Study of Very High Energy Gamma Ray Emission from TeV Blazars

A Thesis

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by

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DECLARATION

This thesis is a presentation of my original research work. Wherever contributions of others are involved, every effort is made to indicate this clearly, with due reference to the literature, and acknowledgement of collaborative research and discussions.

The work was done under the guidance of Professor B. S. Acharya, at the Tata Institute of Fundamental Research, Mumbai.

Debanjan Bose

In my capacity as supervisor of the candidate’s thesis, I certify that above statements are true to the best of my knowledge.

Prof. B. S. Acharya
Date:
Synopsis

Active Galactic Nuclei (AGN) dominate extra-galactic astronomy by virtue of their great luminosities. It is believed that there is a supermassive black hole of mass $10^6 - 10^9 M_\odot$ at the center of AGN, which is accreting mass from the surrounding medium, with two jets emanating perpendicular to the plane of the accretion disk. These jets channel a plasma flowing out with relativistic speed and any radiation produced inside them is greatly modified by Doppler effect. AGNs with jets directed towards us are called blazars. Blazars are subdivided into two groups, radio selected blazars or low frequency BL Lacs (LBLs) and X-ray selected blazars or high frequency BL Lacs (HBLs). They emit highly variable non-thermal radiation with variability ranging from minutes to year. They are detectable at almost all wavebands across the electromagnetic spectrum. Their Spectral Energy Distributions (SEDs) are characterised by two humps [102] (see figure 0.1). First hump is extended from IR to X-ray and second hump from X-ray to $\gamma$-ray (GeV/TeV energy). First peak is believed to be due to the synchrotron emission from charged particles present in the jet. While the Second peak could be due to Inverse-Compton (IC) scattering of synchrotron photons by the same population of charged particles.

There are several reasons which make blazars objects of immense interest. Firstly, one would like to know what kind of astrophysical processes take place inside these sources which are responsible for emission of such high energy photons, how the jets are formed, nature of the charged particles present in the jet etc. Secondly, AGNs are the most probable candidates for origin of cosmic rays with energies $10^{16}$eV and above, the mechanism of acceleration of charged particles to such high energy is still unknown [134]. Study of blazars is also important from cosmology point of view. High energy $\gamma$-rays (GeV/TeV) while traveling through the intergalactic space interact with infra-red and optical photons and produce $e^- - e^+$ pairs. Due to this intergalactic absorption their spectra get modified. If one knows the intrinsic spectra of these sources then Extragalactic Background Light (EBL) flux can be estimated. Observations of blazars at all wavelengths,
Fig. 0.1: Spectral Energy Distribution (SED) of blazar Mkn421

separately or simultaneously, have led to a great progress in understanding their physics. Multiwavelength observations of these blazars have almost become necessity. As their SEDs are extended up to GeV-TeV energies $\gamma$-ray observations play an important role in understanding these sources.

Celestial $\gamma$-rays cover a very wide energy range, several orders of magnitude in energy. Their observations are divided mainly into two domains, MeV-GeV and GeV-TeV $^1$, depending upon the method of observation: space-borne or ground-based. Direct observations of $\gamma$-rays are possible with space borne detectors, but are limited to $\gamma$-rays of energies below a few tens of GeV due to the limitations on the size and exposure time of the detector. Above this energy range, $\gamma$-ray could only be detected through ground-based detectors, although indirectly. When a high energy $\gamma$-ray enters the Earth's atmosphere it produces an $e^- - e^+$ pair. This $e^- - e^+$ pair produces $\gamma$-rays in the field of nucleus via bremsstrahlung. With successive bremsstrahlung emission and pair production an electromagnetic cascade, called Extensive Air Shower (EAS), is generated in the atmosphere. Charged particles in this shower moving at relativistic speeds emit Čerenkov radiation. This radiation can be detected at the ground level during moonless clear nights, with a simple arrangement of a focusing mirror and a Photo Multiplier Tube (PMT) placed at the focus, against Night Sky Background.

$^1$ Also known as Very High Energy (VHE) $\gamma$-rays.
(NSB) photons. This technique is called Atmospheric Čerenkov Technique (ACT) [134]. In this technique γ-rays are to be detected against a predominant background of Čerenkov photons from the EAS induced by cosmic ray charged particles. There are two ways to detect VHE γ-rays. One is the Imaging Atmospheric Čerenkov Technique (IACT) and other is wavefront sampling technique. IACT consists of a large optical reflector with an array of PMTs at the focus, which record the image of each Čerenkov shower. In wavefront sampling technique multiple collectors sample light across the entire Čerenkov wavefront. In this technique an array of telescopes record photon arrival times and densities at several points in the light pool. An array of imaging telescopes is ideal as it samples both lateral and longitudinal development of the Čerenkov shower. HESS array of telescopes is an example of this type of detectors [39].

So far around 100 blazars have been detected in the γ-ray window by satellite based detectors, mainly on board Compton Gamma Ray Observatory (CGRO) which has revolutionized this field [65]. However, in the VHE domain i.e. by ground based experiments, only 12 blazars has been detected, out of which 10 are confirmed detections (6 of them are situated in northern hemisphere and 4 are in southern hemisphere). We have chosen 4 blazars for the present study and they are Mkn421, Mkn501, 1ES1426+428 and ON231. Reasons for their selections are as follows: Firstly all are nearby blazars. Secondly all of them are in the northern hemisphere and hence accessible by Pachmarhi Array of Čerenkov Telescopes (PACT) which is situated in northern hemisphere. Except for ON231, the other three sources are detected with high significance by other ground based experiments at some time or other. Our observation log is shown in table 0.1.

PACT is based on wavefront sampling technique. It is located at Pachmarhi in Central India at an altitude of 1075m (longitude 78°26′E, latitude 22°28′N) [52]. This setup consists of 24 telescopes spread over an area of 80m × 100m in the form of a rectangular array. Separation between neighbouring telescopes is 20m in E-W direction and 25m in N-S direction.

\[2 \text{Mkn421, Mkn501, 1ES1426+428 are of HBL type and ON231 (or W-Comae) is of LBL type} \]
<table>
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<tr>
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<td>–</td>
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<td>570.</td>
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<td>2004</td>
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<td>780.</td>
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<td>870.</td>
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<tr>
<td>2005</td>
<td>930.</td>
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Each telescope consists of 7 parabolic mirrors of diameter 0.9m with f/d~1 mounted para-axially on an equatorial drive and is independently steerable in both E-W and N-S direction over the range of ±45° from zenith. The movement of telescopes is remotely controlled by an Automated Computerised Telescope Orientation System (ACTOS) [63]. All the mirrors are viewed by a fast PMT EMI 9807B of 2" diameter behind a 3° circular mask. Total reflector area of a telescope is approximately 4.45m². Every PMT collects Čerenkov photons and converts them into electrical pulse. The amplitudes and arrival times of these pulses are recorded, this in turn give the energy and arrival direction of the incident showers respectively. The array is sub-divided into 4 sectors with six telescopes in each. Each sector has its own data acquisition system, which is called Field Signal Processing Center (FSPC). Čerenkov pulses from PMTs are brought to the respective FSPC through a low attenuation co-axial cable. Then 7 PMT pulses of a telescope are added to form a Royal Sum pulse. A trigger generated by a coincidence of any 4 out of 6 royal sums which initiates the recording of information regarding pulse heights (photon density) obtained from ADCs, relative arrival times of pulses from TDCs and absolute arrival time of an event. Apart from this there is Master Signal Processing Center (MSPC) at the center of the array, which records information relevant to the entire array for each trigger.

In any VHE γ-ray experiment simulations play a very important role.
Direct calibration of various detector elements is not possible because that would require steady and very high energy celestial $\gamma$-ray beam. Therefore instrument performance can be understood only through detailed simulations of air showers and correct modeling of detector response. We have used CORSIKA [118] package for simulations. This is a detailed Monte Carlo program, which simulates interactions and decays of nuclei, hadrons, muons, electrons and photons in the atmosphere up to energies $10^{20}$eV. All the charged particles as well as photons produced in the atmosphere by $\gamma$-ray or cosmic ray primary are then tracked explicitly along their trajectories up to the observation level. For PACT Čerenkov light emission from the charged particles of the EAS generated by cosmic ray or $\gamma$-rays primaries are simulated using CORSIKA. This yields information about arrival times, directions and location of Čerenkov photons reaching observation level. This information is then passed through detector simulation program to simulate the experimental parameters. All the instrument related and observation site related effects e.g., atmospheric attenuation, reflectivity of mirror, NSB flux, cable attenuation, PMT pulse shape, trigger criteria etc, are incorporated in this program. Detector simulation program writes TDC (timing), ADC (pulse height) informations of each shower for every mirror in a similar way as they are recorded during observations. This simulated data file is then further processed for rigorous analysis. Showers incident vertically are simulated following these methods and cosmic ray trigger rate obtained from simulations is found to match well with the observed trigger rate. Energy threshold for PACT is estimated to be 650 GeV and collection area is about $1.58 \times 10^5$ m$^2$. Expected trigger rates for individual sectors as well as for the whole array are also estimated, which are $\sim 2.5$Hz and $\sim 7.5$Hz respectively, they agree well with the observed trigger rates. TDC distributions from simulations are compared with the observed ones and are found to match well. Similarly ADC values from simulated showers are also in agreement with the observed data.

The arrival direction of each shower is determined by reconstructing shower front using the relative arrival times of Čerenkov photon front at various telescopes. This Čerenkov photon front is fitted with a plane, the
normal to this plane gives the direction of shower axis. Then space angle is estimated as an angle between the direction of shower axis and the source direction. The distribution of space angles obtained from simulations agree with data. Using ADC values one can estimate primary energy of the incident \( \gamma \)-ray at the top of the atmosphere. We tried to obtain cosmic ray spectrum from simulated and experimental ADC data. Derived spectra for both these cases were found to be flatter compared to original cosmic ray spectrum. Simulations are also carried out for inclined showers as well since all the blazars observed using PACT are at some angle with respect to the zenith due to their declination. Moreover this angle varies with hour angle of the source. Therefore to compare simulations with data, showers are generated with inclination angle same as that of the source and trigger rate, energy threshold etc are estimated. Variation of trigger rate with zenith angle obtained from simulations is found to be consistent with the observed data.

PACT observations are conducted in the following way, each night along with the source runs background runs were also taken. Background runs were taken by aligning the telescopes to a dark region with the same declination as that of source but with different RA. Background region RA was chosen in such a way that it covers same hour angle range as source run. Space angle distributions of all the source runs are compared with the corresponding distributions of background runs. This comparison is necessary since there are variations in sky conditions from one night to another. It is mainly due to these reasons background run is taken on every night along with source run. For this comparison it is ensured that both source and background runs have same zenith angle coverage. Further background distributions are normalized with respect to the source distributions by comparing the shape of the distributions in 2.5° to 6.5° window as we do not expect any \( \gamma \)-ray event in this region [80]. This normalization was necessary as source and background runs were taken at different times and sky conditions could be slightly different. Then \( \gamma \)-ray signal is obtained as an excess of source events over the background events in 0°-2.5° region. Based on preliminary checks for data quality and various cuts on the minimum number of tele-
scopes about \( \approx 50\% \) of data were rejected.

Mkn421 is the first blazar detected at TeV energies. It is a nearby blazar with redshift 0.031. This blazar is known to go into flaring state quite often. During flaring state its flux has been detected to be as high as few times that of Crab flux. We have large coverage for this source since year 2000. In year 2000, 2001, 2004 and 2005 for few months this source was in active state [33 , 46], as reported by HEGRA, CAT and WHIPPLE \( \gamma \)-ray telescopes. Count rates are estimated for each night and compared with ASM \(^3\) (All Sky Monitor, on board RXTE) rates, as shown in figure 0.2. In 2003 during 26th February to 5th March there was an international multiwavelength campaign involving X-ray and \( \gamma \)-ray experiments for this source. We observed Mkn421 during this campaign. At this time there was an increase in ambient light level at Pachmarhi and it was found that data is not so useful. For this one week, we have analysed X-ray data from Proportional Counter Array (PCA) on board RXTE and found the source to be in low state. In \( \gamma \)-ray regime also it was reported to be in quiet state. We have obtained time averaged flux for Mkn421 by combining all the data obtained using PACT during 2000-2005 to be \( 4.45(\pm 1.9) \times 10^{-12} \) \text{photons cm}^{-2} \text{s}^{-1}\) above 1.2 TeV, which falls in between the fluxes detected by WHIPPLE at high and low states of this source.

Other blazars which we have observed are Mkn501, 1ES1426+428 and ON231. We have not seen any significant \( \gamma \)-ray flux from any of these sources. Mkn501 is also a nearby blazar with redshift 0.034, but in these 5 years no experiment has detected it in flaring state. Earlier in 1997, a huge flare was detected from Mkn501 by several experimental groups [92]. 1ES1426+428 is a distant blazar (z=0.129), WHIPPLE have seen excess from this source with long duration observations [82 , 36]. PACT is less sensitive than this experiment and we do not have very long duration observations. No experiment has detected significant excess from ON231 above 100 GeV so far [48 , 86]. Hadronic models for LBLs like ON231 predict higher TeV flux than leptonic jet models, thus detection of >100 GeV photons would be very interesting in understanding these sources. We

\(^3\)http://xte.mit.edu/asmlc/srscs/mkn421.html#data
have estimated 3σ upper limits on the flux of γ-rays from these sources, as $1.22 \times 10^{-11}$ photons cm$^{-2}$ s$^{-1}$ ($\geq$ 1.2 TeV), $1.34 \times 10^{-11}$ photons cm$^{-2}$ s$^{-1}$ ($\geq$ 1.2 TeV) and $2.50 \times 10^{-11}$ photons cm$^{-2}$ s$^{-1}$ ($\geq$ 750 GeV) respectively for Mkn501, 1ES1426+428 and ON231.

There are two sets of models that have been proposed to explain the γ-ray emission from these blazars. First set is leptonic or electron models. In this scenario the electrons radiate synchrotron radiation in the magnetic fields associated with the jet and thus produce the first peak in the SED. Then for γ-ray emission, one possibility is that these synchrotron radiated photons themselves will provide soft photon targets, to the same population of electrons, to be boosted to higher energies via Inverse Compton (IC) scattering. This is also called “Synchrotron Self Compton” (SSC) model. In some cases relativistic electrons may collide with soft photons from the microwave background and produce γ-rays, which is known as External Compton (EC) model. So far whatever correlation has been observed between X-ray and γ-ray can be easily explained by these electron beam models. In the second set of models, protons are responsible for emission of such high energy γ-rays instead of electrons. This set of models is referred to as proton or hadronic models.

Mkn421 and Mkn501 are the two extensively studied blazars.
though observed correlation between X-ray and γ-ray emission can be explained easily, there are certain other observed features which can not be explained by any of the above mentioned models. Recently WHIPPLE [?] has reported two important observations about Mkn421. Firstly, at one occasion in 2004 they have seen that γ-ray emission reaches peak a day earlier compared to X-ray. On another occasion they have detected a TeV “orphan” flare. Both these phenomena can not be explained by any of the proposed models. Apart from these there are many features which are still not understood. Therefore many more multiwavelength campaigns are needed to constrain these models.

γ-rays are to be detected against a huge background of cosmic rays. Therefore to improve signal to noise ratio one should reject most of the cosmic rays. In the present analysis cosmic rays are not rejected efficiently. The main reason for this is the plane front approximation to the Čerenkov wavefront which is actually spherical in shape with a radius of curvature of about 8-10km. This approximation introduces error in arrival angle estimation, error increases with shower core distance. It is found from simulations that for vertically incident γ-ray showers the space angle distribution becomes broader and peaks around 0°.5, whereas it was expected to peak close to 0°.1. This seems to be a major limitation of our analysis. We tried to use spherical front approximation, but it could not be implemented for PACT data easily. Also because of inability to get core location, ADC data could not be used to full advantage. Also for PACT due to design constraints there is a large gap between source and background runs in a night. In that course of time sky conditions may change significantly. As a result normalisation constants are being affected. Excess of γ-ray signal is very sensitive to normalisation constants. Over estimation of normalisation constants under estimate γ-ray signal and vice-versa. Ideally if it is possible to take source and background runs with an interval of 25-30 minutes that will help in estimating signal correctly. Going higher up in altitude may also help in improving signal to noise ratio mainly due to lower energy threshold achievable.

The thesis will be organised as follows. First chapter will have brief in-
troduction to blazars and review of various models proposed for the mechanism of non-thermal radiation. The atmospheric Čerenkov technique will be described in chapter 2. Chapter 3 will give details about PACT array. Chapter 4 deals with Monte Carlo simulations and comparison with the data. The summary of observations and data analysis technique will be described in chapter 5. Results and discussion in chapter 6 and summary in chapter 7.
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Chapter 1

Introduction

Astronomy is now performed over the entire range of electromagnetic spectrum. Figure 1.1 shows the electromagnetic spectrum, from radio to gamma-ray energies. As seen in this figure, except for two narrow bands, in radio and in optical wavelengths, Earth’s atmosphere is opaque for the rest of the electromagnetic spectrum. Because of this reason observations of the Universe were limited to the narrow band of optical wavelengths till the middle of 20th century for about three millenia. Since then, after the Second World War, a very rapid development of astronomy in other wavelengths of the electromagnetic spectrum has taken place. This was possible mainly due to the great advancement of technology that mankind has achieved in the last century. Now Radio, Infra-red, Ultraviolet, X-ray, $\gamma$-ray astronomies are all well established, which along with optical astronomy has enriched our knowledge of the physical universe enormously. High energy $\gamma$-ray astronomy is the latest to be added in the list of astronomy. The reader is referred to the review articles [123, 135] for a comprehensive overview of the subject of $\gamma$-ray astronomy. In this chapter we briefly review the $\gamma$-ray astronomy and the observations of active galactic nuclei in the $\gamma$-ray band. This chapter is organized as follows: Motivations for studying celestial sources in the very high energies are explained in section 1.1, an introduction about $\gamma$-ray astronomy is given in section 1.2, various features of active galactic nuclei are discussed in section 1.3 and finally different models of blazars are discussed in section 1.4.
1.1 Scientific Motivation

Our Universe is dominated by objects which emit radiation via thermal processes. However there are objects, largely unseen, which emit radiation via non-thermal processes. This relativistic Universe is of particular interest to the physicists. We are continuously bombarded by cosmic radiations isotropically, whose power law spectrum confirms its non-thermal origin and whose highest energy extends far beyond that achievable by man made accelerators. Origin of these cosmic rays are still a mystery. Thus a study of the origin of cosmic rays is an important motivation for VHE $\gamma$-ray astronomy. Apart from that physicists are also interested in physics and astrophysics of relativistic outflows of particle jets, very high energy radiation, cosmology etc. By observing the sources of very high energy radiation,
we study the conventional physics under extreme conditions, like intense gravitational or magnetic field.

### 1.1.1 Origin of Cosmic Rays

At low energies a resonably well understanding of cosmic ray origin, acceleration and propagation has been achieved [133]. However at higher energies exact sites of cosmic ray acceleration remain unknown. It is generally acknowledged that shock acceleration in supernovae offers a plausible explanation for cosmic ray origin upto $10^{14}$ eV [108, 17, 13]. Somewhat higher energies may be possible but $10^{16}$ eV is the upper limit. So origin of cosmic ray particles with energy $\geq 10^{17}$ eV is still not known. Galactic objects do not have the required size and magnetic field strength to contain a particle at these energies. Thus we have to look for objects of extragalactic origin. Active galactic nuclei (AGN) are one of the most probable candidates [110]. Cosmic rays are mostly charged particles therefore they are deflected by the galactic magnetic field. As a result they lose the sense of direction of their origin. So it is natural to search for neutral radiation like $\gamma$-rays and neutrinos from such sources which could pin point possible acceleration sites of high energy cosmic rays.

