observe the same source at the same time, and only events seen by both telescopes are recorded. There are two different data-taking methods, differing in the way the hadronic background is estimated. Using the so-called **On/Off-method**, the source and an additional region in the sky (with no known gamma-ray source in it) are observed separately. This method has two major disadvantages: First, it wastes valuable observation time for the separate Off-observation, and secondly, it’s almost impossible to perform the observations under identical conditions. Another possibility is to point with the telescopes not directly at the source, but at a position some degrees (for MAGIC by default $0.4^\circ$) away from the source position [134]. Every 20 minutes, the telescopes then switch to the mirrored offset position and back again. A big advantage of this so-called **Wobble mode** is the gain of observation time, as the signal and the background events can be extracted from the same files. Additionally, On- and Off-data are taken simultaneously and therefore under almost identical conditions. In addition to the data runs, so-called **calibration** and **pedestal** events are stored. They are recorded when the Wobble position is changed and interleaved with the data with a frequency of 50 Hz.

- **Auxiliary data:** These files contain supplementary information from the subsystems, like the drive system, the pyrometer, the starguider or the trigger system.

- **Monte Carlo (MC) simulations:** Unlike experiments in particle physics, in the case of Cherenkov Telescopes it’s not possible to generate a test beam. Therefore, Monte Carlo (MC) simulations of gamma-ray induced events are produced in three steps (more details in [135] and [136]): The program **Mmcs** based on CORSIKA [137] simulates the development of gamma-ray induced air showers in the atmosphere and the production of the Cherenkov photons. The simulation of hadronic (for example proton- or helium-induced) showers is used for special studies, but not needed for the standard analysis, as real data containing no strong source can be used for this purpose. The program **Reflector** then uses the output of **Mmcs** and describes the absorption and scattering of the Cherenkov photons in the atmosphere as well as their reflection by the MAGIC mirrors and their position and arrival time in the camera plane. The response of the camera, the trigger system and the DAQ are simulated using the program **Camera**. After **Camera**, the analysis of MC data and physics data is identical.
5. MAGIC Analysis Chain

5.2 Signal Extraction and Calibration

The initial input to the analysis chain are the binary files containing the raw data recorded by the telescopes, and some additional files with supplementary information of the subsystems. Usually, the data is calibrated on-site. In a first step, the program merpp combines the raw data with the information of the different subsystems. The output file is in root format containing so called root-trees, with a set of parameter containers for every entry. The next step is the MARS program CALibrate LIght Signals and Time Offsets (Callisto). Callisto converts the signal saved as counts per FADC time slice into the corresponding number of photoelectrons. To do so, Callisto subtracts the pedestal offset and, using the calibration events recorded during datataking, corrects for shifts in the arrival time. The crosstalk correction routine described in section 5.9.2 is applied in merpp or Callisto.

After every night, the calibrated files are copied to the datacenter situated in Barcelona, where they can be downloaded using GRID or a web page. The datacenter in Barcelona also provides higher stages of processed data, but in order to have control of the used MARS version or the used Random Forrest or Energy Look-up tables (see chapter 5.6), I decided to download the calibrated files and perform the following analysis steps myself, using Mars version M2-8-3.

Additionally, the automatic online analysis is running at La Palma in parallel with the data acquisition. This quick analysis is not as sensitive as a full analysis, but it is very useful to detect high states of variable sources and also to decide about observation strategies.

5.3 Image Cleaning and Shower Parameterization

The calibrated files are used as input files by the executable STandard Analysis and Reconstruction Star.

First of all, star cleans the camera image from signals produced by Night Sky Background (NSB)\(^1\). To distinguish between pixels containing NSB and the ones with signals from Cherenkov photons, an image cleaning process is applied. This process searches in two steps for the core and the boundary pixels of a shower image, whereof the core ones have to fulfill harder criteria than the boundary ones: A pixel is called a core pixel if its signal is above a certain threshold value, if additionally at least one neighboring pixel is also above that threshold and their arrival time is within 4.5 nanoseconds around the mean arrival time of all core pixels. The value of that threshold is 6 phe for MAGIC-I and 9 phe for MAGIC-II. The definition of a boundary pixel is as follows: Its charge is higher than 3 phe for MAGIC-I or 4.5 phe for MAGIC-II, and at least one neighbor is a core pixel with a maximal signal arrival time difference of 1.5 nanoseconds. The threshold values were different for the two telescopes before the upgrade, as they differed in important aspects like the PMTs, the trigger area, their mirrors and digitizing system. All pixels not associated to the shower image are set to zero.

A connected group of core and boundary pixels is called island. While gamma-ray shower images are expected to consist of one island group, hadronic showers contain different sub-showers (see chapter 3.1) and their images can therefore consist of several islands.

For each cleaned shower image, the Hillas parameters (see chapter 3.3) are extracted and stored in the output file. Figure 5.2 gives an overview of the shower extraction including signal extraction, image cleaning and the determination of the image parameters.

\(^1\)Several sources contribute to the Night Sky Background (NSB): Stars, the moon, artificial light or zodiacal light. Atmospheric conditions like high clouds or calima can increase the NSB.
5.4 Data Check

After the image cleaning and the calculation of the Hillas parameters, data of bad quality is sorted out. While some data taken under very bad weather conditions or with severe hardware problems, are excluded at the very beginning of the analysis, an additional quality check is needed at this point. Moonlight, clouds, high humidity or calima\(^2\) can influence the shower development in the atmosphere and therefore strongly affect the data. As there is no standardized data quality selection tool, this task mainly relies on the analyzers experience and also depends on the particular analysis like the observed source and the goal of the analysis. An example how the cuts were defined is given in section 6.1.1.1.

For the final analysis, the following parameters were used for the quality cuts:

- **Mean DC PMT current**: The light of the NSB increases the DC currents of the PMTs in the camera. Therefore, the value of the mean DC current is a good parameter to separate between dark and bright condition. An general value for this cut is mean DC\(^3\) < 1500 nA for dark night data.

- **Cloudiness**: Clouds and haze in the atmosphere strongly absorb Cherenkov photons and thereby influence the air shower images. The cloudiness is a parameter that describes the percentage of the sky that is covered by clouds, going from 0 to 100%. It is measured with the so called pyrometer that is installed at the edge of the reflector of MAGIC-I, more details can be found in [139]. This pyrometer points to the same direction as the telescope and its field of view of 2\(^\circ\) lies within the telescope’s field of view. It measures the reflection of infrared radiation in the range of 8 to 14 \(\mu m\). As this radiation follows Planck’s law describing black body radiation, the temperature of the sky can be calculated. If there are clouds in the field of view, the radiation of the earth’s surface is reflected by the clouds and therefore the temperature rises, so higher temperature means more clouds. As the sky temperature doesn’t only depend on the clouds in the field of view, but also on the temperature, the humidity and the zenith angle, the so called cloudiness parameter is calculated using all these parameters. For this analysis, data with cloudiness > 40% was excluded. In chapter 6.1.1.1 it is explained how the cut value was set.

---

\(^2\)Calima is caused by a duststorm that is stirred up by high winds in the Sahara and is then driven over the Canary Islands by south easterly winds.

\(^3\)This value is calculated as the median over all PMTs, and thereof the mean plus one standard deviation over the time period covered by a star file.
• **Number of identified stars** (nr. of id. stars): An additional parameter to monitor the observational conditions is provided by the starguiding system of MAGIC which is described for example in [140]. It consists of a camera at the center of each mirror, pointing at the same direction as the telescope. The images taken during the measurements are analyzed online for stars in the field of view. By comparing their positions with the positions calculated from a star catalog, the positional offset of the telescope is calculated. Typically, there are 40-50 stars visible in these display images, but if the sky is covered by clouds or fog, this number can decrease rapidly. For this reason, the number of identified stars in a given area in the sky can be used as a second parameter to monitor the conditions in the sky. For the following analysis, data with **number of identified stars < 20** was excluded.

These parameters were calculated as shown in figure 5.3 for the Crab Nebula sample from cycle 5 as a function of the Modified Julian Date (MJD)⁴. Nights not surviving the cuts in mean DC PMT current, cloudiness or number of identified stars were removed from the dataset. For the surviving nights, the following parameter was used as an additional quality check:

• **Rate after cleaning**: As the cleaning removes the events triggered by NSB, the rate after cleaning is mainly dominated by hadronic showers. As the cosmic ray flux on the earth is stable (see chapter 1), fluctuations in the rate are usually caused by changing atmospheric conditions. For this reason, the mean rate was calculated and nights which deviate from this mean by more than 20% for each telescope separately are excluded. The rate distributions for the Crab Nebula data is displayed in figure 5.4.

Using these cuts in mean DC PMT current, cloudiness, nr. of id. stars and rate after cleaning, data taken under bright or bad atmospheric conditions is largely removed. For the routines providing high-level output like signal plots, skymaps (section 5.7), lightcurves or energy spectra (section 5.8), the zenith angle was used for a supplementary cut.

• **Zenith angle**: While observations under large zenith angles can bring some advantages at large gamma-ray energies ($\gtrsim 3T eV$), the minimum attainable energy threshold for an instrument is reached for small zenith angles [141]. As in this work I was especially interested in low energies that allow an overlap with Fermi data, I used as a cut value a zenith angle of $< 35^\circ$.

### 5.5 Stereoscopic Image Reconstruction

Up to this point, the data of both telescopes are processed separately, resulting in the individual star-files for MAGIC-I and MAGIC-II. These star-files contain the image parameters describing the same shower seen by the two telescopes. The MARS routine **SuperStar** converts these star output-files to one file containing all necessary information about the shower. To do so, additional parameters describing the stereoscopic view of the shower are used (see chapter 3).

---

⁴MJD is a modification of the Julian Date that is designed to facilitate chronological calculations. It numbers all days in consecutive fashion, beginning at noon 1 January 4713 B.C., which is Julian Day Number 0. MJD modifies this Julian Date with $\text{MJD} = \text{JD} - 2400000.5$. This way, the MJD begins at midnight rather than noon, and the first two digits of the Julian Date are removed.
Figure 5.3: DC, cloudiness and nr. of id. stars as a function of the Modified Julian Date (MJD) for the Crab Nebula data taken in cycle 5 for MI (blue) and MII (red). One dot corresponds to one star file (≈ 4 min for MII and ≈ 2 min for MI respectively). Data with DC > 1500 nA, cloudiness > 40 or nr. of id. stars < 20 is excluded from the analysis. The corresponding cut-values are indicated by the green horizontal line.
Figure 5.4: Rate distribution for the Crab Nebula data taken in cycle 5 for MI and MII after cleaning and after removal of nights not passing the quality cuts in DC, cloudiness or nr. of id. stars. The rate is shown after a size cut of 100 phe and geometrically normalized for the zenith angle. Data within the range $\pm 20\%$ (blue (MI) and red (MII) horizontal lines) of the mean rate (green line) is accepted.
5.6 Gamma-Hadron-Separation and Energy Reconstruction

The vast majority of all recorded showers are caused by cosmic hadrons, therefore a method is needed to reduce this background. This task is performed with the Random Forrest (RF) method [142], based on multidimensional decision trees that search for statistical differences in the shower parameters of hadronic and electromagnetic showers. The RF is built with the MARS executable coach. Coach has to be fed with a pure electromagnetic and a pure hadronic data sample.

While for the electromagnetic sample MC simulations are used, the hadronic sample consists of real physics data from observations containing no VHE source. This could be observations especially performed for this purpose, or also observations of source candidates that later showed no signal in the analysis. The reason for using real physics data is that the needed amount of hadron showers is too large for usefull MC simulations, and real physics data satisfy the purpose as well as MC simulations. As the shower development depends on the zenith angle of the observation, this background data set should agree with the data as far as possible in the zenith range. Of course, the background data should also agree with the data in the hardware setup like for example the trigger configuration, and also pass the quality checks describes in chapter 5.4, which makes it sometimes difficult to find a good background data set.

The RF then tags to every event a new parameter, the so called hadronness. The hadronness describes the probability of an event to be hadron-like, with hadronic showers peaking around hadronness ≈ 1 and electromagnetic showers peaking around hadronness ≈ 0. This tagging is done by the Mars program MErge and Link Image parameters Before Energy Analysis (Melibea) that uses the SuperStar files as input.

Melibea also performs the energy reconstruction, which means it calculates the estimated energy of the primary particle from the measured shower parameters. In the case of stereo analysis, this is done with Look Up Tables (LUTs) created with MC simulations covering a sufficiently large zenith range. The look-up tables are built with the MARS macro create_Energy_table.

5.7 Signal Plot and Skymap

The next step of the analysis is to find out if the recorded data reveals an enhanced gamma-ray signal from the potential source. This is done with the programs Odie and Caspar.

The program Odie uses Melibea files and searches for a signal based on the parameter $\Theta^2$. $\Theta$ was already introduced in chapter 3 and describes the angular distance between the nominal and the reconstructed source position. While hadronic events are uniformly distributed in $\Theta^2$, gamma events coming from the observed source are centered around $\Theta = 0$. This makes a $\Theta^2$-plot (figure 5.5 for Crab Nebula cycle 5) a powerful tool to extract a gamma-ray signal from a source. Odie calculates the number of excess events, which means the number of signal minus the number of background events, in the so-called signal region with $\Theta^2 < \Theta^2_{\text{cut}}$. The significance of the detection is calculated with the so-called “Li & Ma” formula [143] which considers not only uncertainties of the signal events, but also the error in the background. A source is considered detected if the significance of the excess events is above $5 \sigma$.