### 1.1.2 Physics and Astrophysics

Gamma-rays have very high energy, almost 10 orders of magnitude greater than a photon of visible light. Thus the processes which are responsible for the generation of low energy photons are not applicable for $\gamma$-rays. Most non-thermal processes are linked to relativistically moving plasma. It is generally believed that high energy $\gamma$-rays are produced due to highly accelerated electrons, positrons. The relativistic outflows are coupled with compact relativistic objects - neutron stars, black holes. For example Crab nebula is powered by the spin down of a highly magnetized rotating neutron star. Similarly, AGNs are thought to be powered by the gravitational potential contained in supermassive black holes of masses $10^{8-10} M_\odot$. The typical $\gamma$-ray luminosity of these AGNs are , $10^{49}$ erg s$^{-1}$. These $\gamma$-rays are emitted
Chapter 1. Introduction

from a very compact region (less than the size of our solar system). The theory of this relativistic collimated outflow of charged particles is complicated and not yet understood properly. More observations are required to obtain a detailed theoretical picture of these sources. Study of dark matter is another source of motivation for non-standard physics.

1.1.3 Cosmology

The photon flux from a $\gamma$-ray source is attenuated depending on the energy of the photon, the distance to the source and on the spectrum and the absolute flux of the diffuse extragalactic background radiation at infrared and optical wavelengths as shown in figure 1.2. In this figure energies of $\gamma$-rays are plotted along the x-axis and distance in Mpc along the y-axis. Gamma rays when interact with this IR/optical photon field, produces electron-positron pair. The rest mass energy of an electron is 0.511 MeV, so the threshold for electron-positron pair production is 1.02 MeV. Therefore $\gamma$-rays of energy $10^{15}$ eV could interact with cosmic microwave background (CMB) radiation, produce $e^+e^-$ pairs and get attenuated. At lower energies they interact with light of shorter wavelength, infrared and optical light. Thus TeV energy $\gamma$-rays pair-produce off infrared (IR) light. Unlike CMB infrared-optical background is poorly understood. If the intrinsic source spectra at TeV energies can be inferred from the observations of similar sources situated at different redshifts then the IR photon density can be estimated based on spectral measurements on these sources. This would also provide important information about the epochs of galaxy formation and their evolution in the past.

1.2 Gamma-ray Astronomy

Gamma-ray astronomy is the youngest of all the astronomies. The first source detections were made in the 1960s. It covers almost 14 orders of magnitudes of the electromagnetic energy range ($10^6$ eV to $10^{20}$ eV). The entire field of $\gamma$-ray astronomy is divided into two main domains. First one
Fig. 1.2: Mean free paths of $\gamma$-rays in the intergalactic medium. Below $10^{14}$ eV $\gamma$-rays interact with infrared and optical photons, above $10^{19}$ eV with low frequency radio emission. Large uncertainties (shown by different types of lines) in predicted mean free paths are the result of poorly known fluxes of the extragalactic diffuse background radiation at these wavelengths. Between $10^{14}$ eV to $10^{19}$ eV, $\gamma$-rays interact with the 2.7 K CMBR which is measured very well. Therefore the mean free paths at these wavelengths are predicted with high accuracy [24].

is *spaceborne $\gamma$-ray astronomy*, which ranges from 500 keV to 100 GeV. Gamma rays in this energy range can not penetrate the Earth’s atmosphere without being absorbed or scattered. Therefore, these $\gamma$-rays can only be detected in space using detectors on board satellite or high-altitude balloons. The other domain is that of *ground-based $\gamma$-ray astronomy*, which begins at energy above 100 GeV. At these energies while the $\gamma$-ray itself may not survive but the secondary products of its interaction with the atmosphere produces an electromagnetic cascade. These secondary products are responsible for the emission of Cherenkov light which can be detected on the ground. Various types of $\gamma$-ray detectors are shown schematically in figure 1.3.

The entire $\gamma$-ray spectrum is divided into several energy regions [135]. They are low energy (LE) $\leq$ 30 MeV, high energy (HE) range: 30 MeV to
Fig. 1.3: Spaceborne and ground based $\gamma$-ray astronomy. This figure is taken from [126].
30 GeV, very high energy (VHE) range: 30 GeV to 30 TeV, ultra high energy (UHE) range: 30 TeV to 30 PeV, and extremely high energy (EHE) \( \geq 30 \) PeV. So far no \( \gamma \)-ray source has been detected in UHE and EHE range. Even in VHE range only a fraction of the Universe is observable, the reason being \( \gamma \)-rays of these energy interact with diffuse extra-galactic photon field and get attenuated. Still it is this VHE window which is of intense interest for a \( \gamma \)-ray astronomer. In the last 15 years rapid advances in space based and ground based experiments have revolutionized this field. A large effort has been spent in bridging the gap between spaceborne \( \gamma \)-ray astronomy and ground-based \( \gamma \)-ray astronomy over these years.

### 1.2.1 Spaceborne \( \gamma \)-ray astronomy

Spaceborne \( \gamma \)-ray astronomy covers the high-energy range, i.e. 30 MeV to 30 GeV. The NASA mission SAS-2 was the first satellite which carried a \( \gamma \)-ray detector in space [58]. It was launched in 1972. It made some important detections, like, it mapped the galactic plane, discovered some discrete sources and also detected isotropic \( \gamma \)-ray radiations. In 1975, European \( \gamma \)-ray satellite COSB was launched [45], which confirmed the results of the SAS2 and further extended the \( \gamma \)-ray catalog. Energy range covered by these two satellites was 35 MeV to 5 GeV. They detected \( \sim 25 \) point sources, including Crab and Vela pulsars and active galactic nucleus 3C279 [128, 61, 109]. On 5th April, 1991, NASA’s Compton Gamma Ray Observatory (CGRO), shown in figure 1.4, was launched. It revolutionized the \( \gamma \)-ray astronomy. There were four detectors on board CGRO, namely, BATSE, OSSE, COMPTEL and EGRET [107]. Total energy range covered by this experiment was 20 keV to 30 GeV: BATSE: 20 - 1000 keV, OSSE: 0.05 - 10 MeV, COMPTEL: 0.8 - 30 MeV and EGRET: 20 MeV to 30 GeV. EGRET was the first sensitive instrument to cover energies upto 30 GeV, highest energy covered so far by a satellite. A schematic diagram of EGRET is shown in figure 1.5. It was made up of a spark chamber system [71, 100]. Gamma-rays were detected when they interacted to produce electron-positron pairs in a closely spaced stack of tantulum foils.
The pairs were tracked through the spark chamber layers and their energies were measured in a NaI calorimeter. Trigger was generated by a time-of-flight system. Cosmic ray events were vetoed by an anti-coincidence dome which used to cover the detector. EGRET has provided a deep study of the high energy $\gamma$-ray sky. The 3rd EGRET catalog [65], shown in figure 1.6, consists of 271 sources detected above 100 MeV. These catalog includes 93 AGNs\(^1\), 6 pulsars, 1 solar flare, Large Magellanic Cloud and the nearby radio-galaxy Cen A. It also contains 170 unidentified sources, that are yet to be identified in other wavelengths.

\[\text{Fig. 1.4: Compton Gamma Ray Observatory (CGRO). This figure is taken from [5].}\]

### 1.2.2 Ground based $\gamma$-ray astronomy

Satellite based experiments can detect $\gamma$-rays upto few tens of GeV. Beyond this energy range it is difficult to carry out this experiment on space because of rapidly falling flux of $\gamma$-rays from astronomical sources. For that it would be necessary to use detectors with very large area. Also, it would require

\(^1\text{out of which 66 were detected with high confidence and 27 with low confidence}\)
very long exposure to detect significant number of $\gamma$-rays. In addition to this to measure energy of $\gamma$-rays very deep calorimeter instrument would be needed. This would increase the weight of the detector enormously. Fortunately there is a way to detect VHE $\gamma$-rays at the ground level, albeit indirectly [23]. A VHE $\gamma$-ray creates an $e^-e^+$ positron pair as it propagates down the atmosphere. This pair then emits $\gamma$-ray via bremsstrahlung. Like this with successive pair-production and bremsstrahlung an electromagnetic cascade is developed. Charged particles present in this cascade emit Cherenkov radiation. This radiation can be detected at the ground level [106]. Telescopes which use this technique are called **Atmospheric Cherenkov Telescopes (ACT)**. Detail descriptions about this technique and those telescopes are given in the next chapter 2. Ground based telescopes have also made tremendous progress over the last few years. Almost every year new sources are discovered. Galactic $\gamma$-ray sources, detected with high significance, are **Crab Nebulae, Geminga, PSR 1706-44** etc. Among extragalactic sources, **Mkn 421, Mkn 501, 1ES1426+428** etc, are detected with high confidence level. In the last couple of years or so, HESS and

Fig. 1.5: Schematic diagram of Energetic Gamma Ray Experiment Telescope (EGRET) detector on board CGRO [4].
MAGIC collaborations have discovered many more galactic, as well as extragalactic sources. Figure 1.7 shows the VHE \( \gamma \)-ray sky, as reported in 29th ICRC, 2005. It is seen that compared to space-borne experiments number of sources detected by ground based experiments are much less. The reasons for this could be as follows: (i) The energy spectrum of galactic sources may cutoff at around 100 GeV or so. (ii) lower flux at higher energies. (iii) \( \gamma \)-rays from extragalactic sources get attenuated in the extragalactic space by the diffuse background light as shown in figure 1.2. VHE \( \gamma \)-rays mostly interact with IR/optical lights and produces \( e^- - e^+ \) pairs. Attenuation of these photons increases with the distance. Thus present day ACTs operating in the energy range \( \sim 1 \) TeV can see sources upto a distance of approximately 100 Mpc \((z=0.03)\). Instruments with lower thresholds can see upto larger distances. Detectors with energy threshold of 100 GeV can see upto 2.5 Gpc \((z=1)\). To see beyond \( \sim 4 \) Gpc \((z=3)\) threshold should be about 10 GeV. Therefore more efforts are made to reduce the energy thresholds of the future generation of atmospheric Cherenkov telescopes.
Fig. 1.7: Catalog of VHE $\gamma$-ray sources till year 2005. AGNs are shown by diamonds, Pulsar Nebula by squares, Supernova Remnants by triangles and other sources by circles. Sources marked with black symbols were detected before 2003 and red ones were detected after 2003 mostly by HESS and MAGIC collaboration. This figure is taken from R. A. Ong’s rapporteur talk in 29$^{th}$ ICRC, Pune (2003) [124].

1.3 Active Galactic Nuclei (AGN)

Active Galactic Nuclei or AGNs are a sub-class of galaxies. A galaxy is a system of stars, it contains on an average $10^{11}$ stars. There are several such galaxies in the universe. According to their shape they are classified into ellipticals, spirals and irregulars. Apart from shape they are further classified depending on their luminosities and other physical properties as Normal galaxies, Active galaxies etc. Normal galaxies are those whose observed optical radiation is the sum total of all the stellar emission. Active galaxies are those whose core luminosity exceeds the total stellar emission. Also, there is evidence for relativistic particle acceleration in those objects.

AGNs manifest themselves through extremely luminous emission from the nuclear region of a galaxy which often extends far into the X-ray and $\gamma$-ray band. In addition to the great energy output, they can be highly variable. This rapid fluctuation place strict limits on the maximum size of the energy
source, because an object cannot vary in brightness faster than it takes light to travel from one side of its energy-producing region to the other. Size of the emission region is obtained as [74]

\[ R_{\text{max}} = ct_{\text{var}}\delta \]

where \( c \) is velocity of light, \( t_{\text{var}} \) is variability time scale and \( \delta \) is the Doppler factor. The rapid flickering of AGN means that they draw their energy from a small volume, in some cases less than one light day across. Furthermore, observations of the orbital motion of stars and other material around AGN show that a large mass, ranging up to several billion solar masses, is concentrated within its engine room of the size of our solar system (\( \sim 10^{15} \) cm). This leads to the almost unavoidable conclusion that the central engine is a supermassive black hole. Since a black hole, by definition, emits nothing, the radiation from an AGN could come from material heated to several million degrees in an accretion disk before tumbling into the black hole or, in some cases, being shot away in jets along the central engine’s spin axis in both directions. It is generally accepted that these AGNs are powered by black holes of mass \( 10^8 - 10^9 M_\odot \). About 10% of all AGNs are more luminous at radio wavelengths than at optical ones and are, hence, called radio-loud. The radio emission is believed to originate in the associated jets of the spinning black hole [136]. The key features of an AGN are shown schematically in figure 1.8.

Blazars are the most powerful sub-class of AGN’s comprising radioquasars and BL Lac objects. The radiation emission by them is dominated by a highly variable component of non-thermal radiation produced in relativistic jets close to the line of sight of the observer. The extreme blazar is one in which the viewing angle is zero, i.e. observer is looking straight down the jet. Because of this reason waves and the durations of the outbursts are compressed by a large Doppler factor \( \delta \). The power received by a detector is thus increased by \( \delta^4 \) [19]. If no emission lines are seen, the object is classified as a BL Lacrate object. If it exhibits emission lines, it is classified as a Flat Spectrum Radio Quasar (FSRQ). These sources are often observable in all wavelength bands from radio waves to
\(\gamma\)-rays. The radiation from blazars generally consists of two broad components, one from radio through optical, UV, or even X-ray energies, is most likely due to synchrotron emission from relativistic electrons in the jet. The second emission component extends through X-ray and \(\gamma\)-ray energies and might be due to Compton upscattering of low-energy radiation by the same relativistic electrons which are responsible for the synchrotron emission at lower frequencies. On a power plot these SEDs show a two-humped shape. One of the characteristic features of these blazars is their time variability on scales ranging from hours to years. Blazars which were discovered in radio-surveys are called Low-frequency BL Lacs (LBLs) and in X-ray surveys called High-frequency BL Lacs (HBLs) [26]. For LBLs peak position of the first emission component is at IR/optical energies and peak position of the second emission component is at X-ray energies, as shown in the figure 1.9. Whereas for HBLs corresponding peak positions are at X-ray and \(\gamma\)-ray energies respectively, as shown in figure 1.10.

Fig. 1.8: This is a diagram of a typical AGN: a super-massive black hole at the center surrounded by an accretion disk and two jets of relativistic particle emanates perpendicular the plane of the accretion disk. If this jet is pointed towards us then they are called blazar.
1.3.1 High frequency peak BL Lac (HBL)

In case of High frequency peak BL Lac objects or HBLs high energy emission is extended up to TeV energies. The well established HBLs are Mkn 421, Mkn501 etc [113]. HBLs which are detected so far are mostly close by with redshifts ranging from 0.031 to 0.18.

Variability

HBLs can be highly variable. Extreme variability on time scales from minutes to years is the most distinctive feature of the VHE emission from HBLs. In 1996, Whipple collaboration detected two very intense flares [62] from Mkn421. During the first flare, which occurred on 7th of May, the $\gamma$-ray rate increased with a doubling time of 1.5 hr to a level which is approximately 40 times higher than the baseline level detected that year as shown in the left panel of the figure 1.11. In the second flare, on 15th of May, the $\gamma$-ray rate increased with a doubling time of 15 min to a peak rate that was 15 times higher than the baseline level shown in the right panel. Such
rapid variability implies that the acceleration region where TeV photons are produced must be relatively small.

**Multiwavelength Observations**

Radiation emissions from blazars are variable at all wavelengths across the electromagnetic spectrum. Therefore to understand the mechanisms at work in blazars, their spectra should be measured simultaneously at each wavelength.

**Correlations:** For HBLs it was observed that VHE $\gamma$-rays and X-rays are well correlated. Flares in TeV energies are mostly associated with flares in X-rays for these sources. For Mkn 421 flare in VHE $\gamma$-ray energies are mostly correlated with flare in X-rays. Details of this correlation is discussed in chapter 6. In 1997, the VHE emission in Mkn 501 increased dramatically. During this period X-ray flux had also increased rapidly, as shown in figure 1.12. It was also seen that low-energy emissions like radio, optical/IR are generally not correlated with high-energy emissions like X-rays and $\gamma$-rays.
Chapter 1. Introduction

**Fig. 1.11:** Light curves of two flares observed from Mkn 421 by Whipple collaboration on 7th May 1996 (left panel) and 15th May 1996 (right panel).

**Fig. 1.12:** Daily average of excess X-ray rates (upper panel) and $\gamma$-ray rates (lower panel) from Mkn 501 measured by ASM on board RXTE and HEGRA experiment respectively during 1997 outbursts [76].

*Time lag:* Time lag in emission between wavelengths that are correlated is an important parameter in understanding the emission mechanisms. In most of the cases it is seen that the time lag between X-ray and $\gamma$-ray emis-
sions for HBLs is almost zero, i.e., the emission is almost simultaneous. Time lags of the order of few days have also been noticed for some of the HBLs.

**Spectral Energy Distribution (SED):** Spectral Energy Distributions are expressed as power per logarithmic bandwidth. It is a measure of the power observed at each frequency. Figure 1.10 shows the SED for Mkn 421. This plot is obtained by collecting data from the all the wavelength bands at different times. It is seen that this source shows variability at many wavelengths. But it is not clear whether they are correlated or not. To see if there is any correlation exists between different wavebands simultaneous co-ordinated observations are necessary. Also, a measurement of time lag in radiation emissions between the correlated wavebands could constrain various models.

### 1.4 Blazars: models

Blazars can be observed over 19 decades of energy. Bulk of the observed radiation is non-thermal. Observed $\gamma$-ray luminosity is very high $L_\gamma \approx 10^{49}$ erg s$^{-1}$. There is evidence of particle acceleration in the jet. Ultra-energetic particles are continually accelerated along the jet. High-energy emissions take place near the core and low-energy emissions come from further down inside the jet, as shown in the figure 1.13. Although a supermassive black hole is at the center of the AGN, but it is still not clear what could be the source of energy for the entire system and how jets have formed. There are two different school of thoughts about jet formation. First is based on black hole spin, which says black holes with larger spin (intrinsic angular momentum) could cause the jets to produce via their impact of their spin on the space-time geometry near the black hole. Second thought is accretion disk mechanism, according to this jet is powered directly by accretion onto the black hole. The jet origin depends on the details of the magnetic field configuration near the black hole and initial mass loading of the magnetic field lines.
1.4.1 Beaming

It is surmised from the observed short-term (light-minutes to light-hours) variability that the source emission region is very compact. Therefore, given the observed $\gamma$-ray luminosity $\approx 10^{49}$ erg s$^{-1}$, it would not be possible for the $\gamma$-rays to emerge from the source without absorption by $\gamma-\gamma$ pair production, known as *Compton catastrophe*, unless there is relativistic beaming. It is believed that relativistic jets are Doppler boosted. The Doppler factor, $\delta$, of an object moving at

$$\beta = \frac{v}{c}$$

making an angle $\theta$ with the line of sight is given by

$$\delta = [\Gamma(1 - \beta\cos\theta)]^{-1}$$

Where $\Gamma$ is bulk Lorenz factor, defined by

$$\Gamma = \frac{1}{\sqrt{1 - \beta^2}}$$

Introduction of Doppler factor simplifies the explanation of several observed properties of blazars [16]. Because of Doppler factor, $t_{\text{obs}} = t_{\text{source}}/\delta$, so the size of the emission region which appears to be very small from observed short-time variability increases by a factor $\delta$, and thus $\gamma$-rays could
avoid Compton catastrophe. Secondly, it is very difficult to explain how particles are accelerated to such high energies which are observed. Now, because of relativistic boosting observed \( \nu_{\text{obs}} = \delta \nu_{\text{source}} \) i.e. emitted photon frequency is a factor \( 1/\delta \) less than that actually observed. Hence, the maximum energy that must be achieved are reduced. This also reduces the requirement on source luminosity from the enormous observed luminosity as \( L_{\text{obs}} = \delta^4 L_{\text{source}} \).

1.4.2 Leptonic Model

The double-peaked SEDs of blazars are explained using Compton-synchrotron model. According to this model electrons are accelerated beyond the velocity of the bulk Lorenz outflow. This acceleration is probably caused by the colliding inhomogeneities in the jet. The electrons radiate synchrotron radiation in the magnetic fields associated with the jet and thus produce the first peak in the SED. Second peak in SED is due to Compton upscattering of lower energy radiation by the same relativistic electrons which are responsible for synchrotron emission. This is called Synchrotron self-Compton (SSC) [81]. There is another possibility that relativistic electrons collide with soft photons from the microwave background and produces the second peak. In some cases these external photons are denser and thus dominant targets for inverse Compton scattering.

Even though correlation between X-ray and \( \gamma \)-ray data can be explained by SSC mechanism, a few TeV orphan flares detected from some HBLs (e.g. for Mkn 421, 1ES 1959+650) which were not associated with any X-ray flares can not be explained by SSC mechanism. To explain such orphan flares following models were proposed [97].

**Multiple-Component SSC Models**: According to this postulate, a second dense electron population within a small emission region exists. This has 1200 times larger energy density of this electron population and the emission volume is 5400 times smaller compared to the region where the quiescent emission comes from. This lead to a high inverse Compton to synchrotron luminosity ratio and therefore a \( \gamma \)-ray flare without a strong X-
ray flare. This model does not suffer from Compton catastrophe because optical thickness for internal absorption in pair production process ($\gamma_{\text{TeV}} + \gamma_{\text{seed}} \rightarrow e^+ e^-$) is well below 1 over the full range of $\gamma$-ray energies covered by the TeV observations.

**External Compton Models**: In external Compton models, the $\gamma$-ray flux originates from inverse Compton processes of high energy electrons with radiation external to the jet. Variations of the external photon intensity in the jet frame can cause $\gamma$-ray flares without lower energy counterparts. Such external photon flux could have different origins e.g., from the accretion disk [97, 59].

**Magnetic Field Aligned along Jet Axis**: If the magnetic field in the emission region of the orphan flare is aligned with the jet axis and thus with the line of sight, the observer would not see the synchrotron flare. The electrons, however, would scatter SSC $\gamma$-rays in our direction, and thus we would be able to see inverse Compton flare.

### 1.4.3 Proton Models or Hadronic Models

All these above mentioned models assumes only electrons are responsible for emission of $\gamma$-rays, thus these set of models also being referred as leptonic models. To explain this phenomena some authors have also suggested models where protons, instead of electrons, are responsible for emission of $\gamma$-rays. In proton models, the low energy radiation is produced by a population of non-thermal electrons and high energy emission by accelerated protons, either directly as synchrotron radiation [9, 85] or via proton induced cascade [?]. In this models, the TeV $\gamma$-ray emission originates from a thin surface layer of an optically thick plasma, while the X-ray emission originates from the full emission volume. Thus orphan $\gamma$-ray flares occur as the thin surface layer can produce more rapid flares than the larger X-ray emission region. These models are proposed mainly to explain two phenomena, firstly, production of VHE $\gamma$-rays in AGN and secondly, the origin of extragalactic cosmic radiation with energies upto $10^{20}$ eV and beyond. The protons interact with soft photons in the jet and produce mesons by
Fig. 1.14: Hybrid model of a blazar

These mesons then produce $\gamma$-rays (high energy radiation). The low energy radiation is produced by synchrotron emission from the secondary products of the cascade. In some models $\gamma$-rays are synchrotron radiation from the protons whose energies can reach up to $10^{20}$ eV. But this approach has a serious constraint, they can not account for rapid cooling necessary for the short time variability observed. A by-product of proton models is that the decay of charged pions will produce energetic neutrinos. If the next generation of neutrino telescopes detect such flux then that would put a question mark on leptonic models. But at present it is this leptonic model which has wider acceptance to the physics community. A cartoon of the emission of $\gamma$-rays in the AGN jets is shown in the figure 1.14.
Chapter 2

Atmospheric Cherenkov Technique

Earth’s atmosphere is opaque to all the celestial $\gamma$-rays. By no means these $\gamma$-rays can be detected on ground directly. As mentioned earlier in low energy domain astrophysical $\gamma$-rays can be detected by space borne experiments. Above few tens of GeV it becomes practically impossible to carry out $\gamma$-ray astronomy in space as mentioned in section 1. Fortunately, these high energy $\gamma$-rays when enter the earth’s atmosphere interact with a nucleus of an air molecule and produce relativistic $e^- - e^+$ pairs. These secondary particles produce Cherenkov radiation as they propagate down the atmosphere which can be detected at the ground level with a simple arrangement of a reflector (mirror) and a light collector (photo-multiplier tube) as shown in figure 2.1. This technique is called Atmospheric Cherenkov Technique (ACT) [18, 106, 117]. ACT covers the energy range from about 10 GeV to 100 TeV, known as Very High Energy range. Details of this technique and its various aspects are discussed in the following sections. Cherenkov radiation and its properties are described in section 2.1. Section 2.2, gives details of extensive air shower. General properties of atmospheric Cherenkov telescopes are discussed in section 2.3. Differences between imaging technique and wavefront sampling technique are explained in section 2.4.
Chapter 2. Atmospheric Cherenkov Technique

2.1 Cherenkov Radiation

Cherenkov radiation is produced by dielectric medium when a charged particle passes through it with a uniform velocity, the velocity being greater than the phase velocity of light in that medium. This radiation was first observed in 1900’s by Mary and Pierre Curie. A detailed experimental work was carried out by P. A. Cherenkov and Vavilov between years 1934-1937. Theoretical interpretation of this phenomenon was given by I. E. Tamm and I. M. Frank in 1937. Emission of Cherenkov radiation can be explained in the following way. Consider a charged particle, moving in a dielectric medium with a velocity greater than the velocity of light in that medium (\(v > c_m\), Where \(c_m\) is the velocity of light in that medium). As it passes by the atoms in the dielectric medium, momentarily polarizes them (pushing like charges in the atom away, and inducing a dipole state) as shown in figure 2.2. Once the particle has passed, this polarized state collapses, causing each atom to emit Cherenkov radiation. For slow moving particles (\(v < c_m\)), the polarization is perfectly symmetrical w.r.t particle position,
as shown in figure 2.3, resulting in no electric field at long distances (and thus no radiation). When the particle is moving very quickly, polarization is no longer symmetrical. The state is still symmetric in the azimuthal plane, but no longer along the axis of motion (a cone of dipoles develops behind the electron). There would now be distinct dipole field established in the dielectric, one that can only be collapsed with the emission of Cherenkov radiation. Radiation would be emitted perpendicular to the surface of this cone. This phenomena is very similar to the shockwave produced by supersonic jets as shown in figure 2.4. The Cherenkov radiation is emitted at an angle that depends on the refractive index of the medium and is beamed in the forward direction [116].

![Fig. 2.2: Polarization set up when a charged particle passing through a dielectric at v > c_m. This figure is taken from [2].](image1)

![Fig. 2.3: Polarization set up when a charged particle passing through a dielectric at v < c_m. This figure is taken from [2].](image2)

Cherenkov radiation is **coherent** [115] in nature. From figure 2.5 it is seen that this radiation can be only observed at a particular angle Θ called **Cherenkov angle**, with respect to the track of the particle. The coherent emission takes place when the particle travels from A to B. In same time the light travels from A to C. Waves from arbitrary points P1, P2 and P3 over the track AB are coherent and combine to form a plane wavefront BC. If the velocity of the particle is v (or β·c where c is the velocity of light in the vacuum) and \( \frac{v}{n} \) is the velocity of light in the medium then Θ can be
defined as

\[ \cos \Theta = \frac{c}{\beta \cdot n(\lambda)} \cdot \Delta T \]  

(2.1)

\[ \cos \Theta = \frac{1}{\beta \cdot n(\lambda)} \]  

(2.2)

where \( n(\lambda) \) is the refractive index of the medium for wavelength \( \lambda \) and \( \Delta T \) is the time in which the particles moves from A to B. This equation suggests following things:

- For a given medium of refractive index \( n \) there exists a threshold velocity of particles

\[ \beta_{min} = \frac{1}{n} \]  

(2.3)

below which no radiation takes place. Corresponding threshold energy is

\[ E_{min} = \Gamma_{min} m_0 c^2 \]  

(2.4)
where
\[ \Gamma_{\text{min}} = \frac{1}{\sqrt{1 - \beta_{\text{min}}^2}} \] (2.5)

- For ultra-relativistic case where \( \beta \approx 1 \),

\[ \cos \Theta_{c_{\text{max}}} = \frac{1}{n} \] (2.6)

- Emission takes place in visible and near visible region for which \( n(\lambda) > 1 \). Emission in other wavelengths including X-ray and \( \gamma \)-ray region is not possible since for their energies \( n(\lambda) < 1 \), which will not satisfy the above equation. Thus radiation in X-ray or \( \gamma \)-ray energies is forbidden.

In the atmosphere at ground level, \( n=1.00029 \) and \( \Theta_{c_{\text{max}}} \) is \( 1.3^\circ \). Energy thresholds for Cherenkov emission from electron, muon and proton are 21 MeV, 4 GeV and 39 GeV respectively. The light yield is about 30 photons m\(^{-1}\). In water, where \( n=1.33 \), \( \Theta_{c_{\text{max}}} \) is \( \sim 41^\circ \). Energy threshold for electron is 260 keV and Cherenkov photon yield is 2500 photons m\(^{-1}\).

Number of Cherenkov photons produced per unit path length is given by
\[ \frac{dN}{dl} = 2\pi \alpha \left( \frac{1}{\lambda_2} - \frac{1}{\lambda_1} \right) \left( 1 - \frac{1}{\beta^2 n^2} \right) \] (2.7)
in the wavelength interval \( \lambda_1 \) and \( \lambda_2 \). Here \( \alpha \) is the fine structure constant.

Number of Cherenkov photons produced per unit wavelength interval is given by [106] -
\[ \frac{dN}{d\lambda} \propto \frac{1}{\lambda^2} \] (2.8)

Emission of Cherenkov radiation takes place in the optical band of electromagnetic spectrum with bulk of the light emitted in ultra-violet and blue parts of the spectrum.

There are two more conditions to be fulfilled for Cherenkov radiation to achieve coherence. Firstly, the length \( l \) of the track of the particle in
Chapter 2. Atmospheric Cherenkov Technique

2.2 Extensive Air Shower

A steady rain of cosmic radiation, most of them being charged particles, continuously bombards our Earth at all times from all directions. Energies of these cosmic rays are spread over 14 orders of magnitude, \(10^6\text{eV}\) to \(10^{20}\text{eV}\). About 96% of these cosmic rays are protons, 3% He nuclei and remaining 1% consists of other heavy nuclei, \(\gamma\)-rays, \(e^-\cdot e^+\) etc. Charged
Chapter 2. Atmospheric Cherenkov Technique

particles during their flights through inter-stellar medium get deflected by the inter-stellar magnetic field and thus lose sense of their initial arrival direction. Whereas $\gamma$-rays, even though their flux is much lower than cosmic rays ($\sim 10^{-3}$), retain their sense of directionality. It is this sense of directionality which acts as a great boon for $\gamma$-ray astronomers to search for point sources or possible sites of cosmic ray sources. Cosmic rays as well as $\gamma$-rays initiate a cascade of charged particles and photons in the atmosphere. This cascade is called an extensive air shower (EAS) [130].

2.2.1 Gamma-ray initiated shower

A cosmic $\gamma$-ray when enters the earth’s atmosphere interacts with the matter present in the atmosphere. In this radiation-matter reaction three effects can take place (a) photo-electric effect, (b) compton scattering and (c) pair production. At the energies involved for a EAS initiated by $\gamma$-rays, pair production is the dominant effect. To produce a $e^-e^+$ pair a $\gamma$-ray should have energy of at least 1.022 MeV. If this pair has sufficient energy then they produce $\gamma$-rays in the field of nucleus via bremsstrahlung. These $\gamma$-rays, if their energies are still higher than 1.022 MeV, can produce $e^-e^+$ pairs which may further undergo bremsstrahlung interaction. Thus an electromagnetic shower is generated which consists of $e^-, e^+$ and $\gamma$-rays as shown in figure 2.6. This electromagnetic cascade continues to increase in size until the average energy of the particles falls below the critical energy $E_c$. One radiation length ($\xi$) is the mean distance over which a $\gamma$-ray and a high energy electron loses all but 1/e of its energy. A $\gamma$-ray loses its energy by pair production and high energy electron via Bremsstrahlung. For a photon this radiation length is 48.5 gm/cm$^2$ and for electron 37.7 gm/cm$^2$. Let us assume a $\gamma$-ray of energy $E_0$ produces an $e^-e^+$ pair after traveling a distance $R$. This first interaction takes place at an altitude of about 20 km. During the first interaction each particle will have half of the initial energy on the average. After traveling another distance $R$, each particle will produce a photon of average energy $\frac{E_0}{4}$. Distance $R$ can be expressed in terms of radiation length as $R = \xi_0 \cdot ln2$. At a distance nR into the shower $2^n$
particles are created with an average energy $E_0/2^n$. This multiplicativem process continues until average energy per particle falls below $E_c$ (81 MeV in the air for $e^-e^+$). From this point onwards energy loss by ionization becomes dominant for $e^- & e^+$. At this point cascade reaches a shower maximum, it will have maximum number of particles. For an incident $\gamma$-ray of 1 TeV, shower maximum will occur at an altitude of $\sim 8$-9 km. After that number of particles gradually decreases and the cascade dies away.

Fig. 2.6: EAS initiated by a cosmic $\gamma$-ray.

Electrons and positrons present in the electro-magnetic shower radiates Cherenkov light provided their energies are greater than the minimum threshold required for Cherenkov emission at that altitude. Energy threshold for emission of Cherenkov radiation increases with the altitude as the refractive index of air decreases with altitude. The refractive index $n$ can be written as

$$n = 1 + \delta$$

(2.9)

$\delta$ is proportional to density therefore it decreases with height following the
relation

\[ \delta = \delta_0 e^{-h/h_0} \quad (2.10) \]

where \( h \) is the vertical height above sea level and \( h_0 \) is the scale height equal to 7.1 km. Threshold energy increases with decrease in \( \delta \) following equation

\[ E_{\text{min}} = \frac{m_0 c^2}{\sqrt{2\delta}} \quad (2.11) \]

This threshold is 21 MeV at sea level at STP and increases with the altitude\(^1\).

Figure 2.7 shows the schematic diagram of the Cherenkov light pool at the observation level. The Cherenkov photon yield in air is very little as low as 0.36 photons cm\(^{-1}\) at sea level but its attenuation in the atmosphere is very small. Therefore most of these photons reach to the ground. The number of Cherenkov photons per unit path length is very small. Also these photons are to be detected against a pre-dominant background of Night Sky Background photons and ambient light. Angle of emission of this Cherenkov radiation is small, it is about 1° at 8 km altitude and increases as altitude decreases.

In the lateral distribution of Cherenkov photons for a \( \gamma \)-ray cascade a **hump** [129] like structure is present at a core distance of about 120-140 m. This is because of the following reason. The core distance, \( r \), at which the Cherenkov photons arrive is equal to \( h\theta_c \), where \( h \) is the height of production of these photons and \( \theta_c \) is the Cherenkov emission angle. Increase in \( h \), to a large extent is compensated by decrease in \( \theta_c \), \( h\theta_c \) is roughly constant over the range of 7-20 km. As a result there is artificial focusing of Cherenkov photons at the distance \( r \). High-energy electrons present in the shower are mostly responsible for the **hump**. As these electrons travel down the atmosphere they lose energy by the bremsstrahlung process, thereby increasing the scattering angle (\( \propto 1/E \)) and emit Cherenkov radiation till their energies are higher than the Cherenkov threshold. For high-energy electrons r.m.s scattering angle could be smaller than the Cherenkov angle. Cherenkov emissions from these electrons are focused at a distance \( h\theta_c \). For

---

\(^1\)35 MeV at 7.5 km above sea level
Fig. 2.7: Cherenkov Light Pool at Ground Level

low-energy electrons r.m.s scattering angle is greater than the Cherenkov angle and hence there is no artificial of Cherenkov photons, so they spread out. If the contribution to the density of photons from high-energy electrons is comparable or larger than that due to low-energy electrons, then *hump* will appear, as shown in figure 2.8. This *hump* like shape gets smeared up with increasing primary energy and with the increase in altitude of the observation level. For higher primary energies as the shower maximum approaches the observation level, the product $h\theta_c$ starts decreasing. As a result the region inside 135 m will be filled up more due to high-energy electrons at lower altitudes, thus reducing the prominence of the *hump*. On the other hand as the altitude of observation level increases the shower maximum for a given primary energy comes closer to the observation level and the situation is similar to the case of a fixed observation level but with increasing primary energy. Thus hump reduces as altitude increases.
Fig. 2.8: Due to artificial focusing of Cherenkov photons there is hump like structure seen in case of electromagnetic shower [111].

### 2.2.2 EAS initiated by cosmic ray charged particles

When a charged cosmic ray (also called hadron) enters the Earth’s atmosphere it interacts with air nucleus and produces many secondary particles including three types of $\pi$-mesons ($\pi^\pm$ and $\pi^0$). The neutral pions ($\pi^0$) instantaneously decay into $\gamma$-rays, while charged ones either decay into $\mu^\pm$ which further decay into electrons and neutrinos or interact with air molecule and produces further secondary particles including pions as shown in figure 2.9. These interactions are given below along with their respective decay times ($\tau$).

\[
\begin{align*}
\Pi^0 & \rightarrow 2\gamma \quad \tau = 1.8 \times 10^{-16} s \quad (2.12) \\
\Pi^\pm & \rightarrow \mu^\pm + \nu_\mu (\bar{\nu}_\mu) \quad \tau = 2.5 \times 10^{-8} s \quad (2.13) \\
\mu^\pm & \rightarrow e^\pm + \nu_e (\bar{\nu}_e) + \nu_\mu (\bar{\nu}_\mu) \quad \tau = 2.2 \times 10^6 s \quad (2.14)
\end{align*}
\]
Fig. 2.9: Model of an extensive air shower initiated by a cosmic ray. When an incident proton interacts at the top of the atmosphere it produces three overlapping cascades. Firstly, nuclear cascade, consisting of nuclei and heavy hadrons, which produces additional hadrons and pions. Second is pionic cascade which is initiated and fed by pions produced in the nuclear cascade. The third is electromagnetic cascade initiated by $\gamma$-rays, produced from decaying neutral pions.

These hadron initiated showers also contain large number of $e^\pm$ and a few mesons and other charged hadrons which produce Cherenkov radiation. This Cherenkov light pool is lookwise very similar to those produced by celestial $\gamma$-rays. This poses a major problem in the detection of $\gamma$-rays by the ground based ACTs.

The integral flux of cosmic ray particles above 1 TeV is $\sim 1.7 \times 10^{-5}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$ [88]. For 1° aperture, the cosmic ray rate is $4.1 \times 10^{-9}$ particles cm$^{-2}$ s$^{-1}$ which is 400 times higher than the integral $\gamma$-ray flux from the Crab Nebula above 1 TeV. Success of an atmospheric Cherenkov telescope lies on how well it can distinguish a $\gamma$-ray initiated shower from overwhelming background of hadron initiated showers. There are certain features which enable one to distinguish between a hadron initiated shower and a $\gamma$-ray initiated shower.
2.2.3 Gamma-Hadron separation

Mechanisms for emission of Cherenkov light are identical for γ-ray and cosmic ray initiated EAS. But because of the differences in development of air showers in the atmosphere for γ-ray and cosmic ray Cherenkov light distribution on ground is different [139, 112, 103]. Cosmic ray (or hadron) initiated shower has three sub-cascades, electromagnetic cascade, pionic cascade and nuclear cascade. Pionic and nuclear cascades are less efficient in producing Cherenkov lights. This is because the threshold energies for muons and for protons to emit Cherenkov radiation are much higher compared to that of e±. For a hadronic shower bulk of the Cherenkov light is emitted from electromagnetic component. But only 1/3 rd of the primary energy goes into this component. Therefore for a hadron initiated shower Cherenkov photon density at the observation level is much less than a γ-ray initiated shower of same energy. Therefore to have similar densities energy of the hadron should be higher than that of γ-ray as shown in figure 2.10.