The MARS program Caspar provides a map of excess in sky coordinates (figure 5.6 for Crab Nebula cycle 5). To do so, Caspar projects the reconstructed origins of the shower to the sky and smears them with the angular resolution of the telescopes, the so-called Point Spread Function (PSF). The result is given in test statistics (TS) from [143] equation 17,
using a smoothed background model.

In the case of Mrk421, the focus of the analysis is not on the signal search with *Odie* or *Caspar* (as the source is detected since 1991), but rather on the following steps calculating the lightcurve and the spectrum.

![Diagram](image1)

**Figure 5.5:** $\Theta^2$-plot of Crab Nebula data taken in cycle 5 for zenith $< 35^\circ$, using 1 Off-region. The solid histogram corresponds to the background, while the points with error bars show the signal. The excess events are extracted from the signal region with $\Theta^2 < \Theta_{cut}^2 = 0.0107$ as indicated by the dashed line. The chosen $\Theta^2$-cut is based on the standard cut for full energy range analysis, and mainly depends on the point spread function of the chosen analysis epoch.

![Diagram](image2)

**Figure 5.6:** Skymap of Crab Nebula data taken in cycle 5 for zenith $< 35^\circ$. The white cross in the center of the image shows the position of the Crab Nebula, the white circle represents the Point Spread Function assumed to produce the skymap.
5.8 Flux Estimation and Unfolding

If a source is detected with a significant amount of excess events, its gamma-ray spectrum can be calculated. The spectrum is defined as the number of gamma-ray events \( dN \) within a certain energy range \( dE \) that arrive in the time window \( dt \) and area \( dA \) on Earth:

\[
f(E) = \frac{dN}{dE \, dA \, dt}.
\]  
(5.1)

In case of gamma-ray sources, the spectrum often follows a power law

\[
f(E) = f_0 \left( \frac{E}{E_{\text{norm}}} \right)^{-\alpha}
\]  
(5.2)

with \( f_0 \) the flux normalization, \( E_{\text{norm}} \) an arbitrary normalization energy and \( \alpha \) the spectral index.

The spectrum of a source can be calculated with the MARS executable \texttt{fluxlc} that needs as input \texttt{Melibea} data files and MC simulations. Additionally energy-dependent cuts in hadronness and \( \Theta^2 \) have to be defined by the analyzer depending on the source and analysis goal. Using these cuts, \texttt{fluxlc} calculates the number of excess events in bins of estimated energy. The program also calculates effective observation time, which is the dead time reduced real observation time. Using MC simulations, it also computes the energy dependent effective area. The effective area is defined as the area in which a gamma-ray telescope can detect an airshower, folded with the detection efficiency after all cuts. It depends strongly on the energy of the primary particle \cite{113}. Figure 5.7 presents the differential energy spectrum calculated by \texttt{fluxlc} for the Crab Nebula data taken in cycle 5.

In case of non-detection, \texttt{fluxlc} also calculates upper limits.

An additional task performed by \texttt{fluxlc} is the calculation of lightcurves, i.e. the integral flux per time unit.

![Differential Gamma Energy Spectrum](image)

Figure 5.7: Spectrum of the Crab Nebula in cycle 5 for zenith < 35°, before unfolding, compared with published values.
The spectrum calculated by \( \text{fluxl} \) is given in bins of estimated energy. Due to limited (\( \approx 16\% \) [113]) and biased energy resolution, a significant number of excess events are counted in the wrong energy bin, which means that an event with true energy \( E_i \) can shift to its neighboring bin \( E_{i-1} \) or \( E_{i+1} \) or even further, and thereby affect the spectrum. To correct for this effect, a so called unfolding is necessary. This task is taken over by the macro \( \text{CombUnfold} \). In principle, the aim of the unfolding is to solve the following equation:

\[
Y_i = \sum M_{ij} \cdot S_j
\]  (5.3)

with \( Y_i \) the number of events in bin \( i \) of estimated energy \( E_{\text{est}} \), \( S_j \) the number of events in bin \( j \) of true energy \( E_{\text{true}} \) and \( M_{ij} \) the migration matrix \( M \) that can be obtained by MC simulations. The matrix \( M \) can in general not be inverted to obtain \( S \) as \( M^{-1} \cdot Y \).

Generally, \( S \) could be obtained by minimizing the Least-Squares expression

\[
\chi^2_0 = (Y - M \cdot S)^T \cdot K^{-1} \cdot (Y - M \cdot S)
\]  (5.4)

with \( K \) the covariance matrix of \( Y \). However it can be shown that this leads to large errors of \( S \) [144]. Therefore, more sophisticated methods are needed that use so-called regularization, which means that some constraints on \( S \) are postulated. In the MARS program, several unfolding methods are implemented [145]. As the migration matrix \( M \) also depends on the a priori unknown shape of the spectrum, many different unfolding algorithms with many different parameters each are possible. This makes the unfolding a non-automatic procedure requiring a lot of user interaction, and also the result has to be checked very carefully and compared with the results of other unfolding methods.

Figure 5.8 shows as an example the unfolded spectrum of Crab Nebula data from cycle 5 using different unfolding methods and compared with published values. All tested unfolding methods agree within error bars. Based on experience, the so-called Bertero method as described in [145] proved as the most stable and was therefore used in the following analysis.

Figure 5.8: Spectral Energy Distribution (SED) of Crab Nebula cycle 5 for zenith < 35° after using different unfolding methods and compared with published values.
5.9 Crosstalk Correction for the MAGIC-II Telescope

At the beginning of my work for this thesis in Summer 2009, MAGIC just underwent the change from a mono to a stereoscopic system. The data acquisition system of the new MAGIC-II telescope [127] was based on the Domino Ring Sampler, version 2 (DRS2), that was developed at PSI [146] (figure 5.9). The DRS2 works as a ring buffer with a sampling frequency of 2 GHz. Analog signals are stored in a multicapacitor bank (figure 5.10), where the single capacitors are sequentially enabled by a shift register driven by an internally generated high frequency clock (Domino wave). If a trigger occurs, the signals stored in the ring buffer are read out and digitized.

Figure 5.9: The DRS2 chip with and without ceramic package. Image credit from [147].

Figure 5.10: Schematics of the Domino sampler. Shown on top is the inverters sequence that originates the Domino wave. The shift register on the bottom enables serially the single capacitors connecting them to the output stage. Image credit from [128].

Among many useful characteristics like an excellent timing resolution, very low power consumption and the integration of ten channels in one chip, the DRS2 chip also shows an undesired effect: It produces crosstalk between the individual channels, which means that a signal in one channel of the DRS2 chip creates effects in all other channels of the same chip.\(^5\) The value of the crosstalk is between \(\approx 1-2\%\) of the primary signal, whereby the precise value changes from chip to chip and from channel to channel. As crosstalk from different chips

\(^5\)The deficiencies of the DRS2 chip were known in advance, but the DRS4 chip was not available in due time.
channels adds up, the final crosstalk value in a particular channel can reach up to \( \approx 8-10\% \). The mapping of the DRS2 channels to the pixels in the camera can finally make this relatively small effect important: If channels of the same chip are mapped to neighboring pixels in the camera, pixel islands with crosstalk signals could be produced. These fake islands could finally make gamma-showers look more hadron like (see chapter 3.1), and thereby worsen the gamma-hadron separation and finally worsen the sensitivity. This can be observed in figure 5.11 that compares achieved sensitivity of the MAGIC stereo system in Summer 2009 with the predicted sensitivity obtained with preliminary MC simulations that are not affected by crosstalk. The sensitivity above 500 GeV is worsened by crosstalk effects.

Figure 5.11: Sensitivity of the MAGIC stereo system in 2009. Comparison of preliminary MC simulations (not affected by crosstalk, pink curve) with real data (affected by crosstalk, black curve). The red line shows the sensitivity of MAGIC-I as a standalone system. The sensitivity above 500 GeV is worsened by crosstalk effects.

5.9.1 Crosstalk Test Runs

To investigate the crosstalk effects, test runs with the MAGIC pulse injection system (where a test pulse is injected into the electronic chain at the input of the preamplifier) as well as using the calibration laser where taken. Figure 5.12 illustrates the result of such a crosstalk test run performed with the pulse injection system, where a test pulse was injected in channel 3 of a DRS2 chip. In all other channels of the same chip, perturbation signals show up. Such test runs were taken for all chips and all channels, and with several thousand events each.

5.9.2 Crosstalk Treatment

Based on these test runs, I developed a correction routine to remove the unwanted crosstalk signals and thereby improve the sensitivity. The method comprises the following steps:
5. MAGIC Analysis Chain

1. Define so-called standard perturbation pattern for every channel of the MAGIC-II camera. These patterns describe the expected perturbation caused by an incoming signal in that channel. To smoothen the signals, they are averaged over 5000 runs. Figure 5.12 displays an example.

2. Whenever a signal in a channel exceeds a certain threshold value, the according standard pattern is scaled to the proper peak-height, time-shifted to the proper peak position, and subtracted from all other channels of the same chip. (1-step crosstalk correction)

3. Additionally, I tested a more sophisticated but also more complex method (2-step crosstalk correction). If there are incoming signals in more than one channel of a chip (which is often the case for real data), the measured signals are crosstalk-affected themselves and therefore don’t agree with the true signals. Therefore, an error is made when calculating the time-shift and the scaling factor for the standard pattern. This can be improved if instead of the measured signals the 1-step corrected signals are used to calculate the time-shift and the scaling factor. The correction itself is then applied as in step 2.

Figure 5.12: Crosstalk standard pattern for board 2, chip 3, channel 3. Averaged over 5000 events.
5.9.3 Crosstalk Tests

A correction routine as described in section 5.9.2 should be able to remove a big part of the unwanted signals, if

- Crosstalk is linear (i.e. if crosstalk signals scale linearly with the amplitude of the incoming signal).
- Crosstalk signals add up (i.e. if crosstalk signals of multiple signals in one chip add up linearly).

Therefore, several tests were done before the implementation of the routine.

In order to study the linearity of the crosstalk, the test runs were repeated with test pulses of four different amplitudes. The resulting perturbation patterns were then normalized to the same signal amplitude and compared. As figure 5.13 shows, the normalized patterns agree, which means that crosstalk is linear.

A similar test was performed to study the additivity: Four test pulses were injected to four channels of the same chip simultaneously, and the corresponding standard patterns were subtracted iteratively. As can be seen in figure 5.14, the perturbation signals shrink after every step, meaning that crosstalk signals add up.

An additional test was done to compare the standard patterns of a particular channel for all DRS2 chips. If they would match for all chips, this would simplify the correction routine. As can be seen in figure 5.15, this is not the case. The perturbation caused by a test signal in channel 6 looks different for individual chips, therefore different standard patterns have to be used for the individual chips.

5.9.4 Results and Performance

The correction routine described before was implemented in the MARS programs merpp and callisto, and the performance was tested using a sample from Crab Nebula data including three nights from 13 to 15 November 2009. The result is presented in figure 5.16. After the correction of the crosstalk effect, the achieved sensitivity agrees with the sensitivity obtained by MC simulations that are not affected by crosstalk. Especially in the range above 500 GeV, the achieved improvement is significant.

To test the performance of the crosstalk correction, the number of islands before and after the correction was compared to the number of islands of the MC simulations (see figure 5.17). As expected, there is a large mismatch in the number of islands for large size values before the correction, caused by crosstalk effects. After the 1-step correction and more significantly after the 2-step correction, MC and data agree significantly better.

For the standard analysis, a simplified version of the crosstalk correction applied after the calibration (see section 5.2) and before the image cleaning was used. Thereby, the values of the calibrated charge in each pixel were modified to subtract the effect of the crosstalk.

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6A connected group of pixels after the image cleaning is called an island, see section 5.3
5. MAGIC Analysis Chain

(a) Test pulses with different amplitudes.

(b) Test pulses with different amplitudes, normalized to the same signal amplitude.

Figure 5.13: Crosstalk linearity test: Test runs with different amplitudes (a), normalized to the same signal amplitude (b). The normalized patterns agree.
(a) Standard perturbation caused by signal in channel 1 already subtracted.

(b) Standard perturbation caused by signals in channels 1 and 4 already subtracted.
Figure 5.14: Crosstalk additivity test: Test run with four test pulses injected simultaneously in channels 1, 4, 7, and 10 of a chip. The corresponding standard patterns are subtracted iteratively (a) to (d), whereby the black line indicates the uncorrected signal and the red line shows the corrected signals. After every step, the perturbation signals shrink.

(c) Standard perturbation caused by signals in channels 1, 4, and 7 already subtracted.

(d) Standard perturbation caused by signals in channels 1, 4, 7, and 10 already subtracted.
Figure 5.15: Crosstalk chip scan test: Standard patterns of channel 6 super-imposed for all DRS2 chips. The perturbation caused by a test signal in channel 6 looks different for individual chips, therefore different standard patterns have to be used for the individual chips.