![Photon Positions on Ground for 50 GeV Gamma](image1)

![Photon Positions on Ground for 200 GeV Proton](image2)

Fig. 2.10: The left shows the arrival positions on the ground of all Cherenkov photons in an air shower initiated by a 50 GeV γ-ray. The right shows the same information for an sir shower initiated by a 200 GeV proton [88].

Lateral distribution of Cherenkov photons at the observation level can
also be used to distinguish between a γ-ray initiated shower and hadron initiated shower. As mentioned in the previous section a hump like structure is present in the lateral distribution of Cherenkov photons of a γ-ray initiated shower. Whereas for a hadron initiated shower this hump like shape is not present. In hadronic showers, the source of electrons is pair production by γ-rays which are decay products of π^0's. Because of the transverse momentum of these pions opening angles are larger compared to the secondary particles of a electromagnetic shower, as shown in figure 2.11. Therefore opening angles of electrons in the hadronic showers depend on the opening angles of π^0's. Hence electrons in hadronic cascade need to have much higher energy for Cherenkov angle to exceed r.m.s. scattering angle plus production angles of π^0's compared to electrons in γ-ray cascade. Only very energetic electrons can contribute to hump. As a result there is no sharp peak in the lateral distribution of hadronic showers. Again the interaction length for a primary proton in the atmosphere is about 80 gm cm^{-2} compared to 48.5 gm cm^{-2} for γ-rays. Therefore proton showers will develop further down into the atmosphere as a result there is a more intense pool of Cherenkov light close to the shower axis. Moreover, each sub-cascade of a cosmic ray shower will produce Cherenkov light. Lateral distributions of each of these sub-showers overlap at the ground level and give rise to an irregular density profile as shown in figure 2.10. Because of all these factors hump gets smeared out completely for a hadronic shower, as shown in figure 2.12.

Another distinguishing feature is the timing profile of Cherenkov light pool generated by a γ-ray shower and a hadronic shower. Light striking at large radii on the ground has to travel a longer distance than light near the center of the light pool, as a result Cherenkov wavefront has a concave timing profile. For γ-ray initiated shower this concave shape is very much evident, whereas for protons it is not. Since a hadronic shower is a mixture of several sub-showers, timing profiles of these showers give a very irregular shape at the ground level as shown in figure 2.13.

At energies below 200 GeV Cherenkov photon density decreases rapidly for cosmic ray showers, shown in figure 2.14. This decrease results from
Fig. 2.11: Simulation of the atmospheric showers produced by a 100 TeV cosmic iron nucleus (right), a proton (centre) and a $\gamma$-ray (left). Red denotes electromagnetic particles above 10 GeV, green denotes muons above 10 GeV and black denotes hadrons above 10 GeV. This figure is taken from [6].

rapid energy degradation in hadronic showers which leads to a large number of shower particles being produced below Cherenkov threshold energy. Thus telescopes operating at lower energy thresholds can distinguish a $\gamma$-ray shower from a hadronic shower by comparing their Cherenkov photon density profiles.

Relativistic electrons impinging at the top of the atmosphere also produce electromagnetic cascade. This cascade is very similar to that of $\gamma$-ray initiated cascade. But the electron background is a very small component for ACTs operating at thresholds above $\sim$ 100 GeV.

### 2.2.4 Night Sky Background (NSB) and ambient light

Intensity of Cherenkov light is $10^{-4}$ times that of NSB but the wavelength distributions are different. Cherenkov spectrum peaks towards the shorter wavelengths while the NSB peaks at the longer wavelengths. Normally PMTs are selected with quantum conversion efficiency peaking around ul-
Fig. 2.12: Schematic diagram of the lateral distributions for \( \gamma \)-ray and hadron initiated showers. Gamma-ray shower shows a relatively flat distribution with a hump at 120-130 m from core, whereas for proton shower photon density decreases continuously with increasing core distance.

Ultra violet - blue region and hence PMT photocathode itself acts as a filter to some extent. Secondly, NSB photons arrive randomly in time whereas Cherenkov photons are coherent and last for a few nano seconds. Therefore if a detector has integration time of that order it could record most of the Cherenkov photons. During this short time interval intensity of Cherenkov photons can exceed that of NSB. Moreover a coincidence of pulses from several detectors can reduce the effect of NSB and ambient light drastically.

### 2.3 General properties of atmospheric Cherenkov telescopes

Atmospheric Cherenkov telescopes detect \( \gamma \)-rays from celestial sources indirectly using the mechanism described in the previous sections. A detailed summary of various technical aspects, e.g. energy threshold, collection area etc, of these ACTs are given below.
Fig. 2.13: Lateral timing profiles of the arrival times of the shower wavefronts at different locations are shown for γ-ray and proton showers. Proton initiated showers have more irregular timing profiles. The horizontal axes are positions on the ground, in meters, while the vertical axes are arrival times in nanoseconds. This figure is taken from [131].

2.3.1 Energy Threshold

For a telescope of an ACT energy threshold (E_{th}) is defined as the minimum γ-ray energy for which signal to noise ratio is sufficient to trigger the detector, i.e. E_{th} is inversely proportional to signal to noise ratio [123]. If photoelectron Cherenkov signal S is given by

$$S = \rho A \epsilon$$

(2.15)

where \(\rho\) is density of Cherenkov photons on the ground, A is the area of the reflector and \(\epsilon\) is the efficiency of light collection. Cherenkov photon density, at the ground level within a circle of radius 125 m from core, is proportional to the energy of the primary γ-ray. Thus Cherenkov photon density, i.e. \(\rho_\gamma\) can be defined as

$$\rho_\gamma = y_\gamma E$$

(2.16)
Fig. 2.14: Comparison of the average Cherenkov photon density as a function of primary energy for air showers initiated by $\gamma$-ray and various cosmic ray primaries [88].

where $y_\gamma$ is some scaling factor called Cherenkov photon yield and $E$ is the energy of the primary $\gamma$-ray. Therefore $S$ can be written as

$$S = y_\gamma E A \epsilon \quad (2.17)$$

Noise level, $N$, can be expressed in terms of the fluctuations of the NSB

$$N = \sqrt{B \Omega A \epsilon t} \quad (2.18)$$

$B$ is NSB photon flux, $\Omega$ is the solid angle subtended by a PMT and $t$ is trigger formation time. Thus signal to noise ratio is given by

$$\frac{S}{N} = y_\gamma E \sqrt{\frac{A \epsilon}{B \Omega t}} \quad (2.19)$$

Therefore

$$E_{th} \propto \frac{1}{y_\gamma} \sqrt{\frac{B \Omega t}{A \epsilon}} \quad (2.20)$$
It is seen from this equation that energy threshold of an ACT can be reduced either by reducing the noise contribution from the night sky background or by increasing reflector area.

Present generation of ACTs use not a single telescope but an array of telescopes where more than one telescopes are operated in coincidence. Energy thresholds of such experiments can be reduced even more as compared to that of a single telescope.

2.3.2 Flux Sensitivity

The sensitivity of an ACT is determined by its ability to detect a $\gamma$-ray signal over the cosmic ray background which is isotropic and pervasive in nature [123]. Cosmic ray background flux has power law spectrum.

$$F_{cr}(> E) \propto E^{-\alpha}$$ (2.21)

Around 1 TeV $\alpha \sim 1.7$ $\gamma$-ray flux can be written similarly as

$$F_{\gamma}(> E_{\gamma}) \propto E_{\gamma}^{-\alpha_{\gamma}}$$ (2.22)

If $S$ is the number of $\gamma$-rays detected in a given time $t$ then

$$S = F_{\gamma}(E) A_{\gamma} t$$ (2.23)

where $A_{\gamma}$ is the collection area of the experiment. Background $B$ is given by

$$B = F_{cr} A_{cr} \Omega t$$ (2.24)

where $\Omega$ is the solid angle. Then the minimum number of standard deviations $N_{\sigma}$ is defined as,

$$N_{\sigma} \propto \frac{S}{\sqrt{B}} \propto E^{\frac{1}{2} - \alpha_{\gamma}} \sqrt{t} \sqrt{\frac{A_{\gamma}}{A_{cr} \Omega}}$$ (2.25)

Thus flux sensitivity can be optimized by operating telescope at the minimum possible energy, increasing the observation time and by minimizing the collection area $\times$ solid angle product for cosmic rays while maintaining
a reasonable collection area for $\gamma$-rays. This is assuming no rejection of cosmic rays. Let, $f_a$ be the fraction of $\gamma$-rays accepted and $f_r$ be the fraction of cosmic rays rejected then the above equation becomes,

$$N_\sigma \propto \frac{S}{\sqrt{B}} \propto E^{1.7} \gamma^{0.7} \sqrt{t} \left[ \frac{A_\gamma f_a}{A_{cr} \Omega} \right] \left(1 - f_r \right)$$

(2.26)

Thus flux sensitivity can be improved by increasing $f_a$ and $f_r$.

### 2.3.3 Collection Area

In all other wavebands collection area is determined by the dimension of the telescope, but for an ACT it is not restricted by the physical size of the telescope. The radius of the Cherenkov light pool on the ground is $\approx 120$ m as shown in figure 2.7, therefore the shower detection area is $\sim 5 \times 10^4$ m$^2$. This collection area is very large compared to that of a satellite experiment which is $\sim 1$ m$^2$. A Cherenkov shower can be sampled anywhere in this large area and detected. This ability of an ACT to achieve such large collection area makes it so powerful and it is possible to detect TeV $\gamma$-rays in spite of their low fluxes.

### 2.4 Differences between wavefront sample and imaging techniques

Atmospheric Cherenkov telescopes are divided into two classes, namely, imaging atmospheric Cherenkov telescope and Wavefront Sampling telescopes. Figure 2.15 shows the difference between these two techniques schematically. Detailed descriptions of both the telescopes are given below.

Imaging Atmospheric Cherenkov Telescope (IACT) has an array of PMTs in the focal plane of a large optical reflector constituting a camera and is used to record Cherenkov light picture of each air shower [137]. The camera is triggered when a preset number of PMTs detect a light level above a set threshold within a short integration time. Each phototube actually receives light from a different part of the sky and together the phototube
camera forms a coarsely pixellated image of the night sky. Showers which arrive parallel to the optic axis will have roughly elliptical images. IACTs use the shape and orientation of the air shower image in the camera plane to distinguish between a $\gamma$-ray and hadronic air showers. If the telescope is pointed directly at a point source of $\gamma$-rays, the $\gamma$-ray events in the camera will point towards the center of the camera. Whereas cosmic ray events, being distributed isotropically in angle, will have a random orientation. Also, image of a hadronic shower will be broader and irregular than the image formed by an electromagnetic shower. The incident direction of a $\gamma$-ray event is determined from the shower orientation. The energy of the primary particle can be estimated from the length of the image and by the total charge in all the photo-tubes which have triggered, which correlate with the total Cherenkov yield in the shower. If only one imaging telescope is operating then there are few problems associated with that, e.g. it can not elimi-
nate local muon background, angular resolution is not good since normally an IACT has large field of view and it can not locate core of the shower. Therefore now-a-days scientists are building array of imaging telescopes. This has following advantages, energy threshold can be reduced using a coincidence trigger between telescopes. Multiple images of the same shower improves hadron discrimination, it eliminates local muon background, it locates core position of the shower and also offers better angular resolution as demonstrated by HEGRA [68]. Present generation of IACTs in operation are TACTIC, SHALON-ALATOO, CANGAROO, MAGIC, HESS, VERITAS.

Fig. 2.16: WHIPPLE 10 m imaging telescope, which has pioneered the $\gamma$-ray astronomy

In wavefront sampling technique [44, 21] multiple collectors sample light from across the entire Cherenkov wavefront. In this technique basically lateral distribution is sampled. An array of reflectors is spread across long baseline with one or more PMTs in the focal plane of each reflector. These reflectors record photon arrival times and pulse heights at several points in the light pool. Using this arrival times of Cherenkov photons Cherenkov wavefront can be reconstructed. This in turn gives the arrival
angle of the incident $\gamma$-ray. Pulse height measurement from each PMT can be used to reconstruct lateral density profile of Cherenkov light in shower. This also gives an estimate of the showers total Cherenkov yield which is proportional to the primary energy of the incident photon. Gamma-hadron separation techniques are very different from that of IACTs. One can use density fluctuation, arrival time jitter to distinguish between a $\gamma$-ray initiated shower and hadron initiated shower. It has been found that $\gamma$-hadron separation parameters in wavefront sampling technique is not as powerful when compared with an IACT. The recent experiments which use wavefront sampling method are CELESTE, STACEE, SOLAR 2, PACT.

The next generation of ACTs will use both the waveform sampling and imaging techniques. They will be based on an array of imaging telescopes (IACTs) spread over a large area. HESS, MAGIC, CANGAROO VERITAS and MACE are some such telescopes under operation/construction.
Fig. 2.17: World map of VHE $\gamma$-ray experiments. Among them TACTIC, HESS, MAGIC, CANGAROO, VERITAS are based imaging technique. PACT, STACEE are based on wave-front sampling technique. This figure is taken from R. A. Ong’s rapporteur talk in 29th ICRC, Pune, 2005.
Chapter 3

Pachmarhi Array of Cherenkov Telescopes

Pachmarhi Array of Cherenkov Telescopes (PACT) has been specifically designed to detect Cherenkov emission from charged particles present in the extensive air shower initiated by VHE $\gamma$-rays and cosmic rays. This experiment is based on wavefront sampling technique. In this technique, Cherenkov photons are sampled at several places in the Cherenkov light pool. In this chapter various design features and performance of the telescope orientation system and data acquisition system used in the experiment will be discussed. Details of PACT array will be given in section 3.1. Telescope orientation system will be discussed in section 3.6. In section 3.3 distributed data acquisition system for PACT will be discussed followed by software for PACT in section 3.4. Details of calibrations of various modules used in the PACT will be given in section 3.5.

3.1 PACT Array

PACT [42] is situated at Pachmarhi, on the hills of the Satpura mountain range, in the state of Madhya Pradesh (Central India). The geographical location of PACT is 78° 26' East longitude and 22° 28' North latitude. It is 1075 metres above mean sea level. Cherenkov light pool covers a vast area, typically a circle of radius about 150 m, at the observation level. Hence the telescopes have to be spread out over large area to sample the Cherenkov wavefront. There are 24 telescopes spread over an area of $80 \times 100 \text{ m}$
in the form of rectangular $5 \times 5$ matrix. Photograph of this array is shown in figure 3.1. Separation between neighbouring telescopes is $20\,m$ in East-West direction and $25\,m$ in North-South direction. The entire array is further divided into 4 sectors with 6 telescopes in each as shown in figure 3.2. This minimises signal attenuation over long pulse cables. Also each of these sectors can be operated independently, allowing us to check for consistency between results from different sectors.

### 3.1.1 Configuration of a telescope

All the telescopes are mounted on *equatorial* drives and are independently steerable in both East-West and North-South direction within $\pm 45^\circ$ from zenith. Each of these telescopes has seven para-axially mounted parabolic mirrors (see figure 3.3). These mirrors are made by slumping float glass on a stainless steel mould and all are aluminized on back side. Each mirror has a diameter of $0.9\,m$ and thickness $\sim 6\,mm$. Reflectivity of mirrors was measured to be $\sim 78\%$ at the time of manufacturing in the wavelength range $400\,nm$ to $500\,nm$, but got degraded over the years. During PACT observations from 2000 to 2005 reflectivity was on an average approximately $60\%$. Ideally for a parabolic mirror image is expected to be a point, but because of distortions in the mirror curvature, the image was not a point image, instead image size was $\sim 3\,mm$. Each of these mirrors has focal length of $90\,cm$ with $f/d \sim 1$. Total reflector area of a telescope is approximately $4.45\,m^2$. A fast photo-multiplier tube (PMT), of type EMI 9807B, is fitted at the focus of each mirror behind a $3^\circ$ circular mask. It has average quantum efficiency of $\sim 28\%$ within wavelength range $300\,nm$ to $650\,nm$. High voltages given to PMTs are typically in the range of $1.8\,kV$ to $2.2\,kV$. At these operating voltages gains of these PMTs are $\sim 9 \times 10^6$. All these telescopes are also equipped with a guiding telescope, called elbow telescope, attached to them. Elbow axis is mounted in such a way that its optic axis is parallel to the optic axis of the telescope. Each of the PMT has a shutter which protects the photo-cathode of the PMT. This shutter is remotely controlled by a geared motor system. Photocathodes are exposed to the night sky only
Fig. 3.2: Layout of the PACT telescopes. The big circles represent the telescopes. Seven smaller circles inside represent 7 mirrors in a telescope. Rectangular boxes represent the data acquisition centers.

during observations using these shutters.

3.1.2 Alignment of Mirrors

Optic axes of all the mirrors of a telescope are aligned parallel to each other and also parallel to the axis of the telescope with the help of the guiding telescope. For this purpose telescopes are aligned to a bright star and image of the star is seen in the focal plane of every mirror through the $3^\circ$ mask. Star image should be at the center of the mask. If the image is found to be off for some mirrors then they are adjusted manually to bring the star image at the center. This is done through three struts on which the mirror holder is fastened to the aluminium tray. The accuracy of the alignment is checked with bright star drift scans, which will be discussed in detail in section 3.5.4.
Fig. 3.3: Photograph of one of the telescopes. There are seven parabolic mirrors with PMT fitted at the focus of each mirror.

3.2 Automatic Computerized Telescope Orientation System (ACTOS)

ACTOS [63] is a PC-based system for remotely controlling the movement of the telescopes. Each telescope is on an equatorial mount and is properly counter-balanced as shown in figures 3.4 & 3.5, with steering system attached to it. It can be rotated in East-West (E-W) and North-South (N-S) direction. The control system has an angle transducer, called clinometer, which converts telescope angle information into electrical signals. Apart from this it also consists of stepper motors, motor controllers, signal processing electronics, a host computer and control software.

The stepper motor is coupled with a set of gears which in turn is coupled with the main axle of rotation. Electronic motor drive circuits drive the stepper motors by supplying square pulses at desired frequencies. The step angle of motor is $1.8^\circ$, i.e. the motor shaft moves by $1.8^\circ$ per pulse.
The RA gear ratio is 3270 : 1 and DEC gear ratio is 432 : 1. Since a celestial source move with a speed of 1 degree per 3.98 minutes, to track the source RA shaft should move by \((1/239.33)\) degree in 1 second. Hence, the RA motor shaft should move by \((3270/239.33)\) degree in 1 second. Thus the required number of pulses to RA motor is \(((3270/239.33)/1.8)\)=7.591 Hz. This is the required tracking frequency. But in the experiment tracking frequency used is 7.561 Hz. Because of this difference telescopes will lag behind by 0.0012° over a minute. Which is small compared to the pointing accuracy of these telescopes. Also, telescope positions are continuously monitored and corrections are applied as and when needed. Apart from this two more frequencies, viz 30Hz and 70Hz are used for the fast movement of telescopes. These are used for moving telescopes quickly and to acquire a source or while shifting from one source to another.

The clinometer is a gravity based low cost angle sensor which is used as an absolute angle encoder to infer telescope angle. Clinometer when rotated about its sensitive axis produces a signed dc voltage proportional to the angular displacement with respect to the local vertical. This voltage is about ±60mV per degree, positive on one side of a reference axis in the plane of the clinometer called null axis and negative on the other side. Two
clinometers are mounted on each telescope to get the angles in E-W and N-S directions. Clinometer outputs are fed to a low-pass filter and an integrating type ADC which is read by the host PC. The clinometers are calibrated against the telescope angles by aligning the telescopes manually to bright stars and measuring the clinometer voltages. Clinometer calibration will be discussed in detail in section 3.5.1. Block diagram of ACTOS is shown in figure 3.6.

The motor controller, an interface between the host-PC and the stepper motor carries out the actual task of controlling the stepper motor movement according to the motion parameters like number of correction counts, motor slew speed and the direction of the correction. This semi-intelligent device receives from the computer the above mentioned three parameters and takes over the task of delivering the pulses to the motor. As a result the computer becomes free so that it can attend the next channel in the queue. Once the required number of pulses are delivered to the motor, the RA motor controller restores the tracking frequency to the RA motor in West direction to track the source while the DEC motor controller puts the corresponding motor in hold state.

The software code for ACTOS has been developed in-house in C- lan-
guage under \textit{LINUX} environment. It provides a graphical user interface developed as GTK/GNOME application. It facilitates the user to see the status of all the telescopes like slew speed, pointing errors, limit-switch status etc, online during the course of an observation. It is designed to perform two basic functions namely, aligning all the telescopes to a given celestial source and set them in source tracking mode (\textit{Alignment mode}) and thereafter monitor continuously the position of each telescope taking corrective action if necessary (\textit{Monitoring mode}). After receiving source RA & DEC as input, the required clinometer voltages are calculated which are then compared with the present values to decide the angle through which telescope has to be moved. Accordingly pulses are given to stepper motor. Till the telescopes are aligned it keeps comparing between required clinometer reading and actual reading. Before switching over to monitoring mode from the alignment mode the software makes sure that all the telescopes are aligned within $\pm 0.05^\circ$ of the required direction. If a telescope malfunctions during the course of an observation then that telescope can be made \textit{unused} for the rest of the observation.

In the monitoring mode, the positions of each telescope is monitored sequentially. The typical time taken for an entire cycle is about 4 minutes. If any of the telescope position is found to be off by more than 0.05$^\circ$, then corrections are applied to bring back the telescope to the required position. A log of applied corrections is maintained. If the required correction is unusually large, alarm is set and a warning is sounded.

### 3.3 Distributed Data Acquisition System for PACT

In PACT there are 168 PMTs spread over an area of $80m \times 100m$ to collect Cherenkov photons and convert them into electrical signals. The amplitudes of these pulses are of the order of few tens of mV and they last only for a few nano seconds (risetime $\sim 2 \text{ ns}$). It is, therefore necessary to preserve the shape and size of the Cherenkov pulses to improve the angular as well as energy resolution and also to reject the night sky background. Therefore special care has been taken while designing the data acquisition
system. To minimise the loss of signal due to long cables, PACT is divided into four sectors with each sector having its own Data Acquisition (DAq) system [43, 101]. The DAq system for each sector is stationed in a house at the center of the sector called field signal processing center (FSPC). Pulses from phototubes are brought to the respective FSPC through low attenuation co-axial cable (RG213) of length $\sim 40$ m each. One of the advantages of splitting the array into sectors is that the required length of pulse cables could be reduced by about 60%. Pulses from individual PMTs are processed and informations like, arrival time of pulses, pulse height and other relevant housekeeping informations are recorded by FSPC. At the center of the array there is a control room which houses master signal processing center (MSPC) along with ACTOS and HV distribution unit. Informations relevant to the entire array are recorded by the MSPC.

A block diagram of the Distributed Data Acquisition System (DDAS) developed for PACT is shown in figure 3.7. Most of the hardware in DDAS except for frontend electronics and a few fast digitization modules are de-
signed and fabricated in-house.

### 3.3.1 Field Signal Processing Center (FSPC)

FSPC is designed to process the individual PMT signals, generate event trigger and record data relevant to 6 telescopes of a sector. A portion of DAq system for FSPC is shown in the figure 3.8. Seven PMT signals (A,B.....G) from a telescope are fed into a Fan-out module, which produces three replicas of the input pulses. These three sets of output pulses are then processed. One set is used for trigger generation, another is used as TDC stops and the third set is fed to ADCs (or QDCs).
Data Acquisition System in FSPC

**Trigger generation**: Trigger criteria was set up in the following way. Firstly, one set of output pulses of *Fan-out* module are given to *Fan-in-Fan-out* module, which adds all the 7 analog pulses of a telescope. For this addition cables were fine tuned in such a way so that all pulses arrive simultaneously at *Fan-in-Fan-out*. These analog sums are called *Royal sums*. Figure 3.9 shows the rate vs discriminator threshold curve for a telescope. At lower thresholds royal sum rate is dominated by NSB. But as threshold increases contribution from NSB reduces and beyond 80 mV royal sum rate is purely due to Cherenkov photons. Cherenkov photons are to be detected against a background of NSB photons. Therefore trigger criteria is set so as to eliminate the events arriving purely from night sky background. NSB
photons do not arrive together, whereas Cherenkov photons are coherent and arrive in a flash lasting for 2-5 ns. So if a large number of PMTs are operated in coincidence then effect of NSB can be reduced and system can be operated at lower threshold. To select appropriate trigger criteria a detailed study was carried out with n-fold coincidence of royal sum pulses. In figure 3.10 it is seen that acceptable trigger rate is obtained with 3-fold coincidence but chance coincidence is also high (0.81 per sec) in such case. With 5-fold or 6-fold coincidence trigger rates are very low though chance coincidences are negligible (1.22e-05 per sec and 4.37e-08 per sec respectively). Also shown in figure 3.10 is the trigger rate as a function of Royal sum rate for 4-fold coincidence logic. In this figure it is seen that the trigger rate remains within 3-4 Hz over a range of royal sum rates 10-40 kHz. Chance coincidence for 4-fold coincidence is 0.0032 per sec. Event rate increases to 16 Hz if Royal sum rate increases to 200 kHz, with this chance coincidence also goes up from 1% to 18%. Thus 4-fold coincidence with royal sum rates 10-40 kHz is decided as trigger criteria.

**Chance counter setup**: Chance coincidence arises due to NSB, PMT noise etc. Chance counter setup is shown in figure 3.11. All the six royal-sums are given to a TTL generator. There, except for the first Royal-sum all others are delayed in multiples of 100 ns. This is because width of the
Royal sum pulses is about 100 ns. Then these delayed pulses are given to a majority logic unit. If there is any coincidence between these delayed pulses that will be purely due to chance. Chance rates are monitored during observations to ensure that they are within expected limits.

**Distribution of trigger and Data recording**: Once trigger is generated CAMAC controller initiates data recording process. Information regarding pulse height or photon density given by Analog to Digital Converters
(ADCs), relative arrival times of pulses given by Time to Digital Converters (TDCs), absolute arrival time of an event obtained from Real Time Clock (RTC) of six peripheral mirrors of a telescope are recorded. It also records latch information showing the telescopes which have participated during the event. Common TDC start pulse is generated from event trigger. Because of different heights of telescopes and arrival angle of the shower different PMT pulses arrive at different times. Also there is a small but finite delay required to form the trigger. For these reasons PMT start pulses are suitably delayed by $\sim 150 \text{ ns}$ before they are fed into individual TDC stops. We have used Lecroy and Philips TDC modules which have resolutions of 0.25 ns and 0.2 ns per count respectively. Third set of output pulses of Fan-out module are given to ADCs. ADC gate is generated following the trigger and pulses from various mirrors are digitized by the ADCs. ADC modules have resolution of 0.25 $\text{pC}$ per count. There is a finite time required by the DAq system to process an event, during this period the system remains insensitive. As a result events which are arriving during this period are lost. This is called the dead time of the system. For sector data acquisition systems deadtimes are approximately 1.2 ms.

**ADC gate setup**: We have used Lecroy common gate ADC modules in sector 1 & 2 and individual gate QDC modules in sectors 3 & 4. Therefore ADC gate setup of sectors 1, 2 is different from that of sectors 3 & 4. For sectors 3 & 4 ADC gate is generated individually from Royal sum pulse and event trigger pulse. Since sectors 1 & 2 have common gate ADC modules Royal-sums from two nearest telescopes are fed into an OR-gate to reduce the gate width. Then the OR-output and trigger are given to an AND-circuit. Then that AND-output is used as common ADC gate for those two telescopes as shown in figure 3.13. Typical gate widths for ADC (or QDC) modules are $\sim 40 \text{ ns}$.

### 3.3.2 Master Signal Processing Center (MSPC)

MSPC records data relevant to the entire array. Royal sum pulses of individual sectors are delayed using delay generators and then they are brought
to the control room along with event trigger and veto via router. The typical delay needed is 250 ns, dictated by size of the array. Whenever an event trigger is generated in any station CAMAC controller is interrupted and the Royal sum TDC readings, event arrival times from RTCs, latch information, number of events recorded at various stations are recorded. Block diagram for DAq system for MSPC is shown in figure 3.14. Trigger setup for MSPC is shown in figure 3.15. For master data acquisition system deadtime is approximately 600 µs. MSPC also has a Global Positioning Satellite (GPS) clock. RTCs of all the four sectors and that of the control room are synchronized using the seconds pulse of this clock and by clearing the micro and milli second counters at every second. RTCs are CAMAC based module which records event time precisely from 0.2 µs to 4 digits of day with time resolution of 200 ns.
3.4 Software for PACT

The software developed for PACT consists of the following subgroups.

**Time synchronization of RTCs**: All the RTCs are driven by a common 1MHz clock signal generated by an oven controlled quartz crystal oscillator. Time in each RTC is loaded by remote login from the central control room. 1 Hz sync pulse from the GPS clock is enabled using a hardware switch in the MSPC at preloaded GPS time. The GPS sync pulse also clears the microsecond and millisecond counters in each RTC.

**Data recording and Monitoring**: Data acquisition software initiates the data recording process following the event interrupt. It records RTC latched by event trigger and starts reading the latched data from various CAMAC modules. The data is read and stored in hard disc using double buffer scheme in order to reduce the system dead time. A sector DAq system records 119 words of data per event. In the Main station event data consists
of 52 words. Checksum word is used at the end of each event data to decide the data reliability.

Monitoring interrupt routine reads all the scalars which count the various PMT rates and Royal-sum counting rates during the time interval between two consecutive interrupts is 1 sec\(^1\). Monitoring data size in the individual station is of 57 words and that of main station data is 41 words.

The entire real time software for distributed data acquisition system is developed in C-language in Linux environment. Details of the data formats for both event and monitoring data are given in the **appendix**.

**Online monitoring and Health check-up of data**: Software for on-

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1. This time interval is user defined. We have set this to 1 sec most of the time
Trigger distribution in control room DAS

Fig. 3.15: Trigger setup for main station.

...line display of event and chance coincidence rates for all the sectors was developed. Display of trigger rates of all the four stations along with corresponding chance coincidence rates are shown in figure 3.16. Also, several offline data handling routines were used to check the health of the data. The computer codes were written in IDL-language which work under Linux. One such code checks bit pattern of each TDC, ADC & RTC channel data. It looks for missing bits, if any, in data of various modules so that a quick check on the functioning of the hardware is done. An alarm regarding the malfunctioning of the hardware is set and attended to in due course.

3.5 Calibration of Various Modules

Telescope orientation system and various modules used in DAq were calibrated as explained below.
3.5.1 Clino Calibration

Telescope movement in East-West or North-South direction is controlled by clinometers attached to them. These clinometers are calibrated just after the monsoon, when PACT is re-assembled for observations. For this purpose all telescopes are aligned manually to a bright star and the telescope is set on tracking mode. As the telescopes move from East to West, clinometer voltages are measured and recorded by ACTOS at regular intervals. Every time, it was ensured that the image of the star is at the center of the field of view by manually looking at the guiding telescope. For RA clinometer a linear fit (see figure 3.17) is obtained from the observed data of output voltage $V_{ra}$ and $\theta_{ra}$ as

$$V_{ra} = m_{ra} \times \theta_{ra} + c_{ra}$$  \hspace{1cm} (3.1)
where $m_{ra}$ and $c_{ra}$ are calibration constants. For DEC clinometer, the cross axis angle $\alpha$, as shown in figure 3.18, does not remain constant as the telescope rotates from east to west. Therefore a mere linear fit is not sufficient. Hence a quadratic fit is obtained of the form

$$V_{dec} = A + B \times \theta_{ra} + c \times (\theta_{ra})^2$$  \hspace{1cm} (3.2)$$

where

$$A = m_{dec} \times \theta_{dec} + c_{dec}$$  \hspace{1cm} (3.3)$$

This fit is shown in the figure 3.19 for a fixed $\theta_{dec}$. Constants $m_{dec}$ and $c_{dec}$ are obtained using a linear fit from DEC clinometer reading when the source was at transit against declination angle plot (see figure 3.20). For both the clinometers it is found that residuals are in the range of $\pm 3$mV, which amounts to an error of $\pm 0.05$.

**Fig. 3.17:** *Upper panel:* RA clinometer voltage as a function of hour angle. The straight line is the least squares fit to the observed readings. *Lower panel:* The residual plot.

### 3.5.2 TDC Calibration

Relative arrival times of a shower at mirrors are recorded using TDCs. It is important, therefore to monitor the linearity of TDCs. For this reason
Fig. 3.18: Schematic view of a clinometer mounted at the telescope. The angle $\alpha$ between local vertical and mounting plane of clinometer called cross axis angle.

Fig. 3.19: Upper panel: DEC clinometer voltage as a function of hour angle for a fixed declination. The curve is the quadratic fit to the observed readings. Lower panel: The residual plot.

TDCs are calibrated before starting actual observation. Calibration setup for TDC is shown in figure 3.21. A pulse generator is used to generate trigger and start pulse. TDC start pulse is delayed using lemo cables (RG174) of known lengths (i.e. known delays) and fed into individual TDC stops. The
range over which delays are varied to calibrate TDCs is $\sim 70 \text{ ns}$ to $590 \text{ ns}$. TDC readings between the start and stop pulses are recorded. Delay vs TDC readings are fitted with a straight line, as shown in the figure 3.22, using the following equation

$$\text{delay} = m \times (\text{TDC reading}) + c$$

(3.4)

where $m$ and $c$ are the slope and intercept.

### 3.5.3 ADC Pedestal Run

ADCs are used to measure the charge deposited at each PMT by Cherenkov shower front. From these ADC values primary energy of the incident $\gamma$-ray can be estimated. ADC readings consist of ADC pedestal value and Cherenkov light. ADC pedestal arise due to PMT dark current, electronic noise, night sky background light etc. Cherenkov pulses arrive over-riding the NSB light. Therefore to separate out ADC values due to Cherenkov light, ADC pedestals should be subtracted from ADC readings. To obtain ADC pedestals telescopes are pointed towards a dark region and trigger is generated independently using a pulse generator module. So events which
are recorded are not due to Cherenkov light but purely due to NSB and electronic noise. ADC pedestal distribution for telescope #11 is shown in figure 3.23.
3.5.4 Bright Star Scan

Seven mirrors in a telescope are mounted para-axially, i.e. their optical axes are parallel to each other. Alignment of mirror is done mechanically as described in the section 3.1.2. Then to check the accuracy of alignment a bright star scan is carried out [80]. For this purpose all telescopes are aligned to a bright star (∼ 2 to 3 magnitude star). Then they are parked 5° to the west of the star and recording of count rates from PMTs is started. As the star enters the field of view (f.o.v.) count rate starts increasing, goes through a maximum and then comes down to the baseline value as the star walks out of the f.o.v. We then fit a quadratic function to this count rate profile (as shown in figure 3.24). Centroid of the profile is shown by a dashed-dotted line, whereas expected transit time of star is shown by a solid line. Difference between these two gives the offset of the mirror. If this offset exceeds 0.2° for a particular mirror then that mirror is re-aligned and re-checked.
Fig. 3.24: Bright Star Scan results on ψ-Ursa Major. The counting rates are shown as a function of time (UTC). The vertical lines around the peak of the profile are (i) expected transit time (solid line) (ii) centroid of the count rate profile (dot dashed line) defined by two dashed lines on either side. The baseline and the FWHM are also shown. This figure is taken from [127].

Fig. 3.25: This is the photograph of the Master Signal Processing Center. High Voltage unit and ACTOS are shown by arrows.
Fig. 3.26: Photograph of the DAq system of the *Master Signal Processing Center*.

Fig. 3.27: This is the photograph of one of the *Field Signal Processing Center*. Sector # 3.
Chapter 4

Simulations for PACT

In any Very High Energy (VHE) Gamma-ray experiment simulations play very important role. It is not possible to directly calibrate these experiments since this would require very high energy $\gamma$ ray beam. In absence of direct calibrations instrument performance can be understood only through detailed simulations of air showers and correct modelling of detector response. In this chapter details of the simulation, carried out for PACT, will be discussed. In section 4.1 air shower simulation using CORSIKA will be explained. Detector simulation program and its performance will be discussed in sections 4.2 & 4.3. Inclined shower simulations will be described in section 4.4 and finally details of the comparison between simulations and data will be discussed in section 4.5.

4.1 Simulations Using CORSIKA

CORSIKA (COsmic Ray SImulation for KAscade) is a detailed Monte Carlo program, developed by KASCADE group [66, 72], to study the evolution and properties of Extensive Air Showers (EAS). The computer code is based on a detailed modelling of the air shower which develops in the atmosphere when a very high energy $\gamma$-ray or a cosmic ray particle enters the atmosphere. The CORSIKA program simulates interactions and decays of nuclei, hadrons, muons, electrons and photons in the atmosphere upto energies of $10^{20}$ eV. All these secondary particles produced in the atmosphere are then tracked explicitly along their trajectories considering several
processes, like decay of unstable particles, ionization losses, deflection by multiple scattering and by the geomagnetic field. All these processes with their respective probabilities and opening angles are considered in simulation using appropriate distribution of random numbers. All charged particles and photons constituting the shower are tracked upto the observation level. Also Cherenkov emission from relativistic charged particles in the shower is simulated. CORSIKA uses EGS4 [87] code for the electromagnetic component of the air shower and VENUS [138] and GHEISHA [104] codes for hadronic components. Hadronic interactions above 80 GeV are simulated with VENUS and GHEISHA is used for interactions below 80 GeV. US standard atmosphere parameterized by Linsley [119] is used. We have simulated Cherenkov light emission in the Earth’s atmosphere by the secondaries of the EAS generated by cosmic ray primaries or γ rays using CORSIKA version 6.019.

4.1.1 Inputs to CORSIKA

To generate air showers using CORSIKA package all details are to be provided in INPUT file. These input parameters are:

- **Particle type**: We have used: γ-ray, Proton and Helium.

- **Energy range and slope of energy spectrum**: Energy of a particle is selected using random numbers distributed according to a power law energy spectrum. For present simulations differential slope of -2.49 is used for γ-rays in accordance with the energy spectrum of the Crab nebula as derived from Whipple data [67]. For proton and helium nuclei slope of -2.70 is used in accordance with cosmic ray measurements [114].

- **Primary angle of incidence θ and φ**: γ ray showers are generated with zenith angle θ=0 along the direction of telescope axis. Proton and Helium showers are generated within the aperture of 3° around the telescope axis according to their isotropic distribution. Azimuthal angle φ is selected uniformly in the range 0-360°.
• **Geomagnetic field**: Geomagnetic field appropriate for Pachmarhi is used. Its horizontal and vertical components are $B_x=37.31 \, \mu T$ and $B_z=23.7 \, \mu T$ respectively.

• **Altitude**: PACT altitude is 1075 m

• **Wavelength range**: Wavelength band of 300 to 650 nm is used to match PMT response.

• **Array size and co-ordinates of telescopes**: We have used geometry of PACT array for simulations. An array of 25 telescopes is used, which is divided into 4 sectors (6 telescopes in each sector) with one telescope at the center of the array. E-W and N-S separations of these telescopes are 25 m and 20 m respectively, each telescope has area $4.35 \, m^2$.

• **Impact parameter**: Impact parameter is defined as the distance of shower core from the array center. Impact parameter range used is 0-300 m and impact parameters are selected uniformly within a radius of circle 300 m.

### 4.1.2 CORSIKA Output

Information about particles and Cherenkov photons present in air showers, reaching observation level is written in an output file of CORSIKA. For each Cherenkov photon, x and y co-ordinates of arrival point at observation level, u and v direction cosines, arrival time since the first interaction in nano seconds and height of production of Cherenkov photons are written. Whereas for particles reaching the ground apart from these x, y and z components of momentum are also written. Also some additional informations like height of first interaction, lateral electron density at observational level, longitudinal distribution of photons and particles etc is written for each shower.
4.2 Detector Simulation

CORSIKA simulates production of Cherenkov photons from relativistic particles in air shower. It does not take into account atmospheric attenuation or night sky background since they depend on observation site. CORSIKA also does not consider instrument related parameters like reflectivity, PMT characteristics etc. All these instrument related and observation site related effects are incorporated in detector simulation program developed in house. In the following we discuss in detail all the features involved in our detector simulation program.