Figure 5.16: Sensitivity of the MAGIC stereo system in 2009. Comparison of preliminary MC simulations (not affected by crosstalk, pink curve) with real data before crosstalk correction (black curve) and after crosstalk correction (1-step correction: dark blue; 2-step correction: bright blue). The red line shows the sensitivity of MAGIC-I as a standalone system. The achieved sensitivity above 500 GeV agrees now with the MC simulations.
Figure 5.17: Number of islands for MC simulations (black dots) and data (red dots) before (a) and after ((b), 1-step correction, (c), 2-step correction) as a function of size. After the crosstalk correction, MC and data match better.
6 Mrk421 Observations in 2010 and 2011 by the MAGIC Telescopes

In this chapter, the results from MAGIC observations of Markarian 421 performed in 2010 and 2011 are reported. Section 6.1 describes the available data set and the data selection. The signal plot and the sky map are presented in section 6.2. The resulting lightcurves and energy spectra are investigated in section 6.3, while section 6.4 presents the investigation of a special flaring episode in May 2010. Section 6.5 performs the search for short intranight variability. All results were obtained using the analysis chain described in chapter 5.

6.1 Data set

6.1.1 Data Selection and Quality Cuts

MAGIC observed Markarian 421 during 78 nights between January and June 2010, and for 21 nights between January and June 2011. The data was taken during dark time, twilight and moonlight, and under different atmospheric conditions like different humidity in the air or varying cloudiness, therefore a data check as described in chapter 5.4 was performed.

For the complete dataset, the values of the mean DC PMT current, cloudiness and number of identified stars were extracted and plotted as a function of the Modified Julian Date, as shown for the 2010 data in figure 6.1. Nights not surviving the cuts in DC current, cloudiness or number of identified stars were removed from the dataset. For the surviving nights, the rate after cleaning was used as an additional quality check. As the atmospheric conditions in winter and summer seasons can be different, the rate cut was applied for three time periods with stable rates: Winter 2010 including January and February 2010, Spring 2010 covering March until June 2010, plus the 2011 data from January to June 2011 (as the conditions were stable for all datataking nights). The rate distributions for the 2010 data are shown in figures 6.2 and 6.3. The corresponding plots for the 2011 data are presented in Appendix C.

6.1.1.1 Optimizing Quality Cuts

In the following it is shown how the quality cuts were found, using as an example the night of 15.1.2010. In a first trial, a cloudiness cut of 50% and a nr. of id. stars cut of 10 was used and the intranight lightcurve shown in 6.4 was calculated in 10-minute-bins. This lightcurve seems to show strong intranight variability with the flux decreasing and increasing again by a factor of \( \approx 50\% \).

Having a closer look, one can see that the atmospheric conditions were rather difficult that night: Figure 6.5 shows the cloudiness parameter as a function of MJD. The cloudiness increases from 30% to more than 40% and then decreases again to \( \approx 20\% \), indicating passing clouds. With the chosen cloudiness cut of 50%, all data survives.

Comparing figures 6.4 with figure 6.5, it’s immediately obvious that the lightcurve varies synchronously with the cloudiness, making it very likely that the observed flux change is due to changing cloudiness and not due to changing flux from the source. If there is a
Figure 6.1: Mean DC PMT current, cloudiness and nr. of id. stars as a function of the Modified Julian Date (MJD) for the 2010 data for MI (blue) and MII (red). One dot corresponds to one star file (≈ 4 min for MII and ≈ 2 min for MI respectively). Data with DC > 1500 nA, cloudiness > 40 or nr. of id. stars < 20 is excluded from the analysis. The corresponding cut-values are indicated by the green horizontal line. The telescopes differ in the DC value as they are equipped with different PMTs, also the nr. of id. stars value can vary because of the different angle of view or differences in the brightness of the Starguider LEDs.
Figure 6.2: Rate distribution for MI and MII from January to February 2010 after cleaning and after removal of nights not passing the quality cuts in DC, cloudiness or nr. of id. stars. The rate is shown after a size cut of 100 phe and geometrically normalized for the zenith angle. Data within the range ±20% (blue (MI) and red (MII) horizontal lines) of the mean rate (green line) is accepted.
Figure 6.3: Rate distribution for MI and MII from March to June 2010 after cleaning and after removal of nights not passing the quality cuts in DC, cloudiness or nr. of id. stars. The rate is shown after a size cut of 100 phe and geometrically normalized for the zenith angle. Data within the range ±20% (blue (MI) and red (MII) horizontal lines) of the mean rate is accepted.
Figure 6.4: The lightcurve for Markarian 421 on 15 January 2010, calculated with data surviving a cloudiness cut of 50% and number of identified stars > 10. One time bin corresponds to 10 minutes. The flux seems to decrease and then increase again by \( \approx 50\% \).

Figure 6.5: The cloudiness parameter as a function of MJD for 15 January 2010. One dot corresponds to one star file (\( \approx 4 \) min for MII and \( \approx 2 \) min for MI respectively). The cloudiness increases from 30% to more than 40% and then decreases again to \( \approx 20\% \). The data points with cloudiness 0% are incorrect measurements. With a cloudiness cut of 50%, all data survives.
cloud in the field of view, the cloudiness increases and the flux decreases. Using these cuts it’s therefore possible to generate fake intranight variability, if the conditions are difficult and changing rapidly like in this night. This illustrates the important and critical role of the datacheck in the analysis.

As one goal of this analysis was the search for intranight variability, it’s obvious that this first choice of cuts was unfavorable and had to be improved. In the final analysis, a cloudiness cut of 40% and a nr. of id. stars of 20 was used. This choice was a compromise between two goals: having enough surviving data for analysing single nights on the one hand, and on the other hand removing as much bad quality data as possible.

6.1.2 Final Data Set

In order to obtain a lightcurve covering as many nights as possible, nights that were completely excluded by the quality cuts were not thrown away but labeled as category-B nights and analyzed using the normal analysis chain. Of course, results gained from these B-nights have to be treated very carefully, thus they are always labeled accordingly. In the following, the data set was separated in three different categories: A, B and C, as explained below:

- **A-nights**: Good quality data that survived the quality cuts.
- **B-nights**: Nights excluded by the quality cuts, but the data is still analyzable.
- **C-nights**: Data can not be analyzed, for example because of missing parameters in the data files or because the data was taken only with one telescope.

Table 6.1 shows how 2010 and 2011 data split up in these categories. In Appendix B, a detailed table with all nights of the dataset, the effective observation time and the corresponding category is given.

<table>
<thead>
<tr>
<th>Category</th>
<th>number of nights</th>
</tr>
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<tbody>
<tr>
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</tr>
<tr>
<td>B</td>
<td>13</td>
</tr>
<tr>
<td>C</td>
<td>8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Category</th>
<th>number of nights</th>
</tr>
</thead>
<tbody>
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<td>A</td>
<td>19</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
</tr>
</tbody>
</table>

2010 2011

Table 6.1: The 2010 (left) and 2011 (right) data divided in A-, B- and C-categories.

6.2 Signal Plot and Skymap

Although in the case of Mrk421 the focus of the analysis is not on the signal search (see section 5.7), the signal plots (figure 6.6) and the skymaps (figure 6.7) were produced for 2010 and 2011 data in order to check the data quality and the analysis chain. A zenith angle cut $\delta < 35^\circ$ was applied. The signal plots were calculated using 1-Off position and with a cut value of $\Theta_{cut}^2 = 0.0107$. As expected, the $\theta^2$-plots confirm strong signals with 126.4 $\sigma$ in 2010 and 42.5 $\sigma$ in 2011. Also in the skymaps, Mrk421 appears with a strong signal.
6. Mrk421 Observations in 2010 and 2011 by the MAGIC Telescopes

(a) 2010

(b) 2011

Figure 6.6: Θ²-plot of Mrk421 data taken in 2010 (a) and 2011 (b) for zenith < 35°. The solid histogram corresponds to the background, while the points with error bars show the signal. The excess events are extracted from the signal region with \( \Theta^2 < \Theta_{\text{cut}}^2 = 0.0107 \) as indicated by the dashed line.

Figure 6.7: Skymap of Mrk421 data taken in 2010 (left) and 2011 (right) for zenith < 35°. The white cross shows the position of Mrk421, the white circle represents the Point Spread Function assumed to produce the skymap. The result is given in test statistics (TS) from [143] equation 17, using a smoothed background model.
6.3 Lightcurves and Spectra

6.3.1 The Lightcurve

Figures 6.8 and 6.9 show the lightcurves of Mrk421 in 2010 and 2011 above 200 GeV in 1-night bins and the corresponding background flux. The background flux is used as a control parameter, as fluctuations in the background flux can be a sign of difficulties in the data or the analysis. A- and B-nights are marked accordingly. Mrk421 was very active in the VHE range in the year 2010, with three major flares up to 3 Crab units (C.U.)\(^1\) in January, March and May, alternating with low flux nights and quiescent periods in April and June. In 2011, during the nights observed with MAGIC, Mrk421 was at low state below 1 Crab unit.

Figure 6.8: The lightcurve of 2010 data in 1-night bins with A- B-category nights and the corresponding background flux (black stars). The dashed pink line marks 1 Crab unit, the dotted pink line represents 10% Crab unit. The two nights marked in green are taken under a special trigger configuration (L1-4NN). Three major flares in January, March and June are indicated in blue.

6.3.2 Lightcurves in Different Energy Ranges

Figure 6.10 shows the 2010 and 2011 lightcurves (only A-category) of Mrk421 for 1-night bins in three different energy ranges: 100-300 GeV (low energy), 300-1000 GeV (medium energy), and 1000-50000 GeV (high energy). The highest flux levels but also the largest error bars are observable in the low energy range, and the lowest flux with smallest error bars in the high energy range. The ratio \( \frac{\text{high energy flux}}{\text{low energy flux}} \) or \( \frac{\text{medium energy flux}}{\text{low energy flux}} \) can be used to quantify the hardness of a fluxpoint, as it will be done in section 6.3.4. All lightcurves show variability, the extent of the variability will be investigated further in section 6.3.5.

\(^1\)Crab is a unit of the flux observed from the Crab Nebula, the standard candle in gamma-ray astronomy.
6. Mrk421 Observations in 2010 and 2011 by the MAGIC Telescopes

The 2010 and 2011 lightcurves (only A-category nights) were calculated on different time-scales: 5-minute bins, 10-minute bins, 1-night bins, 3-night bins and 10-night bins were tested. As an example, the lightcurves in 5-minute, 1-day and 10-day bins including energies from 200-50000 GeV are plotted in figures 6.3.3 for 2010 data and in 6.12 for 2011 data.

It can be seen that the choice of the time bin width plays a crucial role when calculating lightcurves: If the time bin is too wide, features of the lightcurve are sometimes smeared out. This is the case for example for the 2010 lightcurve in 10-day bins (figure 6.11(c)), where flares clearly observable in 1-day bins (figure 6.11(b)) get lost. On the other hand, if the time binning is too small, the individual bins may run out of statistics, as it happens for the 2011 lightcurve in 5-minute bins (figure 6.12(a)). It must also be pointed out that wide time bins may represent very different observation times. For example, individual 10-day bins may contain from 1 up to 10 observation nights, depending on the density of the performed observations. This might become a problem when investigating lightcurves with low sampling density, like the 2011 lightcurve. The effect shows up in figures 6.12(b) and 6.12(c), whereby the 1-day and the 10-days lightcurves for 2011 look very similar. The variability of these lightcurves will be investigated in section 6.3.5.
Figure 6.10: 2010 and 2011 lightcurves (only A-category nights) in three different energy ranges.
Figure 6.11: The 2010 lightcurve (only A-category nights) in different time bins. Flares clearly observable in (a) and (b) are smeared out in (c).
Figure 6.12: The 2011 lightcurve (only A-category nights) in different time bins. In (a), individual bins run out of statistics, and lightcurve and background flux show fluctuations. Because of the low sampling density, the 1-day (b) and the 10-days (c) lightcurves look very similar.
6.3.4 Hardness Calculations

With the lightcurves in different energy ranges illustrated in section 6.3.2, the “hardness” of each fluxpoint was calculated using either the ratio \( \frac{\text{high energy flux}}{\text{low energy flux}} \) or \( \frac{\text{medium energy flux}}{\text{low energy flux}} \) respectively. In figure 6.13 this hardness parameter is displayed as a function of the integrated flux for 2010 and 2011 lightcurves. A trend towards increasing hardness with increasing flux can be observed, although the trend is not very clear as the points are widely scattered and the error bars are large. In the following, a constant and a linear function were fitted to the data. The data were better fitted by a linear relation, supporting the trend towards increasing hardness with increasing flux. The fit results are shown in table 6.2.

![Graphs](image1.png)

Figure 6.13: Hardness of the flux for 2010 ((b),(a)) and 2011 ((d),(c)) data (only A-nights). A constant and a linear fit are tested.