- **Atmospheric attenuation**: The development of the shower depends on the density profile of the atmosphere. Elterman’s attenuation model [29], which provides the attenuation coefficients for the Rayleigh and aerosol scattering as well as ozone absorption in an altitude dependent form for the wavelength range 270-1260 nm is used to calculate transmission of Cherenkov photons. Wavelength is assigned to each Cherenkov photon using $1/\lambda^2$ dependence of Cherenkov flux. Using atmospheric transmission function based on Elterman’s table of atmospheric attenuation is taken into account.

- **Night Sky Background (NSB)**: Precise knowledge of NSB flux is very important for any atmospheric Cherenkov experiment because lower energy threshold of the experiment depends on NSB. Wavelength dependence of NSB is given by Allen [11]. We have carried out functional fit for this dependence given by

$$flux = (625.3376 - 0.69886 \lambda + 3.081e - 4 \lambda^2 -
6.6891e - 8 \lambda^3 + 7.1489e - 12 \lambda^4
-3.0001e - 16 \lambda^5) \cdot 10.0/98.6646$$

which is used in detector simulation program.

NSB measured at Pachmarhi over the wavelength range of 300-650 nm was found to be $3.3 \times 10^8$ photons/cm$^2$/s/sr. Arrival times of NSB
photons within PMT pulse duration are generated using Poisson distributed random nos. Wavelength is assigned to each photon using wavelength dependence of Cherenkov photons mentioned above.

- **Reflectivity and Quantum efficiency**: The amount of light reaching the PMT depends on certain factors. For back coated mirrors there is attenuation in glass. Also, if surface of a mirror is not perfectly parabolic, more so for large size mirrors like ours, then a part of light collected by mirror does not focus onto PMT resulting in diluted quality of the image. We have absorbed all these factors in effective mirror reflectivity for simulation, which is 30 % over the wavelength range considered. PMT of type EMI 9807 is used. It has peak Quantum Efficiency of 28% at 380 nm, in accordance with PMT response curve. Wavelength range for Cherenkov photons is kept 300-650 nm as in CORSIKA simulations.

- **Photo multiplier pulse**: The time profile of the Cherenkov pulse and NSB is convolved with PMT response function to simulate voltage-time profile of the pulse. PMT response function includes rise time of 2.2 ns, fwhm of 3.25 ns, decay time of 2.4 ns and PMT transit time jitter of 0.8 ns. PMTs are operated at about -1.8 kV in the experiment. The gain of PMT at this operating voltage is $9 \times 10^6$. This is derived from data provided by manufacturer. We have taken into account variation in the gain of PMTs using Gaussian distribution with a $\sigma$ of $2 \times 10^6$.

- **Pulse attenuation**: The PMT pulse travels a distance of 40 m through RG213 cable before it is electronically processed. Another 2 m of RG174 cable carries the pulse to the front end electronics. The distortion and attenuation by these cables are simulated using information provided by the manufacturer.

- **Trigger generation**: Once the PMT pulses for each mirror are generated they are added together to form the ’royal-sum’ telescope pulse. These royal-sum pulses are then discriminated at a threshold of 55 mV
and a coincidence of any 4 out of 6 telescope pulses generates the trigger. Coincidence window is 100 ns. Once trigger is generated TDC and ADC for each mirror and royal sum TDCs are recorded in every station. Whenever trigger is generated at any of the stations, main station in control room is triggered.

### 4.3 Detector Performance

Using CORSIKA showers were generated for $\gamma$-rays, protons and helium. Details of these showers are summarized in table 4.1. These showers were then passed through detector simulation program and 1012 triggers were obtained for $\gamma$-rays, 1371 for protons and 595 for helium. Energy threshold, collection area, trigger rate etc were estimated for PACT using triggered showers from these samples.

#### Table 4.1: Parameters for $\gamma$-ray, proton and helium showers generated using CORSIKA.

<table>
<thead>
<tr>
<th>Particle type</th>
<th>Total number of showers</th>
<th>Total number of triggers</th>
<th>Energy (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$-ray</td>
<td>4000</td>
<td>1012</td>
<td>0.5-10</td>
</tr>
<tr>
<td>proton</td>
<td>35000</td>
<td>1371</td>
<td>1-20</td>
</tr>
<tr>
<td>helium</td>
<td>5077</td>
<td>595</td>
<td>1-20</td>
</tr>
</tbody>
</table>

**Energy Threshold**: The energy threshold of an ACT is determined by the minimum signal to noise ratio required to detect the Cherenkov photons in the presence of NSB. In any ACT experiment energy threshold is defined as the energy corresponding to the peak of the differential rate curve. For this purpose incident energies are divided into logarithmic bins. In each of these bins using number of incident showers and number of triggering showers differential trigger rate is calculated. Energy threshold for PACT is estimated to be 750 GeV (see figure 4.1).

**Collection Area**: One of the important parameters of any $\gamma$ ray detector is its effective collection area. This area is, in general, an energy dependent quantity which depends on the details of the detector elements and trigger
criteria. The effective area is defined as

$$A_{eff}(E) = \int \epsilon(r, E) A(r) dr$$ (4.1)

Where $\epsilon$ is the fraction of the $\gamma$-rays/cosmic rays showers, which trigger the experiment and are accepted for analysis and $A(r)$ is the area of annulus with radii $r-\frac{dr}{2}, r+\frac{dr}{2}$. Variation of collection area with energy is shown in figure 4.2 for $\gamma$ rays. Collection area is estimated to be $1.4 \times 10^5 m^2$ above threshold for $\gamma$ ray showers.

**Trigger Rate**: Proton and Helium showers are generated following cosmic ray spectrum. These showers are isotropically distributed within a solid angle corresponding to $3^\circ$ and are spread over an area of 300 m. Knowing cosmic ray flux, the duration over which these showers are distributed is estimated. After that trigger rate is obtained as the number of triggers divided by duration. Trigger rate for PACT is estimated to be $\sim 7 \ Hz$ from cosmic rays, $5.43 \ Hz$ from protons and $1.5 \ Hz$ from helium nuclei. We have not considered contribution from heavier elements since it is negligible. This trigger rate agrees well with the observed one (6.5-7.5 Hz).

**Sensitivity**: Sensitivity of any experiment is defined as the minimum detectable flux of $\gamma$-rays in presence of background cosmic rays. Sensitivity
of atmospheric Cherenkov experiments is given as flux of $\gamma$-rays detected at the $5\sigma$ significance level for 50 hours of observation. To estimate sensitivity of PACT equation of the form

$$[(\gamma + c) - c] \times t = 5\sqrt{[(\gamma + c) + c]t}$$

is used. Where $\gamma$ is the signal, $c$ is cosmic ray background & $t$ time of observation in seconds. For PACT it is $2.93 \times 10^{-11}$ $ph\ cm^{-2}\ s^{-1}$, without of any rejection of cosmic ray showers. For estimation of PACT sensitivity Crab spectrum derived from Whipple data, $\frac{dJ_\gamma}{dE}=3.2 \times 10^{-11} E^{-2.49}$ at 1 TeV, was used. Sensitivity of PACT is plotted in figure 4.3 along with present and future satellite and ground based experiments.

4.4 Simulations of Inclined Showers

In the previous two sections we discussed simulations that were carried out for vertical showers only. But most of the sources are observed at some angle with respect to the zenith due to their declination. Also in actual experiment sources are tracked from East to West. So the zenith angle of the source will vary with hour angle. Therefore to compare simulations with
data one should simulate showers with inclination angle same as that of source and estimate their trigger rate, energy threshold, collection area etc. Simulations discussed so far were done with a version of CORSIKA where telescopes are fixed and looking at the vertical direction. For inclined showers we have used IACT option of CORSIKA [14] with telescopes orients such that their axes are along the pointing direction. Also in this version it is possible to give exact X, Y and Z coordinates of the telescopes. Thus it is possible to simulate the PACT array consisting of 24 telescopes with exact geometry. In addition to this we have used one more telescope at the centre of the array which corresponds to the origin of the coordinate system. Each of these telescopes have a radius of 1.5 m.

Figure 4.4 shows the distribution of photons for a shower incident at zenith angle ($\theta$) of $30^\circ$ and azimuthal angle ($\phi$) of $0^\circ$ so that shower is directed along X- or north-south axis. Telescope positions are represented by '+' signs. Figure shows photons intercepted by these telescopes as extended to ground. Larger the height of the telescope, more is the displacement of the shadow cast by telescope from telescope location in ground. CORSIKA writes X-Y coordinates of these photons at the ground level alongwith their direction cosines. Before applying detector response we have to translate
these photons to telescope planes. Procedure for doing this is outlined below.

Consider the case of a shower with $\theta$ of $30^\circ$ and $\phi$ of $200^\circ$. Here we rotate the coordinate reference frame so that $\phi$ is $0^\circ$ in rotated frame so that shower again falls along the X-axis and same algorithm can be used for this rotated frame. Rotation of frame for this case is shown in Figure 4.5.

Procedure adopted for translating photon information from ground to telescope plane is as follows:

In Figure 4.6, TT’ is the telescope. AB is the shadow it casts on the ground. C is the center of the telescope and its projection to ground is C’. Coordinates of telescope center are $(x_0, y_0, z_0)$ and coordinates of C’ are $(x_0, y_0, 0)$. $xx_1(i), yy_1(i)$ are the co-ordinates of i-th photon on ground which we translate to telescope plane as shown in the figure. From geometry shown in the figure, we get the following expressions:

$$x_{incl}(i) = (xx_1(i) - x_0) \times \cos(\theta) \quad (4.2)$$
Fig. 4.5: Distributions of photons on ground for shower incident at $\theta$ of 30° and $\phi$ of 200°. Array is rotated so that shower is incident along X-axis.

\[
zz_1(i) = z_0 + x_{\text{incl}}(i) \times \sin(\theta) \tag{4.3}
\]
\[
x_{\text{proj}}(i) = x_{0\text{old}} + x_{\text{incl}}(i) \times \cos(\theta) \tag{4.4}
\]

Here as a first approximation, we have assumed all the photons to arrive at an angle $\theta$ and not taken into account actual arrival directions of photons given by $u,v$ direction cosines. Hence $Y$ coordinates of photons will remain same as on the ground. Distance for any $i$-th photon when it is translated back to the telescope plane is -

\[
dist(i) = zz_1(i) \times 1./ (\cos(\theta)) \tag{4.5}
\]

where $zz_1(i)$ is the $z$ coordinate of that photon. Figure 4.7 shows the distribution of photons for one of the telescopes after translation to telescope frame. The circle on the left corresponds to telescope periphery in vertical position, prolate shows the same in inclined position. Ellipse around photons corresponds to shadow cast by the telescope on ground in inclined position. Few photons are falling outside the ellipse because their positions are not yet corrected taking into account their actual arrival directions.
Now we take into account actual arrival directions of individual photons as given by their direction cosines. In CORSIKA file $u,v$ direction cosines are given for each photon. After $\phi$ rotation these direction cosines will be

\begin{align*}
  u_1(j) &= u(j) \cos(\phi) + v(j) \sin(\phi) \quad \text{(4.6)} \\
  v_1(j) &= v(j) \cos(\phi) - u(j) \sin(\phi) \quad \text{(4.7)} \\
  w_1(j) &= \sqrt{1 - u_1(j)^2 - v_1(j)^2} \quad \text{(4.8)}
\end{align*}

In Figure 4.8, a photon at A will follow path AB if it is arriving along the direction given by $\theta$. But with direction cosine given by $u, v$ it follows the path AC. Now to calculate correct coordinates of photon we need to know the space angle between them. Direction cosines for AB are,
Fig. 4.7: Distributions of photons in telescope frame. Circle on left shows telescope periphery in vertical position, prolate shows the same for inclined position. Ellipse on the right is projection of telescope on ground.

\[ u_2(j) = \sin(\theta) \quad (4.9) \]
\[ v_2(j) = 0 \quad (4.10) \]
\[ w_2(j) = \cos(\theta) \quad (4.11) \]

so space angle between AB and AC is -

\[ \text{sp\_ang}(j) = \acos(u_2(j) \ast u_1(j) + v_2(j) \ast v_1(j) + w_2(j) \ast w_1(j)) \quad (4.12) \]

so the corrected distance for photon to reach telescope becomes-

\[ \text{dist1}(j) = \text{dist}(j)/\cos(\text{sp\_ang}(j)) \quad (4.13) \]

Now applying corrections for direction cosines new x,y coordinates for photons are –

\[ x_{\text{new}}(i) = xx_1(i) - \text{dist1}(i) \ast u_1(i) \quad (4.14) \]
\[ y_{\text{new}}(i) = yy_1(i) - \text{dist1}(i) \ast v_1(i) \quad (4.15) \]
Figure 4.9 shows photon distributions in telescope plane with reference to the CORSIKA coordinate system. Also shown in the figure are circles corresponding to seven mirrors. All the photons are now contained within the telescope.

So using this algorithm we can translate the photons from ground to planes of respective telescopes.

Following this method showers were generated for $\gamma$ rays and protons at different zenith angles. Details of these showers are listed in tables 4.2 & 4.3. Then average event rates are calculated for each of the samples of proton showers using the fraction of triggered showers. In figure 4.10 we have compared event rate from simulations with data. Dotted line represents event rate observed during observation of ON231 whose declination is $28^\circ$ i.e. almost vertical at Pachmarhi. So in this case hour angle is close to
zenith angle. There is a good agreement between the event rates obtained from simulations and the observed event rate.

![Image of photon distribution](image)

**Fig. 4.9:** Distribution of photons in telescope. Circles corresponding to seven mirrors are shown.

<table>
<thead>
<tr>
<th>Inclination Angle</th>
<th>Total number of showers</th>
<th>Total number of triggers</th>
<th>Trigger rate (Hz)</th>
<th>Energy (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8°</td>
<td>10000</td>
<td>343</td>
<td>4.23</td>
<td>1-20</td>
</tr>
<tr>
<td>15°</td>
<td>10000</td>
<td>708</td>
<td>4.38</td>
<td>1-20</td>
</tr>
<tr>
<td>22°</td>
<td>10000</td>
<td>613</td>
<td>3.79</td>
<td>1-20</td>
</tr>
<tr>
<td>30°</td>
<td>10000</td>
<td>573</td>
<td>3.54</td>
<td>1-20</td>
</tr>
</tbody>
</table>

We have estimated energy threshold and collection area using different samples of γ-ray showers at different inclination angles. We have found that both energy threshold and collection area increases with the angle. Variation of energy threshold and collection area has been shown in figures 4.11 and 4.12 respectively. The values of energy thresholds and collection areas at different inclination angles have been listed in the table 4.4.
Fig. 4.10: In this figure data points with error bar are the event rates obtained from simulation of proton showers at different zenith angles. Dotted line represents the event rate observed during observation for ON231 on 21st March, 2003. ON231 passes close to zenith and transit at 19.2 hours UT.

Fig. 4.11: Variation of energy threshold with the angle of inclination.
Table 4.3: Parameters of Gamma ray showers

<table>
<thead>
<tr>
<th>Inclination Angle</th>
<th>Total number of showers</th>
<th>Total number of triggers</th>
<th>Trigger rate/min.</th>
<th>Energy (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical</td>
<td>2000</td>
<td>489</td>
<td>2.47</td>
<td>0.5-10</td>
</tr>
<tr>
<td>15°</td>
<td>2000</td>
<td>490</td>
<td>2.49</td>
<td>0.5-15</td>
</tr>
<tr>
<td>30°</td>
<td>2000</td>
<td>531</td>
<td>2.05</td>
<td>0.6-15</td>
</tr>
<tr>
<td>45°</td>
<td>2000</td>
<td>690</td>
<td>1.34</td>
<td>0.6-20</td>
</tr>
</tbody>
</table>

Fig. 4.12: Variation of collection area with the angle of inclination.

Table 4.4: Energy thresholds and collection areas

<table>
<thead>
<tr>
<th>Inclination Angle</th>
<th>Energy Threshold (TeV)</th>
<th>Collection Area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical</td>
<td>0.75</td>
<td>1.4×10⁵</td>
</tr>
<tr>
<td>15°</td>
<td>0.90</td>
<td>1.5×10⁶</td>
</tr>
<tr>
<td>30°</td>
<td>1.20</td>
<td>1.8×10⁶</td>
</tr>
<tr>
<td>45°</td>
<td>2.20</td>
<td>2.7×10⁶</td>
</tr>
</tbody>
</table>
4.5 Comparison between Simulation and Experiment

Detector simulation program writes event files for individual sectors and for control room in a similar way as it is done in the experiment. Arrival times of the shower front are recorded using TDCs and information regarding pulse height is recorded using ADCs. A comparative study, for TDC and ADC readings, between simulation and experiment is carried out, which is discussed in the following sections.

4.5.1 Arrival Angle Estimation

Relative arrival times of a Cherenkov shower front, at different locations in the Cherenkov light pool are recorded by TDCs. Arrival angle of the shower is estimated using these TDC values. In the analysis Cherenkov wavefront is approximated by a plane front, normal to this plane gives the arrival angle of the shower. Then space angle is obtained as angle between source direction and the arrival direction of the shower. This analysis procedure is discussed in detail in chapter 5. Figure 4.13 shows typical space-angle distribution of a vertical run\(^1\). Similarly space-angle distributions are obtained for simulated $\gamma$-ray and proton showers. Samples used for this purpose consist of 4000 $\gamma$-ray showers in the energy range 0.5-10 TeV and 10628 proton showers generated in the energy range 1-20 TeV with incident angle 3° of vertical. These are shown in figure 4.14 and 7.6 respectively. The similarity between the distributions as shown in figures 4.13 and 7.6 indicates that there is good agreement between simulations and data.

\(^1\)This run is taken with all telescopes stationary and pointing to zenith
4.5.2 Detector Response

In order to check the detector response functions, as approximated in detector simulation program, 10628 proton showers were generated using CORSIKA in the energy range 1-20 TeV with incidence angle within 3° of vertical. These showers are passed through detector simulation program. Depending on array geometry, photon densities at telescopes etc some of the showers will trigger the array. Number of main station triggers was found to be 452. Space angle distribution of these triggered showers is shown in the left panel of figure 4.16.

In order to isolate effects of detector response, triggers are generated us-
Fig. 4.15: Space angle distribution obtained from simulated proton showers.

ing photon threshold of 450 photons per telescope (instead of pulse height) and with same trigger criteria (at least 4 telescopes in a sector and at least one sector triggering). This number corresponds to the 55 mV Royal sum threshold on an average for a single telescope. In this method resolution of the detector is not used at all. Number of triggering showers obtained with this method is 486 for proton showers compared to 452 triggers obtained using detector simulation program for the same sample. Left panel in the figure 4.16 shows the space angle distribution of proton showers with detector response and right panel shows the corresponding distribution without detector response. It is expected that the distributions shown in the left panel is slightly broader and have less events than that of the right panel, which corresponds to fixed photon threshold. There is good agreement between these two simulations indicating that the detector response is modelled correctly.

4.5.3 Comparison of ADC data

Apart from TDC i.e. (arrival time of shower front), the other information which is recorded in the experiment is charge deposited at each of the PMTs. This charge is recorded by ADCs. Using these ADC values one can estimate primary energy of the incident $\gamma$ ray at the top of the atmosphere. ADC distributions obtained from a vertical run and that of simulated showers are
compared for one of the PMTs as shown in figure 4.17. These two agree quite well.