<table>
<thead>
<tr>
<th>Year</th>
<th>Fit</th>
<th>( \chi^2/ndf ).</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010 HE/LE</td>
<td>Constant</td>
<td>4.87</td>
</tr>
<tr>
<td>2010 HE/LE</td>
<td>Linear</td>
<td>2.63</td>
</tr>
<tr>
<td>2010 ME/LE</td>
<td>Constant</td>
<td>3.35</td>
</tr>
<tr>
<td>2010 ME/LE</td>
<td>Linear</td>
<td>1.97</td>
</tr>
</tbody>
</table>

(a) 2010

<table>
<thead>
<tr>
<th>Year</th>
<th>Fit</th>
<th>( \chi^2/ndf ).</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011 HE/LE</td>
<td>Constant</td>
<td>2.50</td>
</tr>
<tr>
<td>2011 HE/LE</td>
<td>Linear</td>
<td>1.00</td>
</tr>
<tr>
<td>2011 ME/LE</td>
<td>Constant</td>
<td>2.88</td>
</tr>
<tr>
<td>2011 ME/LE</td>
<td>Linear</td>
<td>2.10</td>
</tr>
</tbody>
</table>

(b) 2011

Table 6.2: Constant and linear fits of the hardness distribution plotted in 6.13 for 2010 (a) and 2011 (b) data. The data are better fitted by a linear relation, indicating a trend towards increasing hardness with increasing flux.
6.3.5 Variability Calculations

As a parameter to quantify the variability of the source, the fractional variability amplitude \( F_{\text{var}} \) \cite{148} \cite{149} \cite{150} is used. It corrects for the effects of measurement noise and is defined as follows:

\[
F_{\text{var}} = \sqrt{S^2 - \frac{\sigma^2_{\text{err}}}{x^2}} 
\]  (6.1)

\[
S^2 = \frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})^2 
\]  (6.2)

\[
\frac{\sigma^2_{\text{err}}}{x^2} = \frac{1}{N} \sum_{i=1}^{N} \sigma^2_{\text{err},i} 
\]  (6.3)

with \( \bar{x} \) the squared mean flux, \( S^2 \) the variance and \( \frac{\sigma^2_{\text{err}}}{x^2} \) the mean square error of the flux points. According this definition, \( F_{\text{var}} = 0 \) for a stable source. Accounting for the effect of flux measurement errors, the error of \( F_{\text{var}} \) can be estimated according \cite{150}

\[
\Delta F_{\text{var}} = \left( \frac{\sigma^2_{\text{err}}}{x^2 F_{\text{var}}} \right)^2 + \left( \frac{1}{x^2} \sqrt{\frac{\sigma^2_{\text{err}}}{N}} \right)^2 
\]  (6.4)

The fractional variability amplitude \( F_{\text{var}} \) was calculated for the lightcurves in different timescales, as presented in section 6.3.3, in the energy range 200-50000 GeV. The resulting values are listed in table 6.3 and displayed in figure 6.14. As expected, the \( F_{\text{var}} \) value is higher for the 2010 than for the 2011 lightcurves, with larger errors in 2011 because of the higher flux uncertainties. For 2010 data, the \( F_{\text{var}} \) distribution is not compatible with a constant fit (\( \chi^2/\text{ndf}=21.77 \)), and the lightcurves show larger \( F_{\text{var}} \) values for shorter time bins. In contrast, the 2011 \( F_{\text{var}} \) distribution is constant within error bars (\( \chi^2/\text{ndf}=0.30 \)). This may indicate that the sampling of the 2011 lightcurve was not dense enough to compare different time bins, or that the variability was in general low at all timescales.

Figure 6.14: \( F_{\text{var}} \) values for the Mrk421 lightcurves in different time bins for 2010 (a) and 2011 (b). A constant function was fitted to the data (red line). For 2010 data, a trend towards higher variability for shorter time bins can be observed. For 2011 data, the variability remains constant within error bars for all time bins. This may indicate that the sampling of the 2011 lightcurve was not dense enough to compare different time bins.
Table 6.3: The fractional variability amplitude $F_{\text{var}}$ for the 2010 and 2011 lightcurve on different timescales.

<table>
<thead>
<tr>
<th>Time bin</th>
<th>$F_{\text{var}}$ 2010</th>
<th>$\Delta F_{\text{var}}$ 2010</th>
<th>$F_{\text{var}}$ 2011</th>
<th>$\Delta F_{\text{var}}$ 2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 min</td>
<td>0.62</td>
<td>0.01</td>
<td>0.47</td>
<td>0.03</td>
</tr>
<tr>
<td>10 min</td>
<td>0.59</td>
<td>0.01</td>
<td>0.48</td>
<td>0.03</td>
</tr>
<tr>
<td>1 night</td>
<td>0.55</td>
<td>0.01</td>
<td>0.51</td>
<td>0.03</td>
</tr>
<tr>
<td>3 nights</td>
<td>0.54</td>
<td>0.01</td>
<td>0.49</td>
<td>0.03</td>
</tr>
<tr>
<td>10 nights</td>
<td>0.51</td>
<td>0.01</td>
<td>0.50</td>
<td>0.03</td>
</tr>
</tbody>
</table>

The same was done for lightcurves calculated in different energy ranges, as displayed in section 6.3.2, in 1-night time bins. As the results in table 6.4 and figure 6.15 show, the variability slightly increases with the energy. The $F_{\text{var}}$ value reaches a maximum value of 0.62 for the 2010 lightcurve and 0.59 for the 2011 lightcurve in the high energy range that includes energies between 1000 and 50000 GeV. For both years, the $F_{\text{var}}$ distribution is not compatible with a constant fit. It results in $\chi^2/ndf=6.12$ for 2010 and $\chi^2/ndf=4.50$ for 2011.

Figure 6.15: $F_{\text{var}}$ values for the Mrk421 lightcurves in different energy ranges for 2010 (a) and 2011 (b). A constant function was fitted to the data (red line). For both years, a trend towards higher variability for higher energies can be observed.

Table 6.4: The fractional variability amplitude $F_{\text{var}}$ for the 2010 and 2011 lightcurve in different energy ranges.

<table>
<thead>
<tr>
<th>Energy range</th>
<th>$F_{\text{var}}$ 2010</th>
<th>$\Delta F_{\text{var}}$ 2010</th>
<th>$F_{\text{var}}$ 2011</th>
<th>$\Delta F_{\text{var}}$ 2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>100-300 GeV (Low Energy)</td>
<td>0.48</td>
<td>0.04</td>
<td>0.38</td>
<td>0.03</td>
</tr>
<tr>
<td>300-1000 GeV (Medium Energy)</td>
<td>0.56</td>
<td>0.013</td>
<td>0.50</td>
<td>0.03</td>
</tr>
<tr>
<td>1000-50000 GeV (High Energy)</td>
<td>0.62</td>
<td>0.02</td>
<td>0.59</td>
<td>0.09</td>
</tr>
</tbody>
</table>
6.3.6 The Spectrum

In figure 6.16, the unfolded overall spectral energy distributions (SEDs) for the 2010 and 2011 datasets are presented. For the unfolding, the Bertero Method (see chapter 5.8) was used. In the more active year 2010, the flux was higher and the spectrum harder. Three different functions were tried to fit the SEDs: a pure power law \( (f_0 \cdot (E/r)^\alpha) \), a curved power law \( (f_0 \cdot (E/r)^\alpha + b \cdot \log_{10}(E/r)) \) and a power law with cutoff \( (f_0 \cdot (E/r)^\alpha \cdot \exp(-E/E_0)) \). The fit details are listed in tables 6.5 and 6.6. The power law with cutoff is favored over the curved power law and even more clearly over the simple power law.

\[
\frac{E^2 \cdot dN/dE}{dN/dE} \quad \text{after correlated fit}
\]

(a) SED for the combined 2010 dataset: Pure power law fit.

(b) SED for the combined 2011 dataset: Pure power law fit.

(c) SED for the combined 2010 dataset: Curved power law fit.

(d) SED for the combined 2011 dataset: Curved power law fit.

(e) SED for the combined 2010 dataset: Power law with cutoff.

(f) SED for the combined 2011 dataset: Power law with cutoff.

Figure 6.16: SED’s for the combined 2010 ((a),(c),(e)) and 2011 ((b),(d),(f)) datasets. Three fit functions were tested, the datapoints used for the fit are marked in red. The power law with cutoff is favored over the curved power law and over the simple power law.
6.4 May Flare

6.4.1 Analysis of L14NN and Moon Data

During the period from 16 to 20 May 2010 Mrk421 showed a flaring episode with the flux twice reaching \( \approx 2.5 \) C.U., going back to 1 C.U. or even less in between. While the flaring episode in January 2010 was investigated by Burkhard Steinke (MPI Munich) as part of his PhD thesis, and the flaring episode in March is being studied by Shangyu Sun (MPI Munich) in the context of his thesis, the flaring episode in May has not been studied in detail before. The analysis of this data was however not straight forward and required further investigation.

- In the night of the first flare on 18 May, a special trigger configuration was used for technical tests, the so-called L1-4NN configuration (see chapter 4). The MAGIC standard trigger [151] consists of three levels, whereof in the second step a next neighbor (NN) logic is applied. While in the standard operation 3NN pixels are required to fire this trigger level, the setting on this night was 4NN. In order to analyse this 4NN data, a special RF (see Appendix E.2) was built with corresponding MC files and Off data of the same trigger configuration. To test this 4NN-RF, a Crab sample including only 4NN-data was then analyzed (see Appendix F.3). The resulting SED is plotted in figure 6.17. It agrees well with the SED calculated with the standard, good quality Crab sample (see Appendix F).

- In the second flare night on 20 May, the moon was present. The data of this night was excluded by the quality check described in section 6.1.1, as the DC current was always between 2000 and 3000 nA. In order to find out if the standard analysis chain can handle this moon data sufficiently enough, an additional Crab sample including
only data taken under moonlight conditions (1500 nA < DC < 3000 nA) was set up (see Appendix F.4). As a size cut of 150 phe was applied, the SED was calculated for energies above 150 GeV (figure 6.17). The obtained moon data SED agrees well with the standard Crab SED. At energies above \( \approx 1000 \) GeV, the moon data SED is slightly lower than the standard Crab SED, but still the data points agree within error bars.

![SED for Crab](image)

Figure 6.17: SED for Crab calculated with three different data samples: good quality data sample (red), data taken under moonlight conditions (blue), data taken with a special trigger configuration (green).

### 6.4.2 Flaring Episode Lightcurve

Using the special analysis chain for the data of 18 May and applying a size cut of 150 phe for the data of 20 May, the flaring period was analyzed. Figure 6.18 illustrates the lightcurve with the particular nights separated in flare and adjacent periods. In the two flare nights, the flux reaches \( \approx 2.5 \) C.U. The night of 19 May is marked as B-quality, as data with DC current 1500 nA < DC < 1600 nA was not excluded for this analysis, in order to improve the statistics.

### 6.4.3 SED of Flares and Adjacent Periods

For the individual periods, the SED’s were calculated and fitted with a simple power law \( (dF/dE = f_0 \ast (E/r)^\alpha) \) above 300 GeV. The simple power law fit was chosen as it allows to compare directly the indices of the power law. The unfolded SED’s are presented in figure 6.19, with the corresponding parameters of the power law function listed in table 6.7.

The resulting fit parameters show that the flaring episodes have slightly smaller spectral indices than the nights before and in between the flares, corresponding to a harder energy spectrum, but the differences between the indices are small and the error bars are large.
6. Mrk421 Observations in 2010 and 2011 by the MAGIC Telescopes

Figure 6.18: Lightcurve and background of flaring period in May 2010. Flaring (F1, F2) and adjacent (P1, P2) periods are marked, data points are plotted in red (A-quality night), green (4NN night) and blue (B-quality night).

Figure 6.19: SEDs for flares and adjacent periods in May 2010. A pure power law is fitted to the data above 200 GeV. The spectra of the flaring nights are harder than the nights before and in between the flare, but the differences between the spectral indices are small.

Table 6.7: Parameters for the pure power-law fit to the flares (F1, F2) and adjacent periods (P1, P2) in May 2010.
6.5 Search for Intranight Variability

Mrk421 is known to show very fast flux variations in the TeV range, with doubling times down to 15 [93], [95] or 10 [152] minutes. The duration of these short intranight flares imposes restrictions related to the size and velocity of the emission region, therefore it is essential to search for intranight flares. In night-by-night lightcurves, short flickering is however smeared out, thus it is necessary to have a closer look at the intranight lightcurves.

6.5.1 Search Procedure

In order to be sensitive to variations on different timescales, the intranight lightcurves for all A-category nights were calculated in bins of 10, 5 and 2 minutes, an example is plotted in figure 6.20. The signal and the background of these intranight lightcurves was then fitted with a constant function and the $\chi^2/\text{ndf}$ was calculated for signal and background. Nights with a high $\chi^2/\text{ndf}$ in the signal but moderate $\chi^2_{\text{bg}}/\text{ndf}$ in the background, are candidates for intranight variabilities. The $\chi^2_{\text{bg}}/\text{ndf}$ is thereby used as control parameter, as high values of $\chi^2_{\text{bg}}/\text{ndf}$ indicate background fluctuations and are therefore a sign for difficulties with the data or the analysis. Based on experience, a cut value of $\chi^2/\text{ndf} > 3$ for the constant fit to the signal and $\chi^2_{\text{bg}}/\text{ndf} \leq \chi^2/\text{ndf}$ was chosen. Figures 6.21 and 6.22 show scatter plots of the $\chi^2$ of the signal versus the $\chi^2$ of the background for the three time binnings. Additionally, the nights with the highest flux levels were added to the list of candidates. In table 6.9 all candidate nights are listed.

<table>
<thead>
<tr>
<th>Night</th>
<th>Candidate because...</th>
</tr>
</thead>
<tbody>
<tr>
<td>20100108</td>
<td>High $\chi^2/\text{ndf}$ in 10-min binning</td>
</tr>
<tr>
<td>20100111</td>
<td>High flux</td>
</tr>
<tr>
<td>20100114</td>
<td>High $\chi^2/\text{ndf}$ in 5-min and 2-min binning; high flux</td>
</tr>
<tr>
<td>20100115</td>
<td>High $\chi^2/\text{ndf}$ in 10-min and 2-min binning; high flux</td>
</tr>
<tr>
<td>20100119</td>
<td>High $\chi^2/\text{ndf}$ in 10-min and 5-min binning; high flux</td>
</tr>
<tr>
<td>20100120</td>
<td>High flux</td>
</tr>
<tr>
<td>20100123</td>
<td>High $\chi^2/\text{ndf}$ in 10-min binning</td>
</tr>
<tr>
<td>20100206</td>
<td>High $\chi^2/\text{ndf}$ in 10-min binning; high flux</td>
</tr>
<tr>
<td>20100211</td>
<td>High $\chi^2/\text{ndf}$ in 5-min binning</td>
</tr>
<tr>
<td>20100311</td>
<td>High flux</td>
</tr>
<tr>
<td>20100318</td>
<td>High $\chi^2/\text{ndf}$ in 10-min and 5-min binning</td>
</tr>
<tr>
<td>20100418</td>
<td>High $\chi^2/\text{ndf}$ in 10-min, 5-min and 2-min binning</td>
</tr>
<tr>
<td>20100530</td>
<td>High $\chi^2/\text{ndf}$ in 5-min binning</td>
</tr>
<tr>
<td>20110604</td>
<td>High $\chi^2/\text{ndf}$ in 10-min and 5-min binning</td>
</tr>
</tbody>
</table>

Table 6.8: List of all 14 candidates for intranight variability.

These 14 candidate nights were then investigated more closely to find out if they include intranight variability. To do so, the lightcurves were inspected by eye, and also the weather and observational conditions were checked. Special attention had to be paid to fast changing weather conditions like passing clouds, because they can, as demonstrated in section 6.1.1.1, produce fake variability. Such nights were therefore excluded from the search for intranight variability. Likewise excluded were nights with holes in their lightcurve. Such holes could arise when part of the data is excluded during the datacheck, or if the observation during the night is stopped and later started again. Also nights with very low
Figure 6.20: The intranight lightcurve of 18 April 2010 in three different time bins: 10, 5 and 2 minutes. A constant function is fitted to the signal and the background, and the $\chi^2/ndf$ is calculated. In this example, the $\chi^2/ndf$ of the signal is high compared to the $\chi^2/ndf$ of the background in all time binnings, so the night is a candidate for intranight variability.
Figure 6.21: The $\chi^2/\text{ndf}$ of the straight-line fit to the signal versus the $\chi^2_{bg}/\text{ndf}$ of the straight-line fit to the background for three different time binnings for 2010 nights. Nights with $\chi^2_{s}/\text{ndf} > 3$ and $\chi^2_{bg}/\text{ndf} \leq \chi^2_{s}/\text{ndf}$ (area marked in red) are candidates for intranight variability (red marks).
Figure 6.22: The $\chi^2_{s}/ndf$ of the straight-line fit to the signal versus the $\chi^2_{bg}/ndf$ of the straight-line fit to the background for three different time binnings for 2011 nights. Nights with $\chi^2_{s}/ndf > 3$ and $\chi^2_{bg}/ndf \leq \chi^2_{s}/ndf$ (area marked in red) are candidates for intranight variability (red marks).
significance in the lightcurve bins, for example when the flux was very low, were excluded from the set, as they can show large fluctuations. An example of an excluded candidate night is the night of 11 February 2010. As can be seen in figure 6.23, the straight line fit to its lightcurve resulted in high $\chi^2/\text{ndf}$. A closer look at the cloudiness parameter indicates that the high and varying cloudiness caused fluctuations and holes in the lightcurves.

Table 6.9 presents the result of this investigation for all candidate nights. Two observation nights of 6 February 2010 and 18 April 2010 fulfilled the criteria (good weather conditions, no holes in the lightcurve and sufficient significance in the lightcurve bins), and are investigated more closely in the following.

![Lightcurve and BG estimate evolution](chart1.png)

(a) Lightcurve of 11 February 2010 in 5-minute bins.

![Cloudiness of 11 February 2010](chart2.png)

(b) Cloudiness of 11 February 2010.

Figure 6.23: The intranight lightcurve from 11 February 2010 in 5-minute bins (a) that results in high $\chi^2/\text{ndf}$ of the straight-line fit to the signal (see table 6.9). The corresponding plot of the cloudiness parameter (b) reveals high and fast changing cloudiness, resulting in holes and fluctuations of the lightcurve.
### Flare Analysis

#### Flare of 6 February 2010

During the night of 6 February 2010, MAGIC observed Mrk421 for 40 minutes under good weather conditions. The average flux of Mrk421 was $\approx 2$ C.U., with a $\chi^2$ probability of 6% for a constant function fit. At the beginning of the observation, the flux of Mrk421 was at $\approx 1$ C.U., increasing then to a level of almost 3 C.U before decreasing again (figure 6.24).

To fit the lightcurve, a flare model used in [152] and [153] was applied. It assumes a rapid flare with exponential rise and fall times on top of a stable background flux:

$$F = F_{\text{baseline}} + \frac{a}{2} \left( \frac{t-t_0}{\tau_{\text{rise}}} + \frac{t-t_0}{2\tau_{\text{fall}}} \right)$$  \hspace{1cm} (6.5)

with the free parameters $F_{\text{baseline}}$, the rise and fall time constants $\tau_{\text{rise}}$ and $\tau_{\text{fall}}$, the flare amplitude $a$ and the flare maximum time $t_0$. The resulting fit function is plotted in figure 6.24. It results in a $\chi^2/ndf$ of 13.68/17 and a $\chi^2$ probability of 69%, which means that the chosen fit function describes the flare well. The fit parameters are listed in table 6.10.

The obtained rise time of $9.51 \pm 8.20$ minutes is comparable to values found in the literature. Gaidos et al. [93] reported a flare with a doubling time < 15 minutes on the night of 15 May 1996. A flare with a doubling of $21 \pm 2$ minutes that occurred on the night of 22 March 2001 was studied by Aharonian et al. [95]. Wagner et al. [152] analyzed the flare rise and fall times in a sample containing 56 nights, and reported typical rise and fall doubling times of about 20-30 minutes, with the shortest detected rise and fall doubling times $\approx 10$ minutes.

However, the error of the obtained rise time is quite large, as the individual time bins run out of statistics.

#### Flare of 18 April 2010

The Mrk421 observation time on 18 April 2010 was $\approx 1$ hour, the weather conditions were good. The flux varied between $\approx 3$ C.U. and 0.5 C.U., with a mean flux of $\approx 1$ C.U.
6. Mrk421 Observations in 2010 and 2011 by the MAGIC Telescopes

Figure 6.24: Lightcurve of 6 February 2010 in 2-minute bins. The fit function describes a flux variation on top of a stable emission (see text for explanation).

<table>
<thead>
<tr>
<th>Night</th>
<th>Fit function</th>
<th>Fit prob.</th>
<th>$\chi^2/ndf$</th>
<th>$t_0$ [MJD]</th>
<th>$\tau_{\text{rise}}$ [min]</th>
<th>$\tau_{\text{fall}}$ [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010/02/06</td>
<td>1 Flare</td>
<td>69%</td>
<td>13.68/17</td>
<td>55233.11</td>
<td>9.51 ± 8.20</td>
<td>6.95 ± 8.70</td>
</tr>
<tr>
<td>2010/02/06</td>
<td>Constant</td>
<td>6%</td>
<td>30.84/20</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.10: Fit parameters for the flare of 6 February 2010. The fit function is described in the text (equation 6.5).

The probability for a constant value fit is almost zero. The choice of a good fit function is however difficult for this night, as the rising edge of the main flare is not covered by the observation time. Several fit functions were tested:

- A fit function describing only the falling edge of the flare

  $$ F = F_{\text{baseline}} + \frac{a}{t - t_0} \frac{1}{\tau_{\text{fall}}} $$  

  results in a $\chi^2/ndf$ of 64.16/28 and a $\chi^2$ probability of 0.01%, which means that the function doesn’t fit the data well (figure 6.25(a)).

- The fit function described in equation 6.5 was also tested (figure 6.25(b)). With a $\chi^2/ndf$ of 54.81/27 and a $\chi^2$ probability of 0.12%, this function doesn’t fit the data very well either.

- Additionally, fit functions describing several flares on top of a stable emission according to [153] were tested

  $$ F = F_{\text{baseline}} + \frac{a}{t - t_0} \frac{1}{\tau_{\text{rise}}} + \frac{a_2}{t - t_0} \frac{1}{\tau_{\text{rise}}^2} + \frac{a_3}{t - t_0} \frac{1}{\tau_{\text{rise}}^3} + \cdots $$  


The resulting fits are plotted in figure 6.25(c) for 2 Flares and in figure 6.25(d) for 3 flares on top of a stable emission. With a $\chi^2/ndf = 34.62/24$ and a fit probability of 7.42% for a fit with two flares and a $\chi^2/ndf = 26.4/21$ and a fit probability of 19.14% for three flares, these functions describe the data better. However they should be regarded with great caution. Especially the fit function describing three flares is very sensitive to statistical fluctuations, and the derived very short rise and fall times for the second and third flares in the order of 1 minute are unreliable.

The parameters of all tested fit functions are listed in table 6.11.

<table>
<thead>
<tr>
<th>Night</th>
<th>2010/04/18</th>
<th>2010/04/18</th>
<th>2010/04/18</th>
<th>2010/04/18</th>
<th>2010/04/18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit function</td>
<td>Falling edge</td>
<td>1 Flare</td>
<td>2 Flares</td>
<td>3 Flares</td>
<td>Constant</td>
</tr>
<tr>
<td>Fit prob</td>
<td>0.01%</td>
<td>0.12%</td>
<td>7.42%</td>
<td>19.14%</td>
<td>0%</td>
</tr>
<tr>
<td>$\chi^2/ndf$</td>
<td>64.16/28</td>
<td>54.81/27</td>
<td>34.62/24</td>
<td>26.4/21</td>
<td>102/30</td>
</tr>
<tr>
<td>$t_{01}$ [MJD]</td>
<td>55303.951</td>
<td>55303.957</td>
<td>55303.956</td>
<td>55303.956</td>
<td></td>
</tr>
<tr>
<td>$\tau_{rise1}$ [min]</td>
<td>3.95 ± 1.94</td>
<td>6.28 ± 5.86</td>
<td>7.80 ± 6.92</td>
<td>0%</td>
<td></td>
</tr>
<tr>
<td>$\tau_{fall1}$ [min]</td>
<td>7.28 ± 1.61</td>
<td>3.57 ± 0.77</td>
<td>7.21 ± 2.94</td>
<td>8.15 ± 3.02</td>
<td>0%</td>
</tr>
<tr>
<td>$t_{02}$ [MJD]</td>
<td>55303.986</td>
<td>55303.98065</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau_{rise2}$ [min]</td>
<td>2.52 ± 2.56</td>
<td>0.72 ± 0.42</td>
<td>0%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau_{fall2}$ [min]</td>
<td>7.61 ± 4.09</td>
<td>0.19 ± 0.41</td>
<td>0%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t_{03}$ [MJD]</td>
<td>55303.985</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau_{rise3}$ [min]</td>
<td>1.54 ± 0.85</td>
<td></td>
<td>0%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau_{fall3}$ [min]</td>
<td>0.87 ± 4.72</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.11: Parameters of the different fit functions to the flare of 18 April 2010. The fit functions are described in the text.

6.5.2.3 Constraints on the Emitting Region

The search for and investigation of short flux variations as illustrated in figures 6.24 and 6.25 are an important part of TeV blazar research, as they yield information about the emitting region. The most common model describing the emission in such objects is the so-called homogeneous synchrotron self-Compton (SSC) model (see chapter 2.3.1). This model assumes a single population of highly relativistic electrons that are injected in a spherical zone in the jet, where they cool by emitting synchrotron radiation and by the inverse Compton process. The emission zone is relativistically moving under a small angle $\theta$ to the observer’s line of sight.

If the spectrum of the relativistic electrons is assumed to be a broken power law, the SSC model is completely described by seven parameters [154], including the magnetic field intensity, the radius and Doppler factor of the emitting region and four parameters describing the electron spectrum. Six observable quantities that have to be described by the seven-parameter model can, at least in principle, be derived from the multiwavelength SED. In reality, the available data describing the SED is limited and the uncertainties are large.