**Core Distance Dependence**: For a given primary energy, value of ADC will depend on distance of the telescope from shower core. For example, a shower of high energy with large core distance and shower of lower energy but smaller core distance might give same ADC value. To see how ADC values vary w.r.t. energies and with core distances, average ADCs are calculated in the following way. Initially the ADCs of the six peripheral PMTs of a telescope are added to obtain telescope ADCs as in the experiment. Then based on royal sum TDC information, the telescopes which have triggered (whose pulse height is above the discrimination threshold) are identified. The average ADC for the shower is then calculated as an average of these telescope ADC values, i.e. average of those telescopes which have triggered. This is Avg(ADC). Then they are divided into three groups of shower core distances 0-100m, 100-200m, 200-300m and plotted against shower primary energy in figures 4.18, 4.19 for γ-ray and proton showers respectively. From these figures it is clear that in case of proton ADC values
show more scatter for a given energy. This is due to two reasons. Firstly, proton showers are isotropic and come with different zenith angles within the aperture of $3^\circ$ around the telescope axis. Depending on arrival angle of these showers w.r.t. telescope axis amount of Cherenkov photons and hence the charge deposited in the PMT will vary. This does not apply in the case of $\gamma$ rays emanating from point source where arrival direction for all showers is along the telescope axis. Secondly, proton showers intrinsically have larger density fluctuations compared to $\gamma$ ray showers due to differences in the kinematics of showers.

**Cosmic Ray Spectrum** : We tried to obtain cosmic ray spectrum from simulated data. We start with the simplest method. Avg(ADC) per triggered telescope per shower is plotted in figure 4.20 against energy for simulated proton showers. A straight line fit to logE vs logADC (slope=0.255 and intercept=2.45) is shown by a solid line in the figure. Then using this straight line fit energy is estimated for each of the triggered showers. Distribution of fitted primary energies is plotted in figure 4.21 as shown by dashed line. It follows a power law of slope of -0.85 (slope 3 in the figure). Energy distribution of incident protons is shown by solid line. This is the input power
Fig. 4.18: Avg(ADC) vs Energy for different core distances for γ ray showers

Fig. 4.19: Avg(ADC) vs Energy for different core distances for proton showers
law spectrum with integral slope -1.7. Depending on the trigger criteria some of the showers will trigger the array. Higher energy shower are more likely to trigger than the lower energy showers. Hence the energy spectrum of triggered showers is flatter as shown by dotted line in the same figure. It has a slope of -1.38 which does not agree with the slope of -0.85 obtained above. The discrepancy between these two spectral slopes is due to following reason. Energies assigned to showers with Avg(ADC) below the best fit line are underestimated and for showers with avg. ADCs above the line energies are overestimated. Because of this spectrum of estimated proton energies is extending well beyond the range of 1-20 TeV of incident proton energies.

Nevertheless, we applied this method to a vertical run data to compare simulations with data. We compared Avg(ADC) distributions of simulated proton showers and data (see figures 4.22, 4.23). Figure 4.23 shows observed ADC distributions in the data collected at all the four stations separately. It is clear that the observed distribution of station 2 is closest to the simulation. Therefore we have normalized the other three distributions w.r.t the distribution of station 2. Then using the fit mentioned above we obtained energy spectrum for the Vertical run. Its slope is found to be -1.5
as shown in the figure 4.24, which does not agree with the fitted slope of -0.85 of simulated showers.

Because of this reason we tried to estimate cosmic ray spectrum by another method.

Firstly triggered showers were classified into 4 groups according to their average ADC values per telescope: values between 45-65, 65-85, 85-105 and above 105. For each of these sub-groups distribution of energy is made. These distributions are fitted with a functional form \( f(x) \), a gaussian with a n degree polynomial, as shown below (see figure 4.25):

\[
f(x) = A_0e^{-z^2/2} + A_3 + A_4x + A_5x^2,
\]

where \( z = (x - A_1)/A_2 \)

Co-efficients of this function are given in table 4.5 for each of the 4 groups.

Then for each triggered shower the energy is estimated using random numbers and weighted according to corresponding function. Distribution of energies is shown in figure 4.26. It has a slope of -1.23. The same procedure is then applied to a vertical run data, which gives cosmic ray energy spectral
Fig. 4.22: Distribution of Avg(ADC) values per shower in simulated shower due to proton primary.

Fig. 4.23: Distribution of Avg(ADC) values of triggered telescopes per shower seen in each station due to a vertical run.
Fig. 4.24: Cosmic ray spectrum obtained from vertical run using linear fit.

Table 4.5: Coefficients of gaussian function combined with polynomial

<table>
<thead>
<tr>
<th>ADC values</th>
<th>$A_0$</th>
<th>$A_1$</th>
<th>$A_2$</th>
<th>$A_3$</th>
<th>$A_4$</th>
<th>$A_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>45-65</td>
<td>11.88</td>
<td>7.60</td>
<td>0.065</td>
<td>361.34</td>
<td>-82.79</td>
<td>4.76</td>
</tr>
<tr>
<td>65-85</td>
<td>47.12</td>
<td>7.69</td>
<td>0.39</td>
<td>340.10</td>
<td>-63.77</td>
<td>2.97</td>
</tr>
<tr>
<td>85-105</td>
<td>-19.28</td>
<td>8.97</td>
<td>0.39</td>
<td>-1181.61</td>
<td>292.87</td>
<td>-17.58</td>
</tr>
<tr>
<td>&gt; 105</td>
<td>-17.09</td>
<td>7.48</td>
<td>-0.45</td>
<td>-531.25</td>
<td>134.69</td>
<td>-8.13</td>
</tr>
</tbody>
</table>
Fig. 4.25: Distribution of primary energy of the shower, grouped into their average ADC value:

*Top left:* Average ADC is 45 to 65, *Top right:* 65 to 85, *Bottom left:* 85 to 105 and *Bottom right:* > 105. The fitted function is gaussian with n-degree polynomial.

index as -1.1 (figure 4.27). This slope agree well with the expected value of -1.23. But this method has a drawback that it cannot give correct energy for individual showers even though it can predict average behaviour correctly.
Fig. 4.26: Cosmic ray spectrum estimated using gaussian with n-degree polynomial fit for simulated showers.

Fig. 4.27: Cosmic ray spectrum obtained for a vertical run data using gaussian with n-degree polynomial fit.
Observations and Data Analysis Technique

This chapter deals with details of the methodology of observations and data analysis technique. Observation methods are given in section 5.1. Analysis technique is described in section 5.2. In section 5.3 details of vertical run analysis are discussed. Procedures to analyse source runs are explained in section 5.4.

5.1 Observation Method

Observations using PACT have following constraints:

- The density of Cherenkov photons is awfully low (as discussed in chapter 2) restricting the observations to clear moonless nights. Some groups have attempted observations during low moon phases using filters [37]. However, we do not have any such filters and our observations are confined to moonless dark nights; typically ± 10 days of new moon (before moonrise and after moonset).

- Monsoon is pretty severe at Pachmarhi where PACT is located. The average annual rainfall at Pachmarhi is 180 cm. During monsoon period (late June to early September), it is virtually impossible to use PACT due to heavy rains and cloudy sky. Therefore each year PACT is partially dismantled and closed for observations for about 3-4 months.
• Soon after the monsoon, PACT is reassembled and the system is checked for mirror alignment, telescope orientation systems and functioning of electronic systems. Also various calibrations are performed as described in chapter 3. Some of these activities do need clear sky and have to be performed at the cost of observation time.

Because of the above mentioned constraints, each observation season starts after the end of monsoon and lasts till May or early June. The observations consist of several small observations cycles lasting for about 20 days centered around new moon. Each observation cycle usually begins with a *Bright Star Scan* followed by a *Vertical run* and ends with a *Vertical run*. Observations of various sources and background regions are usually confined to nights between the two vertical runs.

Each night source run is taken by pointing all telescopes to the source direction. Same night background run is taken either before or after the source run by aligning all telescopes to a dark region (a region with the same declination as that of the source but with different RA). Background region RA is chosen in such a way that it covers same zenith angle range as source run. Sometimes background runs are split into two halves, with one run before the source run covering the eastern sky and other after the source run for western sky. This is to ensure maximum coverage for source.

Sometimes observations were carried out by aligning half the telescopes (2 sectors) pointing to the source and the other half to the background region, so that both source and background regions were observed simultaneously. However, these types of observations posed problems during data analysis as the geometry of the set up was different for source and background. We have not used those data here in this thesis. We will confine to data taken using all 4 sectors. At times some sectors were off both for source and background runs. We require a minimum of 2 sectors for observations.

### 5.1.1 Blazars observed by PACT

We have observed four blazars using PACT. They are Mkn421, Mkn501, 1ES1426+428 and ON231. Co-ordinates and redshifts of these four blazars
are given in table 5.1. First three are HBL type blazars and last one LBL type. The reasons for selecting these sources are:

1. They are nearby blazars (redshift \( z \leq 0.13 \))

2. These sources are situated in the northern hemisphere as shown in figure 5.1 and are easily accessible by PACT.

3. Mkn 421 and Mkn 501 are well established flaring sources of TeV \( \gamma \)-rays.

Our observation log for these sources from 2000 to 2005 is listed in table 5.2. Equal amount of background data have been collected for each of these sources.

---

Fig. 5.1: Catalog (till 2005) of extragalactic sources of VHE \( \gamma \)-rays. HBLs are shown by red dots. ON231 and 3C66A are the two LBL type of blazar (pink dots).
Table 5.1: Celestial co-ordinates (RA & DEC) and redshifts (z) of 4 AGN’s observed by us.

<table>
<thead>
<tr>
<th>Source</th>
<th>RA</th>
<th>DEC</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mkn 421</td>
<td>11h 04m 39s</td>
<td>38°11′24″</td>
<td>0.030</td>
</tr>
<tr>
<td>ON231</td>
<td>12h 21m 42s</td>
<td>28°12′48″</td>
<td>0.102</td>
</tr>
<tr>
<td>1ES1426+428</td>
<td>14h 28m 41s</td>
<td>42°39′24″</td>
<td>0.129</td>
</tr>
<tr>
<td>Mkn 501</td>
<td>16h 53m 40s</td>
<td>39°45′15″</td>
<td>0.034</td>
</tr>
</tbody>
</table>

Table 5.2: Observation log for Blazars

<table>
<thead>
<tr>
<th>year</th>
<th>observation duration (mins.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mkn 421</td>
</tr>
<tr>
<td>2000</td>
<td>3510.</td>
</tr>
<tr>
<td>2001</td>
<td>1960.</td>
</tr>
<tr>
<td>2002</td>
<td>1860.</td>
</tr>
<tr>
<td>2003</td>
<td>1770.</td>
</tr>
<tr>
<td>2004</td>
<td>2270.</td>
</tr>
<tr>
<td>2005</td>
<td>930.</td>
</tr>
</tbody>
</table>

5.2 Analysis Technique

In data analysis we obtain the arrival angle of each shower by using their relative arrival times at each PMT (or telescope) using plane wavefront approximation. Analysis procedure is discussed in details in the following sections.

5.2.1 Calculation of Time-Offsets or T0’s

Arrival angle of a shower is obtained by measuring relative arrival times of the shower at each PMT (or telescope). Thus it is important to measure these times accurately. A finite but constant delay between pulses from different PMTs (or telescopes) arises due to unequal cable lengths, differences in electronic propagation delays and differences in photo-multiplier transit times. These delays are called time-offsets or T0’s [132]. T0’s are estimated using cosmic ray showers detected with the telescopes in the vertical positions this is called **vertical run**. The time difference between Cherenkov
Chapter 5. Observations and Data Analysis Technique

photons arriving at PMTs (or telescopes) placed side by side should be zero on the average for vertical showers (after correcting for the differences in height of PMTs). Thus the average of time delays between two PMTs (or telescopes) from a large sample of data, is entirely due to difference between the two time-offsets (T0’s). T0’s are obtained in the following way -

If $T_{0i}$ and $T_{0j}$ are the time offsets for the PMTs $i$ and $j$, we can write an equation of the form

$$T_{0i} - T_{0j} = T_{ij} \quad (5.1)$$

where $T_{ij}$ is the mean delay between a pair of PMTs after correcting for the time difference due to differences in height (z-coordinate) of those PMTs (or telescopes).

The total $\chi^2$ can be expressed as

$$\chi^2 = \sum_{i,j=1; i \neq j}^{n} W_{ij}(T_{0i} - T_{0j} - T_{ij})^2 \quad (5.2)$$

where $n$ is the total number of PMTs, $W_{ij}$’s are the statistical weight factors. $\chi^2$ minimization will give a set of $n$ equations of the form

$$\sum_{i,j=1; i \neq j}^{n} W_{ij}(T_{0i} - T_{0j}) = \sum_{i,j=1; i \neq j}^{n} W_{ij}T_{ij} \equiv T'_i \quad (5.3)$$

Thus we have a set of simultaneous equations, which can be written in a matrix form

$$WT0 = T' \quad (5.4)$$

Time offsets for $(n - 1)$ detectors can be obtained w.r.t. $n$th detector by solving the above matrix equation. T0’s are obtained for individual PMT signals as well as Royal sum telescope pulses.

5.2.2 Arrival Angle Estimation

Celestial $\gamma$-rays are not affected by the interstellar magnetic field, therefore they retain their directionality. Whereas cosmic rays, being charged particles, are scattered by the interstellar magnetic field, as a result they
are isotropic. Thus a source emitting $\gamma$-rays will be reflected as an excess of events in the on-source direction compared to off-source direction. As mentioned earlier, secondary particles created by VHE $\gamma$-rays emit Cherenkov radiation. Most of the Cherenkov emission takes place near the shower maximum ($\sim 8$-$10$ km above sea level). These Cherenkov photons arrive at the ground level in the form of a thin disk (thickness $\sim 1$ m), whose radius is $\sim 150$ m. By measuring the arrival times of the Cherenkov shower front at several locations in the light pool, one can estimate the arrival direction of the incident $\gamma$-ray/cosmic ray accurately.

The arrival direction of each shower is determined by reconstructing shower front using the relative arrival times of Cherenkov photons at various telescopes (or PMTs). Cherenkov photon front is then fitted with a plane, normal to this plane gives the direction of shower axis. Suppose there are two telescopes $A$ and $B$ as shown in the figure 5.2, separated by a distance $D$. Consider an inclined Cherenkov shower which arrives at $B$ first and then after some delay of $\Delta t$ at $A$. Then in principle one can obtain the arrival angle $\theta$ from the following equation

$$\sin\theta = \frac{c\Delta t}{D} \quad (5.5)$$

However, actual situation is more complicated with large number of telescopes. So it is necessary to generalise this approach [132, 30]. Let $x_i, y_i, z_i$ be the coordinates of the $i^{th}$ PMT (or telescope) and let $l, m, n$ be the direction cosines of the shower axis and $t_i$ the arrival time of the photons at this telescope, then the equation relating them is given by

$$lx_i + my_i + nz_i + c(t_i - t_0) = 0 \quad (5.6)$$

where $t_0$ is the time at which the shower front passes through the origin of the coordinate system. Then the arrival direction of the shower can be estimated by a $\chi^2$ minimization method, where

$$\chi^2 = \sum_{i=1}^{n} W_i (lx_i + my_i + nz_i + c(t_i - t_0))^2 \quad (5.7)$$

where $W_i$ is the statistical weight factor for the $i^{th}$ timing measurement. The values of $l, m, n$ and $t_0$ are obtained by solving equations $\delta\chi^2/\delta l = 0,$
Fig. 5.2: Arrival angle determination of a shower arriving at two telescopes A and B separated by distance D. Shower front arrives first at B and after some delay of $\Delta t$ it arrives at A.

$\delta \chi^2/\delta m = 0$, $\delta \chi^2/\delta t_0 = 0$ and $l^2 + m^2 + n^2 = 1$. In this method terms containing $\delta n/\delta l$ and $\delta n/\delta m$ have been ignored as they are small. Using these direction cosines arrival angles $\theta$ and $\phi$ of the shower are obtained.

Space angle is estimated as an angle between the direction of shower axis and source direction (pointing direction of the telescope). For this purpose source direction is calculated in terms of $\theta_s$ and $\phi_s$ angles using Right Ascension ($\alpha$) and Declination ($\delta$).

\[
H = \text{LST}(\text{Local Sidereal Time}) - \alpha
\]
\[
a = \sin^{-1}(\sin \delta \sin \lambda) + \cos \delta \cos \lambda \cos H
\]
\[
A = \cos^{-1}\left[\frac{(\sin \delta - \sin \lambda \sin a)}{\cos \lambda \cos a}\right]
\]
\[
\text{zenith} = 90^\circ - a
\]

Here $H$ is hour angle, $\lambda$ is observer’s geographical latitude and $a$ & $A$ are altitude and azimuth angles of the source. Like this space angles are obtained for events with at least 4 valid TDCs for source as well as background runs. Our hardware is such that the first pulse arriving after the TDC start acts as TDC stops. Subsequent pulses if any in that channel are neglected. Thus
it is possible that sometimes pulses unrelated to the shower arriving before the genuine pulse. Therefore to reject such pulses 4-fold logic is used in the experiment.

5.2.3 Comparison of Space Angle Distributions Between Source and Background Runs

Space angle distributions of events in source runs are compared with the corresponding distributions of background runs. Showers arriving at larger angles travel longer paths in the atmosphere compared to the showers which are arriving at smaller angles. So the showers arriving at larger angles encounter more atmospheric mass and as a result there will be more attenuation for these showers. Thus energy thresholds of these showers will be higher. For this reason it is ensured that both source and background runs have same zenith angle coverage. Background runs are normalised with respect to source distributions by comparing the shapes of the distributions in 2.5° to 6.5° window since we do not expect any γ-ray event in this region [80]. This normalization is necessary since there are variations in the sky conditions, like, variation in ambient temperature, ambient light etc, at different times of the same night. Differences between the number of source and background events is calculated for each bin as \((S_i - cB_i)\) where \(c\) is a constant. We tried two different methods to obtain normalization constant. Firstly, ratio of all the events, for source and background runs, between 2.5° to 6.5° window was taken as normalization constant. Since number of events in this region are very low for both source as well as background runs, normalization constant obtained in this way would be biased. Secondly, we obtained normalization constant by \(\chi^2\) minimization method. We defined,

\[
\chi_k^2 = \sum_{i=2.5}^{6.5} (S_i - c_k B_i)^2
\]

(5.13)

\(c_k\) was varied over the range 0.5 to 2.0 in steps of 0.001. Then normalisation constant \(c_k\) was chosen such that \(\chi_k^2\) was minimum as shown in figure 5.3. Thus γ-ray signal is obtained as an excess of source events in 0° to 2.5°
region using the following equation.

\[ \text{no. of } \gamma \text{ rays} = \sum_{i=0}^{2.5} (S_i - c_k B_i) \]  

Figure 5.4 shows the ratios of source events over background events in each bin between 2.5° to 6.5° window.

![Graph showing variation of \( \chi^2 \) with normalization constants for a source run.](image)

**Fig. 5.3:** This figure shows variation of \( \chi^2 \) with normalization constants for a source run.

### 5.3 Analysis of Vertical Run Data

During a vertical run all telescopes remain fixed pointing towards zenith. Triggers are mostly due to cosmic rays. T0’s are obtained using these data. T0’s play a crucial role in the arrival angle estimation. Therefore we start each observation cycle with a vertical run. Values of T0’s for telescopes should not vary from run to run. Any variation in T0’s would suggest that there was some alteration in the set up. Figure 5.5 shows the TDC counts for a vertical run. It was seen that TDC counts form a narrow band which remains flat throughout the run. These TDC counts were then converted into time delays in ns using TDC calibration constants as shown in the figure 5.6.
Then time difference between two detectors $i$ and $j$ ($T_{ij}$) was calculated and the distributions were obtained. Values within $< T_{ij} > \pm 3\sigma$ were retained. This is to minimize the effect of isolated large fluctuations in photon arrival times [122]. $T_{ij}$ distributions before and after cut for a telescope is shown in figure 5.7. After that T0’s were obtained following equations given in section 5.2.1. It was observed that in a season T0s of all 24 telescopes were stable within 2-4 ns, as shown in table 5.3. First column in the table gives Telescope number. T0’s obtained from four vertical runs in 2003 for all telescopes are listed in next four columns. Sixth column gives mean T0 followed by sigma in column seven.