To determine the last parameter, a seventh observable quantity is needed: the minimum timescale of variation $t_{var}$. It is directly linked to the radius and the Doppler factor of the emission region via a causality constraint: The observed variability in the flux level cannot
Figure 6.25: Lightcurve of 18 April 2010 in 2-minute bins. Different fit functions are tested (see text for explanation).
be shorter than the time needed by light to travel along the radius of the emission region. This leads to the formula [93]:

$$R \leq \frac{ct_{var}\delta}{(1+z)}$$

(6.8)

with $t_{var}$ the minimum timescale of variation, $\delta$ the Doppler factor of the emission region, $c$ the speed of light and $z$ the redshift.

Assuming the Schwarzschild radius of the central black hole as the smallest, most-natural size of the system [155], this formula can be used to derive a lower limit of the Doppler factor $\delta$ out of the obtained variability timescales, even without knowledge of the SED. To find a conservative approximation, only the doubling time obtained from the flare of 6 February 2010 is used, as the fit to the lightcurve of 18 April 2010 can not be clearly determined. With $c = 3 \times 10^5 \text{ km/s}$, $z = 0.0308$ for Mrk421 and a doubling time of $t_{var} \approx 9.51 \text{ minutes}$ one finds $R \leq 1.66 \cdot \delta \cdot 10^8 \text{ km}$. Estimates for the mass of the supermassive black hole in Mrk 421 range from $M_{M\text{rk421}} \approx 2 \cdot 10^8 M_\odot$ to $M_{M\text{rk421}} \approx 9 \cdot 10^8 M_\odot$ [156] [157]. With $M_{M\text{rk421}} \approx 2 \cdot 10^8 M_\odot$ as a lower limit and $R_S = 2GM/c^2 \approx 3kmM/M_\odot$ the event horizon of the black hole, one finds $\delta > 3.6$.

This is a moderate lower limit compared to values of $\delta$ up to $\approx 50$ found in the literature [79] [158], where the SED of the source was modeled with leptonic and hadronic models. The high Doppler factors obtained with these models are also important to avoid strong gamma-gamma absorption in the SSC model. However, they are in disagreement with the relatively slow apparent speed of shocks on parsec scale, as measured with the Very Long Baseline Array (VLBA) that imagines the radio emission from relativistic jets [159].

To resolve this contradiction, different and more complex models than the SSC model have been proposed: One proposed solution is that the jet decelerates along its length [160], an alternative is a jet with a complex velocity structure [161], [162]. Also jets with toroidal or helical B fields [163] could provide explanations.

### 6.6 Summary

In this chapter, the behavior of Mrk421 in the years 2010 and 2011 observed by the MAGIC telescopes was studied. As in previous years, Mrk421 proved to be variable, with flux states up to three Crab units in 2010, and a general low flux state always below one Crab unit in 2011. Trends for increasing hardness with increasing flux level could be found in the data, corresponding with earlier observations for example by the Whipple and the HEGRA telescopes.

The search for short intranight variabilities was performed systematically, and revealed two nights clearly showing short time variability. One of these observations covers the complete flare including rising and falling edge. The corresponding rise time of $\approx 10$ minutes is compatible with the shortest rise time values found in the literature for Mrk421.
7 Multiwavelength Results

Mrk421 is known to emit photons over a wide energy range from radio to TeV, with a highly variable flux in all energy bands. Simultaneous observations in different energy bands may give a more complete picture of the source, and allow to learn more about the processes that are driving the emission. In the following, the results of two additional telescopes were combined with the MAGIC results: The KVA (Kungliga Vetenskapliga Academy) telescope located at La Palma has observed Mrk421 in the optical R-band, while the Fermi Gamma-ray Space telescope investigated the source at energies between 30 MeV and 300 GeV. To put the three energy ranges in context, they are marked in figure 7.1 that displays the spectral energy distribution of Mrk421 taken during an extensive multiwavelength campaign in 2009 [79].

![Spectral energy distribution of Mrk421](image)

Figure 7.1: Spectral energy distribution of Mrk421 taken during a multiwavelength campaign in 2009. The energy bands observed by KVA, Fermi and MAGIC are marked. Adapted from [79].

7.1 The Fermi Gamma-Ray Space Telescope

The Fermi Gamma-ray Space Telescope [52] (figure 7.2), formerly Gamma-ray Large Area Space Telescope (GLAST), is a space-based gamma-ray observatory. It was launched 11 June 2008, and travels in a low-earth circular orbit at an altitude of 550 km with a period of 95 minutes. On board the Fermi telescope are two scientific instruments, the Gamma-ray Burst Monitor (GBM), looking for sudden rays of gamma flares at keV energies, and the Large Area Telescope (LAT) [164] that provided the data used in this chapter.
The LAT is an imaging gamma-ray detector providing data in the energy range from about 20 MeV up to 300 GeV, with decreasing sensitivity above 30 GeV. This allows for blazars like Mrk421 an overlap between Fermi and MAGIC observations (figure 7.1). Opposite to Cherenkov Telescopes, Fermi LAT is characterized by a wide field of view of about 60° from the instrument axis corresponding to 20% of the sky. The LAT is pointed upwards by Fermi all the time so that the earth doesn’t block the view. The instrument axis rocks 35° north for one orbit, then 35° south for one orbit. In doing so, the LAT surveys the entire sky every two orbits (every three hours). Depending on the energy, the angular resolution is about 3° at 100 MeV and 0.04° at 100 GeV.

As gamma-rays at these high energies can’t be focused using mirrors or lenses, a technique similar to that used in detectors for high-energy particle accelerators is applied. Incoming gamma-rays hit thin metal foils, where they produce an electron and a positron in a pair...
production process. As these charged particles move on, they leave ionization tracks in thin silicon strip detectors, which allows to determine their path. After passing this tracker, the particles energy is measured in a cesium iodide calorimeter. In total, 16 modular towers as shown in figure 7.3, each 37 cm square and 66 cm tall, are used for the LAT. Additionally, a thin plastic anticoincidence detector around the outside allows to distinguish between charged cosmic rays and gamma-rays. In combining the information from the tracker, calorimeter and anticoincidence detector, the energy and the direction of the incoming gamma-rays can be determined.

The data obtained by LAT is freely available, along with standard analysis software from NASA’s Fermi Science Support Center [165]. All Fermi results presented in this chapter were analyzed by Dorothee Hildebrand, ETH Zurich.

7.2 The KVA Optical Telescope

KVA (Kungliga Vetenskapsakademien, Royal Swedish Academy of Sciences) is a 35 cm optical telescope [166] located on the Roque de los Muchachos at the canary island La Palma (figure 7.4), operated remotely by the Tuorla Observatory in Finland [167]. It is mainly used for long-term monitoring of blazars and optical support observations for the MAGIC telescopes. The observations are done in the R-band, and the fluxes are determined using calibration stars in the same CCD frame as the object. From the observed flux, the host galaxy contribution has to be subtracted. The lightcurves presented in this chapter were provided by the Tuorla group [168].

![Figure 7.4: The KVA building at La Palma. Image credit: R. Rekola.](image)

7.3 Results

7.3.1 Lightcurve Correlation

Blazars like Mrk421 show variability all across the electromagnetic spectrum, it’s therefore of special interest to compare the lightcurves obtained with different instruments and in different energy bands. The Mrk421 lightcurves for 2010 and 2011 respectively were calculated in 1-night bins for MAGIC and KVA and in 3-night bins for Fermi. The choice
of the bin size is crucial, as a tradeoff has to be made between a good resolution of the lightcurve and the need for enough statistics per bin. The choice of a 3-nights binning for Fermi is a good compromise, but still the error bars are significantly larger than for KVA and MAGIC. The resulting lightcurves are presented in figures 7.5 and 7.6. The VHE and optical lightcurves show opposite behavior in 2010 and 2011. While Mrk421 was very active in the VHE range and showed low optical flux in 2010, its VHE flux was low in 2011 and the optical flux was high and variable. The HE flux measured by Fermi was similar in both years.

The relationship between different energy bands can be examined in different ways. One possibility is the use of so-called **flux-flux correlation plots**. These plots are produced by pairing flux points within a certain time window. These flux-flux pairs are then normalized by dividing each flux value by the mean of that energy band, and filled in a scatter plot. Trends in such scatter plots can be a sign of correlation in the two investigated emission bands.

As a more formal method to investigate the correlation between different energy bands is the so-called **discrete correlation function (DCF)** introduced in [169]. The DCF allows to find correlation between two different data trains $a_i$ and $b_j$. It is defined as follows: For all measured flux point pairs $(a_i, b_j)$ associated with the pairwise lag $\Delta t_{ij} = t_i - t_j$, an unbinned discrete correlation is calculated:

$$ UDCF_{ij} = \frac{(a_i - \bar{a})(b_j - \bar{b})}{\sqrt{\sigma_a^2 - \bar{e}^2_a}(\sigma_b^2 - \bar{e}^2_b)} $$

with $\bar{f}$ the mean of the data series $f$, $\sigma_f$ its standard deviation and $\bar{e}_f$ the corresponding measurement error.

Averaging over the $N$ pairs for which the corresponding $\Delta t_{ij}$ fall in the time bin centered on the time lag $\tau$ with the bin size $\Delta \tau$, i.e. $\tau - \Delta \tau/2 \leq \Delta t_{ij} < \tau + \Delta \tau/2$, gives the function $DCF(\tau)$:

$$ DCF(\tau) = \frac{1}{N} \sum UDCF_{ij}. $$

A positive value of $DCF$ at a certain time lag $\tau$ indicates a possible correlation between the two time series $a_i$ and $b_j$ at this time lag, whereas a negative value may suggest a possible anti-correlation.

The standard error of the DCF is then calculated using

$$ \sigma_{DCF}(\tau) = \left( \sum [UDCF_{ij} - DCF(\tau)]^2 \right)^{1/2}. $$

### 7.3.1.1 MAGIC-Fermi Correlation

As figure 7.1 illustrates, observations by Fermi and MAGIC describe the high-energy peak of the SED of Mrk421. Fermi observations characterize the ascending slope, while MAGIC investigates the descending slope. Correlation studies between Fermi and MAGIC will therefore provide information about the behavior of this high-energy peak at different flux states. If the lightcurves are correlated, this may indicate a shift of the complete high-energy peak towards higher flux at flaring state. Anticorrelation on the contrary may be caused by a shift of the high-energy peak towards higher energy. The lack of correlation may imply a hardening of the descending slope observed by MAGIC, while the ascending slope remains unchanged.
Figure 7.5: 2010 lightcurves of Mrk 421 for MAGIC (a), Fermi (b) and KVA (c). While Mrk421 was very active in the VHE range with high flux states, the optical flux was low. The HE flux state was similar in 2010 and 2011. Even with the choice of 3-night binning in the HE range, the error bars are significantly larger.
Figure 7.6: 2011 lightcurves of Mrk 421 for MAGIC (a), Fermi (b) and KVA (c). In 2011, the VHE flux of Mrk421 was low, in contrast to the optical flux that was high. The HE flux measured by Fermi is comparable for 2010 and 2011.
Figure 7.7: Correlation analysis for 2010 data for MAGIC and Fermi in 3-night bins. (a) illustrates the paired normalized flux points, (b) the flux-flux scatter points. A constant and a linear function were fitted to the flux-flux scatter points. The linear function fits the data better, indicating correlation between MAGIC and Fermi.
Figure 7.8: Correlation analysis for 2011 data for MAGIC and Fermi in 3-night bins. (a) shows the paired normalized flux points, (b) the flux-flux scatter points. It’s difficult to make a statement about correlation on the basis of 2011 data, as the data set is small and the VHE flux was low during all year. Nevertheless, a linear function was fitted to the flux-flux scatter plot, resulting in an almost constant function, indicating no correlation.
7. Multiwavelength Results

Figure 7.7 displays the 2010 lightcurve with the paired MAGIC-Fermi flux points and the corresponding flux-flux scatter plot. A bin size of 3 days was chosen in order to get enough statistics for Fermi. The 25 flux-flux points lying within a time window of three days could be used for this analysis. Although the scatter is quite large, an increase in Fermi flux with increasing MAGIC flux is recognizable. The flux-flux scatter plot was fitted with a first degree polynomial. A linear trend with a positive gradient would indicate correlation between MAGIC and Fermi flux points. A \( \chi^2 \) goodness-of-fit of \( \chi^2/ndf = 24.68/23 \) and a \( \chi^2 \) probability of 36.70% for a steepness \( 0.24 \pm 0.10 \) suggests a trend for linearity and therefore correlation between Fermi and MAGIC. However there were some bins with low flux in MAGIC, while the flux in Fermi was high. The constant fit results in a \( \chi^2/ndf = 30.56/24 \) and a \( \chi^2 \) probability of 16.70%, and therefore describes the data worse. The DCF for a time lag \( \tau = 0 \) gives a value of 0.93 ± 0.62, supporting the trend for linearity, but with a large error bar resulting from the large uncertainty in the Fermi lightcurve.

The interpretation of these results has to be taken with care however, as such correlation studies have to handle several difficulties. One of them is the simultaneity of the data: As MAGIC only observes the source for rather short time intervals in the order of 10 minutes up to some hours, only some of the data in each time bin is taken really simultaneously. This problem can not easily be solved because the sensitivity of Fermi is much lower than the sensitivity of MAGIC, so the integration time is much longer. Another difficulty is the limited sampling of the MAGIC lightcurve.

For the 2011 data it’s very difficult to make a statement about the correlation, as the MAGIC sample is small and the flux detected by MAGIC was low at all observed nights. Nevertheless, a linear fit was tried for the 16 flux-flux points. The fit results in an almost constant function with a \( \chi^2/ndf = 16.44/14 \) and a \( \chi^2 \) probability of 28.73%, indicating no correlation. The DCF for a time lag \( \tau = 0 \) gives 0.38 ± 0.70.

7.3.1.2 KVA-MAGIC Correlation

The connection between the optical and the VHE gamma-ray states is not clearly established yet. Several blazars were detected in the gamma-ray regime thanks to observations that were triggered by high optical flux alerts [170], [171], and since the beginning of its observations MAGIC has successfully performed optically triggered target of opportunity (ToO) observations of AGNs. On the other hand it is not clear if the detections triggered by optical emission were just chance occurrences.

In the case of Mrk 421, the optical and the VHE lightcurves in the considered period seem to show opposite trends, as is noticeable in figures 7.5 and 7.6. In 2010, when MAGIC reported several flares and a general high gamma-ray flux, the flux detected by KVA was always low and with only minor flux increases. In contrast, the behavior in 2011 was exactly opposite: While the gamma-ray flux was very low at all observed nights, the optical flux was in general high with several flares.

Nevertheless the correlated lightcurves and the corresponding flux-flux scatter plots were produced for 2010 (7.9) and 2011 (7.10). For 2010, a first degree polynomial was fitted to the 35 flux-flux points. The fit function with a steepness of \( 0.313 \pm 0.009 \) has a very high \( \chi^2/ndf \) of 1264.31/33 with a \( \chi^2 \) probability of almost 0. Nevertheless, the DCF for a time lag \( \tau = 0 \) has a positive value of 0.48 ± 0.19. This result has to be interpreted with care, but it could give a hint that while there is one population of flux-flux points that is not correlated at all and cancels out in the calculation of the DCF, there is a second population that shows a hint for correlation and gives positive DCF values. The constant fit resulted in \( \chi^2/ndf \) of 2735.25/34.

For 2011, the 10 flux-flux points are so widely scattered that no fit function was tested.
7. Multiwavelength Results

Figure 7.9: Correlation analysis for 2010 data for KVA and MAGIC in 1-night bins. (a) displays the paired normalized flux points, (b) the flux-flux scatter points. A constant and a linear function were fitted to the data. The linear function fits the data better, but both fit functions result in high $\chi^2/ndf$. A positive DCF value of $0.48 \pm 0.19$ might indicate a trend for linearity for only part of the flux-flux points.
7. Multimwavelength Results

Figure 7.10: Correlation analysis for 2011 data for KVA and MAGIC in 1-night bins. (a) shows the paired normalized flux points, (b) the flux-flux scatter points. The flux-flux points are so widely scattered that no fit function was tested.
7.3.2 Combined SEDs

Continuous Fermi observations combined with the extensive data set collected by MAGIC, allow to investigate the complete high-energy SED peak and its changes over different time periods or flux states. The simultaneous observation of both the ascending and the descending slope may give a more complete picture of the spectral behavior of Mrk421 at GeV and TeV energies.

The high-energy SED peak measured by Fermi and MAGIC was calculated separately for the 2010 and 2011 datasets, as plotted in Figure 7.11(a) for 2010 and in Figure 7.11(b) for 2011 (blue data points). The different shapes of the 2010 and 2011 SEDs indicate that Mrk421 was in a different state during these two years. In 2010, it showed several flaring episodes and general high flux-state, while in 2011 it was in low state during all observed nights. The question arises, if the 2010 and 2011 SEDs contrast the high state behavior with the low state behavior of the source.

In order to find out, two episodes with the highest and the lowest states respectively were analyzed: January 2010 with an episode of flares, and June 2010 with very low flux during all observed nights. The resulting SEDs (red data points in figure 7.11) support this assumption: The January 2010 and the overall 2010 SEDs (figure 7.11(a)) have the same shape, with the January SED showing slightly higher flux values. It seems that the overall 2010 SED is defined by its flaring episodes, with the January SED illustrating a purer high-state SED. The MAGIC SED excluding the January data results in a significantly lower flux, as indicated by the yellow data points. Figure 7.11(b) shows the low state of the source in 2011 and June 2010. The June SED is running out of statistics and is therefore missing data points in the overlap region between Fermi and MAGIC.

A comparison of low (2011) and high state (2010 and January 2010) SEDs is presented in figure 7.12, including also the data points obtained by the KVA telescope and – for completeness – the SED for 2010 excluding January. The SED points obtained by the KVA telescopes remain constant within error bars, as the fluctuations within the individual years are large and therefore the error bars are large. The slope of the Fermi spectrum remains virtually unchanged within error, a behavior that is in agreement with earlier observations mentioned in chapter 2.3.2.2 that showed no change of the Fermi photon index between August 2008 and March 2010 [79].

To investigate the behavior of the high-energy SED peak, a power law with cutoff \( (f_0 \times (E/r)^\alpha \times \exp \left( -E/E_0 \right) ) \) was fitted to the combined Fermi and MAGIC data points in order to describe the position of the cutoff energy for different flux states. Thereby, the lowest
energy MAGIC points were removed from the fit as they are close to the lower energy
limit. The results are presented in figure 7.13 and the corresponding fit details are listed
in table 7.1. As can be observed, the cutoff energy $E_0$ shifts toward higher energies with
increasing flux $f_0$. This is in agreement with Fossati et al. [96] (see chapter 2.3.2.2), who
investigated the SED of Mrk421 during one week in 2001 with increasing brightness, and
suggested that the IC peak moved to higher energies with increasing hardness of the TeV
spectrum.

\[
\begin{array}{cccccc}
\text{Period} & f_0 \ [\text{cm}^{-2}\text{s}^{-1}\text{TeV}^{-1}] & \alpha & r \ [\text{TeV}] & E_0 \ [\text{TeV}] & \chi^2/\text{ndf} \\
2010 \text{ Jan} & (1.33 \pm 0.02) \cdot 10^{-9} & -1.80 \pm 0.01 & 0.30 & 2.06 \pm 0.09 & 57.30/16 \\
2010 & (9.31 \pm 0.11) \cdot 10^{-10} & -1.80 \pm 0.006 & 0.30 & 1.84 \pm 0.06 & 88.13/17 \\
2010 \text{ w.o. Jan} & (5.85 \pm 0.13) \cdot 10^{-10} & -1.86 \pm 0.008 & 0.30 & 1.61 \pm 0.09 & 40.40/9 \\
2011 & (4.02 \pm 0.16) \cdot 10^{-10} & -1.91 \pm 0.01 & 0.30 & 0.78 \pm 0.05 & 42.01/13 \\
\end{array}
\]

Table 7.1: Details for the power law with cutoff fit ($f_0 \cdot (E/r)^\alpha \cdot \exp(-E/E_0)$) to the low
and high state Fermi and MAGIC spectra presented in figure 7.13. With increasing flux
$f_0$, the cut-off energy $E_0$ shifts toward higher energies.

The result also agrees with the Fermi-MAGIC lightcurve correlation found in figure 7.9:
The increasing flux level concerns the complete MAGIC spectrum, but only a small part
of the SED measured by Fermi. Therefore one would expect correlation between Fermi
and MAGIC lightcurves, but with less change in the Fermi flux points, as it is the case in
7.4 Summary

The launch of the Fermi satellite in 2008 has opened up new possibilities for a deeper understanding of the VHE sky. Thanks to the low energy threshold of the MAGIC experiment, the investigation of the complete high-energy SED peak covered by Fermi and MAGIC data became possible.

The lightcurve correlation between MAGIC and Fermi as well as between MAGIC and the optical telescope KVA gave further insights in the behavior of Mrk421. While there is a trend for correlation in the lightcurves of MAGIC and Fermi, no correlation between MAGIC and KVA was found.

The high-energy SED peak of Mrk421 was calculated for different flux states, and was described with a power law with exponential cutoff. While within errors there was no substantial change in the ascending slope described by Fermi data, the cutoff energy shifted with increasing flux toward higher values within the MAGIC energy range, corresponding to a hardening of the high-energy SED peak. This finding implies that Mrk421 is much more variable in the TeV range than in the GeV range – a behavior that was already reported in previous publications and could describe an intrinsic feature of this source type.
8 Summary, Conclusions and Outlook

Markarian 421 (Mrk421) is one of the closest known TeV blazars to Earth, and one of the strongest TeV sources. It is observed regularly with the MAGIC telescopes. In this thesis, data recorded in the years 2010 and 2011 have been studied.

Especially in 2010, Mrk421 was very active and showed several flares, which allowed to investigate the variability and the spectral behavior of the source. A flaring episode in May 2010 was investigated in detail, and the search for short intranight variability was performed systematically for both years.

With the launch of the Fermi Gamma-ray Space Telescope in 2008, new possibilities to analyze the behavior of Mrk421 have opened up. By combining the MAGIC with Fermi data, the complete high-energy peak of the SED at different time periods and flux states could be studied. This can be observed in figure 8.1 that presents a comparison of SEDs corresponding to different flux levels for data recorded with MAGIC and Fermi. With increasing flux level, the cutoff energy shifts toward higher energies within the MAGIC energy range, corresponding to a harder energy spectrum. Thereby, the Fermi spectra remained virtually stable in flux state and spectral index during the period of investigation. The measured MAGIC spectra agree well with observations by the HEGRA telescopes in the periods from December 1999 until May 2001 [95], as the solid black lines indicating the energy spectra of three different flux levels show. As Mrk421 underwent strong TeV gamma-ray outbursts up to 14 Crab units in 2001, the HEGRA spectrum corresponding to the highest flux level lies well above the MAGIC spectra.

Figure 8.1: Combined Fermi and MAGIC SEDs for 2011 (low state), 2010 and January 2010 (high state). Additionally, the energy spectra for three different flux levels observed with the HEGRA telescopes between 1999 and 2001 are indicated by black lines [95].
However, during a short period in summer 2012, well after the investigated time period, the energy spectrum measured by Fermi showed a strong flux increase [172], although the spectral index remained stable. This could indicate that there are at least two different forms of high flux states, that may differ in the behavior of the Fermi energy spectra. Unfortunately, Mrk421 could not be observed by any IACT during that period, so that the descending slope of the IC peak could not be covered.

With the new generation IACTs and the Fermi satellite, we are in an excellent position to continuously extend our knowledge about Mrk421 - all we need is some luck that nature provides us with interesting flares. A combination of regular monitoring and flare hunting is thereby the most promising way to catch more flares simultaneously by IACTs and Fermi. As the existing IACTs are always restricted by their dense scheduling plans, new experiments that could contribute to a dedicated TeV monitoring are important, like the First G-APD Cherenkov Telescope (FACT) [173], that is located on the Canary Island of La Palma and uses Geiger-mode avalanche photodiodes as photosensors. In the case of flare hunting, great expectations are placed on the Cherenkov Telescope Array (CTA) that is currently under construction and is expected to improve the sensitivity of existing IACTs by an order of magnitude [174].
A Apparent Superluminal Motion in AGN Jets

Observing individual knots (or blobs) within a jet, they seem to move faster than the speed of light. This geometrical effect is explained in the following.

Figure A.1 shows an object that is moving with velocity $v$ under an angle $\alpha$ relative to the line of sight. Within time $t$ it travels from point A to point B. A signal emitted at point A when the object left needs time $t_c = v \cdot t \cdot \cos(\alpha)/c$ to reach point C, i.e. the time difference between the object reaching point B and the signal reaching point C is $\Delta t = t - t_c = t - v \cdot t \cdot \cos(\alpha)/c$.

![Diagram](https://via.placeholder.com/150)

Figure A.1: Motion of an object that can result in apparent superluminal velocities. See text for explanation. Image credit from Adrian Biland.

Assuming the distance to the observer is so large that signals emitted from points B and C, respectively, need identical time to reach the observer, the two signals arrive at the observer with the time difference $\Delta t$. Since it is usually not possible to observe the movement of an astronomical object in three dimensions, it looks for the observer that the object moved within $\Delta t$ from point C to point B, a distance of $\Delta d = v \cdot t \cdot \sin(\alpha)$. This results in an apparent velocity

$$v_a = \frac{\Delta d}{\Delta t} = \frac{v \cdot t \cdot \sin(\alpha)}{t - v \cdot t \cdot \cos(\alpha)/c} = \frac{v \cdot \sin(\alpha)}{1 - v \cdot \cos(\alpha)/c} \quad (A.1)$$

and with $\beta = v/c$

$$\beta_a = \frac{\beta \cdot \sin(\alpha)}{1 - \beta \cdot \cos(\alpha)} \quad (A.2)$$

As can be seen in figure A.2, for highly relativistic velocities, the apparent speed can be superluminal. Therefore, measuring apparent superluminal motion allows to extract information about the real velocity of the object and the angle to the line of sight.
Figure A.2: Apparent velocities for relativistically moving objects as a function of angle relative to the line of sight for selected velocities. As can be seen, the apparent velocity can be superluminal. See text for explanation. Image credit from Adrian Biland.
## B Final Data Set

### 2010

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Table B.1: The dataset of Mrk421 taken by the MAGIC telescopes in 2010, divided in A-, B- and C-categories for all nights separately.
## Data Table

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Table B.2: The dataset of Mrk421 taken by the MAGIC telescopes in 2011, divided in A- and C-categories for all nights separately.
C Data Selection Plots Mrk421 2011
Figure C.1: Rate distribution for MI and MII from January to June 2011 after cleaning and after removal of nights not passing the quality cuts in DC, cloudiness or nr. of id. stars. The rate is shown after a size cut of 100 phe and geometrically normalized to the zenith angle. Data within the range ±20% of the mean rate is accepted.
C. Data Selection Plots Mrk421 2011

(a) DC distribution.

(b) Cloudiness distribution.

(c) Number of identified stars.

Figure C.2: mean DC PMT current, cloudiness and nr. of id. stars as a function of MJD for the 2011 data for MI (blue) and MII (red). One dot corresponds to one star file (≈ 4 min for MII and ≈ 2 min for MI respectively). Data with DC > 1500 nA, cloudiness > 40 or nr. of id. stars < 20 is excluded from the analysis.
D Analysis Parameters

D.1 General Analysis and Selection Parameters

In the following, some general parameters used in the analysis are listed:

- Stereo observation.
- Observation mode: Dark night, twilight and moon. Separation between dark and bright condition: mean DC < 1500 nA.
- Quality cuts at star level: DC < 1500 nA, cloudiness < 40 %, nr. of id. stars > 20, rate after cleaning within ± 20 % of mean rate within a stable time period.
- 3NN MCs (4NN MCs for analysis of 28 May 2010, see section 6.4)
- MARS Version 2-8-3.
- Melibea: Stereo DISP & Ghost-busting, Energy-Tables
  - FluxLC.UserCuts: (MNewImagePar_1.fLeakage1<0.3) && (MNewImagePar_2.fLeakage1<0.15) && (MImagePar_1.fNumIslands<2) && (MImagePar_2.fNumIslands<2) && (sqrt(pow(0.0033703*MSrcPosCam_1.fX,2.)+pow(0.0033703*MSrcPosCam_1.fY,2.))>0.365) && (sqrt(pow(0.0033703*MSrcPosCam_2.fX,2.)+pow(0.0033703*MSrcPosCam_2.fY,2.))>0.365) && (sqrt(pow(0.0033703*MSrcPosCam_1.fX,2.)+pow(0.0033703*MSrcPosCam_1.fY,2.))<0.435) && (sqrt(pow(0.0033703*MSrcPosCam_2.fX,2.)+pow(0.0033703*MSrcPosCam_2.fY,2.))<0.435)
- Fluxlc Size: FluxLC.MinSize: 50.
- Fluxlc Hadroness: FluxLC.had: 0.973, 0.989, 0.959, 0.977, 0.989, 0.99, 0.952, 0.772, 0.555, 0.459, 0.433, 0.431, 0.425, 0.413, 0.392, 0.377, 0.364, 0.347, 0.323, 0.294, 0.263, 0.225, 0.209, 0.242, 0.496, 0.652, 0.29, 0.897
- Fluxlc Theta2: FluxLC.alp: 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.05, 0.04, 0.03, 0.02, 0.02, 0.02, 0.02, 0.02, 0.02, 0.02, 0.02, 0.02, 0.02, 0.02, 0.02, 0.02, 0.02, 0.02, 0.02
- One wobble position for background estimation.
- Theta2 cut lightcurve: 0.02
E The Random Forest

E.1 The 3NN Random Forest

In the following, a list of all Superstar-files from the background sample for the standard (3NN) RF is presented. The same quality cuts as described in chapter 6.1.1 were applied to the data. The RF covers a zenith range from 5 - 50°.

20091117_05003572_S
20091119_05003614_S
20091119_05003615_S
20091119_05003620_S
20100124_05005050_S
20100124_05005053_S
20100313_05005834_S
20100313_05005835_S
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20100313_05005842_S
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20100714_05008612_S
20100714_05008613_S
20100714_05008615_S
20100714_05008616_S
20100714_05008617_S
20100714_05008618_S
20100715_05008653_S
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20100715_05008656_S
20100715_05008657_S
20100715_05008658_S
20100715_05008659_S
20100716_05008691_S
20100716_05008692_S
20100716_05008693_S
20100716_05008694_S
20100716_05008696_S
20100717_05008723_S
20100717_05008724_S
20100717_05008725_S
All Superstar-files selected to form the background sample for the non-standard (4NN) RF are listed in the following. The same quality cuts as described in chapter 6.1.1 were applied to the background data. As no additional 4NN data with no source in it could be found in the MAGIC data center for low zenith angles (below 15.6°), some files with low rate were kept in the dataset in order to cover the low zenith range. The RF covers in total a zenith range from 7.2 - 35°.

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20091120_05003649_S
20091120_05003650_S
20091120_05003651_S
20091120_05003652_S
20091120_05003653_S
20091120_05003654_S
20091120_05003655_S
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20091124_05003840_S
20091124_05003841_S
F Crab Nebula Analysis

F.1 Crab Nebula Data Cycle 5

This data set was built in order to check the analysis of Mrk421 data from 2010. It consists of data taken in twelve nights between November 2009 and February 2010, covering a total effective observation time of 11.8h. The data was processed with the standard stereo analysis chain described in chapter 5, using the Random Forest described in Appendix E.1 and Monte Carlo simulations in standard trigger configuration (3NN). The data quality check was performed as described in chapter 6.1.1. Plots describing the results of the data selection and the resulting spectrum are shown in chapter 5.

F.2 Crab Nebula Data Cycle 6

The cycle 6 Crab Nebula set consists of eleven nights between September 2010 and January 2011, covering a total effective observation time of 5.8h. It was analyzed to crosscheck the Mrk421 results from 2010. It was processed the same way as the cycle 5 data. Plots describing the results of the data selection and the resulting spectrum are shown in the following (figures F.1 to F.4).

F.3 Crab Nebula Data: L1-4NN Trigger Configuration

Using this data set, the analysis from 18 May 2010 data taken under a special trigger configuration (L1-4NN, see chapter 6.4) was cross-checked. To process this data a special RF was set up with special L1-4NN MC simulations and background data. The data set includes data from three nights between October 2009 and February 2010, covering 83 minutes. In the following, results of the quality check are shown as well as the resulting spectrum (figures F.5 to F.8).

F.4 Crab Nebula Data: Moonlight Conditions

The aim of the analysis of this data set was to check if data taken under moderate moonlight conditions like it was the case on 20 May 2010 (see chapter 6.4) can be analyzed with the standard analysis chain using the standard RF. For this purpose, MAGIC data with DC values $1500 \text{ nA} < \text{DC} < 3000 \text{ nA}$ was extracted from six different nights between March and December 2012. An additional rate cut was applied in order to remove outliers, leaving a total of 75 minutes data. Results of the quality check are shown in the following, as well as the resulting spectrum obtained with the standard analysis chain (figures F.9 to F.11). As a size cut of 150 phe was applied, the SED was calculated for energies above 150 GeV. Below $\approx 1000 \text{ GeV}$, the obtained moon data SED agrees well with published values. Above 1000 GeV, the obtained moon data SED is slightly lower than the expected Crab SED, but still agrees within error bars with the SED obtained with a good quality data sample (figure 6.17).
Figure F.1: DC, cloudiness and nr. of id. stars as a function of the Modified Julian Date (MJD) for the Crab Nebula data taken in cycle 6 for MI (blue) and MII (red). One dot corresponds to one star file (≈ 4 min for MII and ≈ 2 min for MI respectively). Data with DC > 1500 nA, cloudiness > 40 or nr. of id. stars < 20 is excluded from the analysis. The corresponding cut-values are indicated by the green horizontal line.
Figure F.2: Rate distribution for the Crab Nebula data taken in cycle 6 for MI and MII after cleaning and after removal of nights not passing the quality cuts in DC, cloudiness or nr. of id. stars. The rate is shown after a size cut of 100 phe and geometrically normalized for the zenith angle. Data within the range ±20% (blue and red horizontal lines) of the mean rate (green line) is accepted.
Figure F.3: Spectrum of the Crab Nebula in cycle 6 for zenith < 35°, before unfolding, compared with published values.

Figure F.4: Spectral Energy Distribution (SED) of Crab Nebula cycle 6 for zenith < 35°, after using different unfolding methods and compared with published values.
Figure F.5: DC, cloudiness and nr. of id. stars as a function of the Modified Julian Date (MJD) for the Crab Nebula data taken under special trigger condition (L1-4NN) for MI (blue) and MII (red). One dot corresponds to one star file (≈ 4 min for MII and ≈ 2 min for MI respectively). Data with DC > 1500 nA, cloudiness > 40 or nr. of id. stars < 20 is excluded from the analysis. The corresponding cut-values are indicated by the green horizontal line.
Figure F.6: Rate distribution for the Crab Nebula data taken under special trigger condition (L1-4NN) for MI and MII after cleaning and after removal of nights not passing the quality cuts in DC, cloudiness or nr. of id. stars. The rate is shown after a size cut of 100 phe and geometrically normalized for the zenith angle. Data within the range ±20% (blue and red horizontal lines) of the mean rate (green line) is accepted.
Figure F.7: Spectrum of the Crab Nebula data taken under special trigger condition (L1-4NN) for zenith < 35°, before unfolding, compared with published values.

Figure F.8: Spectral Energy Distribution (SED) of Crab Nebula data taken under special trigger condition (L1-4NN) for zenith < 35°, after using different unfolding methods and compared with published values.
Figure F.9: DC and rate distribution as a function of the Modified Julian Date (MJD) for the Crab Nebula data taken under moderate moonlight conditions for MII (red) and MI (blue). One dot corresponds to one star file (≈ 4 min for MII and ≈ 2 min for MI respectively). Data with 1500 nA < DC < 3000 nA is selected for the moonlight sample (indicated by the green lines). An additional rate cut is applied to the selected moonlight data. The rate is shown after a size cut of 100 phe and geometrically normalized for the zenith angle. Data within the range ±20% (blue and red horizontal lines) of the mean rate (green line) is accepted.
Figure F.10: Spectrum of the Crab Nebula data taken under moderate moonlight conditions for zenith < 35°, before unfolding, compared with published values. An additional size cut of 150 phe is applied.

Figure F.11: Spectral Energy Distribution (SED) of Crab Nebula data taken under moderate moonlight conditions above 150 GeV, for zenith < 35°, after using different unfolding methods and compared with published values. An additional size cut of 150 phe is applied.
G List of Acronyms and Abbreviations

AGN  Active Galactic Nuclei
AMC  Active Mirror Control
CMB  Cosmic Microwave Background
C.U. Crab units
DAQ  Data AcQuisition
DC  Direct Current
DRS2 Domino Ring Sampler version 2
eV  electron Volt, $1\text{eV} = 1.6 \cdot 10^{-12} \text{J}$
EAS  Extensive Air Shower
FADC Flash Analog Digital Converter
FOV  Field Of View
G-APD Geiger Mode Avalanche Photodiode
GeV  Giga electron Volt, $1\text{GeV} = 10^9 \text{eV}$
GRB  Gamma-ray burst
H.E.S.S. High Energy Stereoscopic System
HE  High Energy
IACT Imaging Air Cherenkov Telescope
IR  Infrared
LE  Low Energy
LT0  Level 0 Trigger
LT1  Level 1 Trigger
LT2  Level 2 Trigger
LUT  Look Up Table
MI  MAGIC-I, the first MAGIC telescope
MII  MAGIC-II, the second MAGIC telescope
MAGIC Major Atmospheric Gamma-ray Imaging Cherenkov Telescope
MC  Monte Carlo
MeV Mega electron Volt, $1\text{MeV} = 10^6 \text{eV}$
MJD  Modified Julian Date
ndf  number of degrees of freedom
NN  Next Neighbor
NSB  Night Sky Background
NVA  Normalized Variability Amplitude
phe  photoelectron
PMT  Photomultiplier Tube
PSF  Point Spread Function
QSO  Quasi-Stellar Radio Source
RF  Random Forest
SED  Spectral Energy Distribution
TeV  Terra electron Volt, $1\text{TeV} = 10^{12} \text{eV}$
UV  UltraViolet
VERITAS Very Energetic Radiation Imaging Telescope Array System
VHE  Very High Energy
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[17] IceCube Neutrino Observatory.  
http://icecube.wisc.edu/.


[22] SIMBAD Astronomical Database, CDS, Observatoire Astronomique, 67000 Strasbourg.

http://simbad.u-strasbg.fr/simbad/.


[38] AGASA (Akeno Giant Air Shower Array).  
http://www-akeno.icrr.u-tokyo.ac.jp/AGASA/.


[40] BESS (the Balloon-borne Experiment with a Superconducting Spectrometer).  

[41] AMS (Alpha Magnetic Spectrometer) 02.  
http://ams.cern.ch/.

[42] PAMELA (Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics).  

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[50] ESA Science & Technology: INTEGRAL.  

[51] AGILE (Astrorivelatore Gamma a Immagini L’eggero).  
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[54] MAGIC (Major Atmospheric Gamma-ray Imaging Cherenkov Telescopes).  
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