5.4 Source Run

Procedures to analyse source run are given below.

5.4.1 Preliminary Checks

Before doing actual analysis we carry out certain checks on data to judge its quality. Firstly, we see the event rate (or trigger rate) plot. If we find some
Table 5.3: T0’s of 24 telescopes of PACT for different vertical runs for 2002-2003 season are listed in this table. Telescopes 11-16 are from sector # 1, 21-26 from sector # 2, 31-36 from sector # 3 and 41-46 from sector # 4.

<table>
<thead>
<tr>
<th>Telescope #</th>
<th>Vertical run numbers.</th>
<th>Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>391</td>
<td>407</td>
</tr>
<tr>
<td>11</td>
<td>-34.12</td>
<td>-37.28</td>
</tr>
<tr>
<td>12</td>
<td>-38.09</td>
<td>-41.38</td>
</tr>
<tr>
<td>13</td>
<td>-51.04</td>
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</tr>
<tr>
<td>14</td>
<td>-39.43</td>
<td>-38.33</td>
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<td>16</td>
<td>-56.37</td>
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<td>21</td>
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<td>-50.13</td>
</tr>
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<td>22</td>
<td>-59.99</td>
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<td>26</td>
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<td>31</td>
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<tr>
<td>46</td>
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<td>0.00</td>
</tr>
</tbody>
</table>
Fig. 5.5: Scatter plot of TDC counts vs event number for TDC # 11 and TDC # 12 for a vertical run.

Fig. 5.6: Distributions of TDC counts in ns are shown for six telescopes in sector 2.

large spikes or dips in this plot, we delete those stretches of data. Modules are also checked for their behaviour during run. If some modules malfunc-
tion during run, data from those modules are discarded during analysis.

For analysis of control room data, where informations regarding all the telescopes of the array are recorded, we obtained ratio of the number of triggered events for source and background runs in a given night for all telescopes. This comparison is done with events which are recorded over the same zenith angle range for both source and background runs. Since events are mostly dominated by cosmic rays ratio would be close to 1, as shown in the figure 5.8. ACTOS gives us information about telescope orientation, pointing accuracy etc. But it was found that sometimes some telescope participated less efficiently in one of the runs (either sources or background). In that case this ratio would be different for that telescope. Then that telescope was rejected using software cuts for further analysis. At times more than one telescopes were rejected.

For a given night if source (or background) run was rejected depending on any of the conditions mentioned above then corresponding background (or source) run was also rejected.
5.4.2 Arrival direction estimation

In figure 5.9 scatter plot of TDC counts of two TDCs is shown for a source run. Each source run was first analysed using T0’s obtained from nearest vertical run. But most of the sources are observed at some angle with respect to zenith due to their declinations. For this reasons T0’s were fine tuned in the following way. In the first iteration all telescopes with valid TDC information were used for the fit and the observed – expected delays or residues were calculated for each event. If the T0’s are correct, the mean value should be zero. In subsequent iterations, telescopes with absolute difference, between observed and expected delays, greater than 6 ns are rejected in order to measure this mean accurately.

Residue cut of 6 ns was selected because of the following reasons. In figure 5.10 distribution of number of degrees of freedom (ndf), i.e. number of telescopes present in an event, is plotted for different residue cuts. It was seen that with lower residue cut of 3 ns events were re-fitted by rejecting
larger number of telescopes, as a result peak of the distribution shifts towards the lower ndf and there were very few events at higher ndf’s. On the other hand ndf distributions were found to be similar for residue cuts of 6 ns, 10 ns and 100 ns. But with higher residue cuts the error in the arrival angle estimation increases. Thus we used 6 ns for residue cut.

Figure 5.11 shows the observed − expected delay distributions for various telescopes based on royal sum pulses. For some telescopes the mean value of observed − expected distribution deviates from zero. This could be either due to inaccurate pointing of these telescopes or there were errors in calculation of time offsets (T0’s). This also could be due to source angle effect. Therefore T0’s are adjusted in such a way that observed − expected delay is ≤ 1 ns. It is made sure that at least 4 telescopes per sector were accepted, otherwise the event was rejected.

Thus fine tuned T0’s were obtained for all the source and corresponding background runs in an observation cycle. Then average T0’s were calculated from all the runs (source as well as background) for the source to be analysed. These average T0’s were then used to obtain space angles of showers for these runs. Figure 5.12 shows the NDF distribution for a source (top)
Chapter 5. Observations and Data Analysis Technique

Fig. 5.10: NDF distributions with different residue cuts for a Mkn 501 run.

Fig. 5.11: This figure shows the typical observed − expected delay distribution for all 6 telescopes of sector 2.

and background run (bottom). Distributions of $\chi^2$ for the plane front fit of showers in one such pair of runs are shown in figure 5.13. Scatter plot of zenith angles of a source run is shown against hour angle in the figure 5.14 (shown by dots), solid line represents the zenith angle of the source calcu-
lated as explained earlier. Similar plot for *azimuth* angles is shown in the lower panel.

![Graph](image1)

**Fig. 5.12:** *upper panel* shows NDF distribution for a Mkn 501 run and *lower panel* shows corresponding distribution for the background run.

![Graph](image2)

**Fig. 5.13:** *upper panel* shows $\chi^2$ distribution for the plane front fit of showers for a source run and *lower panel* shows corresponding distribution for the background run.
Fig. 5.14: upper panel: Scatter plot of Zenith angles vs hour angle. Solid line represents the zenith angle of source calculated from real time. lower panel Same for Azimuth angles.

5.4.3 Comparison of space angle distributions between source and background runs

Space angle distributions of all source runs (in bins of 0.1°) are compared with the corresponding distributions of background runs over the same zenith angle range. A cut was imposed on the number of telescopes to be ≥ 8 for the comparison. Excess of source events was calculated following equations given in section 5.2.3. Figure 5.15 shows the typical space angle distribution of a source run, background run and the difference between the two distributions.

5.4.4 Analysis of fictitious source

To verify analysis method discussed above some tests were carried out. For this purpose some of the vertical runs were analysed following this technique. These runs were taken over the period of 5 years from 2000 to 2005. Each run was split into two approximately equal halves. Space angle distributions were obtained for both the halves. Then comparison was done assuming one half as a source run and the other half as a background run. The
fitted $\theta$ and $\phi$ distributions for one half of a vertical run is shown in figures 5.16 and 5.17 respectively. Figure 5.18 shows the space angle distributions of two halves of a vertical run, taken on 27th November, 2005. Excess or deficit of events within 2.5° space angle obtained from comparisons of several halves of vertical runs are plotted in figure 5.19 as event rate/minute. Mean excess event rate/minute is found to be $1.67 \pm 0.43$, which is consistent with zero. Vertical runs are taken by pointing all the telescopes towards zenith in a fixed position. Therefore all the events are due to cosmic rays. Since cosmic rays are isotropic, excess events are not expected from these runs. Fluctuation in excess event rates gives an estimate of the noise level in extracting $\gamma$-ray signal using PACT.

### 5.4.5 Post Analysis Rejection

Some runs were rejected after analysis based on certain criteria given here. For some runs it was found that the peak positions of the space angle distributions were shifted with respect to each other for source and corresponding background runs (see figure 5.20). Also there were runs with unequal widths for space angle distributions for source and background regions.
These runs were rejected because of the difficulty in normalization and current procedure results in either large excess or deficit of events. Another rejection criteria was set based on the values of normalization constants. Runs with normalization constants within 0.8 to 1.2 were accepted, others were rejected. Since cosmic rays form majority of the triggers, any normal-
Fig. 5.18: Space angle distributions of two halves of a Vertical run taken on 27th November, 2005.

Fig. 5.19: Rate/minute of excess events obtained from some vertical runs.

...
of source and background run it was found that the normalization constant was not within ±0.2 of this average value then that pair was rejected.

![Normalized space angle distribution](image)

**Fig. 5.20**: Shifted space angle distribution.
Chapter 6

Results

In this chapter we will present our results obtained from observations of four blazars namely Markarian 421, Markarian 501, 1ES1426+428 and ON231. We have carried out multiwaveband study of Mkn 421 and undertaken a comparative study of its flaring and quiscent states. Results from this study are also discussed here.

6.1 Markarian 421

Markarian 421 is a nearby blazar (z=0.031). It was observed by EGRET on six occasions between 1991 and 1993 [79]. On each occasion source was relatively weak. The average integral flux above 100 MeV was estimated to be \((1.7 \pm 0.3) \times 10^{-7} \gamma \text{ cm}^{-2} \text{ s}^{-1}\) and the average differential spectral index was estimated to be \(-1.71 \pm 0.15\) [123]. Mkn 421 is the first blazar detected at TeV energies by Whipple \(\gamma\)-ray observatory in 1992 [94]. The initial detection had statistical significance of 6.3\(\sigma\) and was based on 7.5 hours of observations. The quoted flux \(\phi (E > 0.5 \text{ TeV}) = 1.5 \times 10^{-11} \gamma \text{ cm}^{-2} \text{ s}^{-1}\) represented a level \(\sim 30\%\) of that of the Crab nebula. Later in 1994 - 1995 an independent detection was made by HEGRA CT1 and CT2 Cherenkov telescopes [91]. Many large outbursts were detected from this source since its discovery in 1992. In May 1994, a flare was observed in which the TeV \(\gamma\)-ray flux increased by almost an order of magnitude on the time scale of a few days [73]. Strongest flares were detected from this source in 2001 and 2004 by many ground based atmospheric Cherenkov
HEGRA has observed Mkn 421 for a long time from December 1999 until May 2001. The time averaged flux of $\gamma$-rays in the 1999/2000 season was estimated to be $(1.43 \pm 0.04_{\text{stat}} \pm 0.2_{\text{syst}}) \times 10^{-11}$ photons $\text{cm}^{-2} \text{s}^{-1}$ and photon index was $3.19 \pm 0.04_{\text{stat}} \pm 0.04_{\text{syst}}$ in the energy range 500 GeV to 10 TeV. Whereas in 2000/2001 season flux increased to $(4.19 \pm 0.04_{\text{stat}} \pm 0.04_{\text{syst}}) \times 10^{-11}$ photons $\text{cm}^{-2} \text{s}^{-1}$ and corresponding photon index was $2.19 \pm 0.02_{\text{stat}} \pm 0.04_{\text{syst}}$ [34]. There is indication of spectral hardening based on 2000/2001 spectrum. They have fitted both the energy spectra by a power law with exponential cutoff at $3.6_{\text{stat}} (0.4-0.3)_{\text{syst}} + 0.9_{\text{stat}} (0.8-0.8)_{\text{syst}}$ TeV. Similar extensive study was carried out by Whipple telescope on Mkn 421 over the period of 2003-2004, which was part of a multiwavelength monitoring campaign involving $\gamma$-ray, X-ray, optical and radio telescopes [46]. They have noticed that photon index varies from 2.73 to 2.11 during low and high state of Mkn 421 respectively. They have also fitted the spectra with a cutoff power law but with the cutoff energy fixed at 4.96 TeV.

### 6.1.1 Previous Multiwavelength Observations

Many multiwavelength campaigns have been carried out for Mkn 421. In 1995 for the first time an extensive multiwavelength campaign was carried out to measure the multiwavelength properties of Mkn 421. Observations were conducted over a two week period with the Whipple $\gamma$-ray telescope, EGRET, ASCA (X-rays), the Extreme Ultra Violet Explorer (EUV), an optical telescope and an optical polarimeter. This campaign revealed, for the first time, the correlation between X-rays and VHE $\gamma$-rays [50]. There was another multiwavelength campaign conducted in late April 1998, involving Whipple telescope and BeppoSAX satellite, which happened to coincide with a flare. This campaign established the hour-scale correlation between X-rays and VHE $\gamma$-rays in blazars [82]. A very intense flare was detected from Mkn 421 in the early months of 2001. Multiwavelength campaigns were carried out during this period involving X-ray and $\gamma$-ray detectors. Figure 6.1 shows light curves at $\gamma$-ray (Whipple, STACEE) and telescopes e.g., Whipple, HEGRA, STACEE etc [47].
X-ray energies (RXTE) for one such campaign which took place during that period. Strong correlation was also noticed during that period between X-ray and $\gamma$-ray. A long multiwavelength campaign was carried out for Mkn 421 for 2003 and 2004 seasons involving $\gamma$-ray, X-ray, optical and radio telescopes [46]. In April-May 2004 this source was detected in a very active state at higher energies i.e. X-rays and $\gamma$-rays. This large amount of multiwaveband data allowed Blazejowski et al. to carry out detailed study of cross-band correlation and broad band spectral variability, over a wide range of fluxes.

**Spectral Energy Distribution (SED)**: SED derived from contemporaneous multiwavelength observations of Mkn 421 shows two humps as shown in the figure 6.2. The peak position of the first hump is at X-ray energies. Because of this Mkn 421 is classified as HBL type of blazar. Peak position of the second hump is located in VHE band. Generally, first hump is attributed to synchrotron radiation by the relativistic electrons present in
the jet and the second hump is attributed to inverse Compton scattering of synchrotron photons by these electrons. Correlation between X-rays and VHE $\gamma$-ray emissions observed in Mkn 421 favours the Synchrotron Self-Compton (SSC) scenario. Also, during flare both X-ray and $\gamma$-ray spectrum were found to harden significantly.

![Fig. 6.2: Spectral Energy Distribution of Mkn 421 from contemporaneous and archival observations. This figure is taken from [125].](image)

### 6.1.2 Observation of Mkn 421 using PACT

We have observed Mkn 421 using PACT since 2000. Data were collected from Mkn 421 every year from 2000 to 2005. For each source run an equal amount of data were also collected from corresponding background run. After preliminary checks for data quality, as described in chapter 4, about $\sim 50\%$ of data were retained. This corresponds to approximately about 205 hours of on-source data. Source and background runs taken in the same night were analysed using procedure outlined in chapter 4 and $\gamma$-ray signal, as excess events, was obtained. Then post analysis cuts were applied to these runs and finally $\sim 96.3$ hours of data were retained. The results are summarized in tables 6.1 to 6.6. Each of these tables contains 6 columns.
Table 6.1: Details of Mkn 421 runs for year 2000

<table>
<thead>
<tr>
<th>MJD</th>
<th>Duration (ha)</th>
<th>Trigger rate (Hz)</th>
<th>ndf</th>
<th>normalisation constant</th>
<th>Excess $\gamma$/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>51578.903</td>
<td>-6.9° to 29.9°</td>
<td>2.6</td>
<td>9/12</td>
<td>0.82</td>
<td>3.5(±0.8)</td>
</tr>
<tr>
<td>51583.879</td>
<td>-5.3° to 20.1°</td>
<td>3.8</td>
<td>11/12</td>
<td>1.01</td>
<td>13.8(±1.4)</td>
</tr>
<tr>
<td>51586.865</td>
<td>-5.7° to 15.6°</td>
<td>3.1</td>
<td>12/12</td>
<td>0.80</td>
<td>7.2(±1.4)</td>
</tr>
<tr>
<td>51606.837</td>
<td>6.6° to 24.1°</td>
<td>3.7</td>
<td>12/12</td>
<td>0.84</td>
<td>0.97(±1.7)</td>
</tr>
<tr>
<td>51608.885</td>
<td>-6.7° to 16.2°</td>
<td>3.7</td>
<td>12/12</td>
<td>0.84</td>
<td>0.83(±1.5)</td>
</tr>
<tr>
<td>51611.816</td>
<td>-4.6° to 21.1°</td>
<td>3.1</td>
<td>11/12</td>
<td>0.96</td>
<td>0.31(±1.2)</td>
</tr>
<tr>
<td>51612.816</td>
<td>-8.1° to 17.7°</td>
<td>4.6</td>
<td>12/12</td>
<td>0.91</td>
<td>-13.9(±1.6)</td>
</tr>
<tr>
<td>51613.813</td>
<td>-2.3° to 18.6°</td>
<td>3.4</td>
<td>10/12</td>
<td>0.95</td>
<td>1.97(±1.3)</td>
</tr>
<tr>
<td>51614.826</td>
<td>11.5° to 31.0°</td>
<td>3.4</td>
<td>11/12</td>
<td>0.84</td>
<td>11.0(±1.4)</td>
</tr>
<tr>
<td>51635.757</td>
<td>0.3° to 17.9°</td>
<td>3.0</td>
<td>12/12</td>
<td>0.85</td>
<td>9.43(±1.4)</td>
</tr>
<tr>
<td>51641.750</td>
<td>9.3° to 31.4°</td>
<td>2.0</td>
<td>9/12</td>
<td>0.90</td>
<td>2.62(±1.0)</td>
</tr>
</tbody>
</table>

First column gives MJD corresponding to the mid point of our source observations. Second column is the source hour angle (ha) range covered. Trigger rates observed during the source runs are listed in third column. Fourth column gives number of degrees of freedom i.e. number of telescopes used for analysis/number of telescopes used for observation. Normalization constants are given in column five and finally excess events as $\gamma$-ray rate per minute in column six.

Figure 6.3 shows the lightcurve of PACT from 2000 to 2005 in the upper panel. In the bottom panel the light curve of ASM\(^1\) (All Sky Monitor on board RXTE) over the same period, is shown for comparison. As mentioned earlier sensitivity of PACT is such that to have reasonable signal to noise ratio we need to add data from several nights and thereby increase the observation duration. Average $\gamma$-ray rate was found to be $0.48 \pm 0.21$ per minute after combining all the data from 2000-2005. The average zenith angle of Mkn 421 at Pachmarhi is $\sim 30^\circ$. At this declination energy threshold and corresponding collection area of PACT were estimated to be 1.2 TeV and $1.8 \times 10^5$ m\(^2\) respectively, as given in chapter 3. Thus time averaged integral flux for Mkn 421 was obtained as $4.45(\pm 1.9) \times 10^{-12} \, \gamma \, cm^{-2} \, s^{-1}$

\(^1\)http://xte.mit.edu/asmlc/srcs/mkn421.html#data
Table 6.2: Details of Mkn 421 runs for year 2001

<table>
<thead>
<tr>
<th>MJD</th>
<th>Duration (ha)</th>
<th>Trigger rate (Hz)</th>
<th>ndf</th>
<th>normalisation constant</th>
<th>Excess $\gamma$/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>51932.951</td>
<td>8.1° to 14.9°</td>
<td>4.5</td>
<td>11/12</td>
<td>0.85</td>
<td>18.95(±3.1)</td>
</tr>
<tr>
<td>51934.951</td>
<td>-8.1° to 26.2°</td>
<td>4.8</td>
<td>10/12</td>
<td>1.24</td>
<td>-5.14(±1.3)</td>
</tr>
<tr>
<td>51937.923</td>
<td>2.3° to 19.5°</td>
<td>2.8</td>
<td>10/12</td>
<td>0.99</td>
<td>-9.44(±1.5)</td>
</tr>
<tr>
<td>51939.938</td>
<td>9.3° to 18.6°</td>
<td>3.3</td>
<td>10/12</td>
<td>1.18</td>
<td>-4.66(±2.1)</td>
</tr>
<tr>
<td>51940.931</td>
<td>7.1° to 17.0°</td>
<td>2.6</td>
<td>12/12</td>
<td>1.20</td>
<td>-2.70(±2.2)</td>
</tr>
<tr>
<td>51957.868</td>
<td>-2.3° to 16.9°</td>
<td>2.2</td>
<td>11/12</td>
<td>0.98</td>
<td>2.28(±1.2)</td>
</tr>
<tr>
<td>51958.837</td>
<td>7.0° to 21.8°</td>
<td>1.6</td>
<td>10/12</td>
<td>0.82</td>
<td>1.80(±1.1)</td>
</tr>
<tr>
<td>51959.861</td>
<td>10.5° to 29.8°</td>
<td>1.9</td>
<td>12/12</td>
<td>1.10</td>
<td>-7.97(±1.2)</td>
</tr>
<tr>
<td>51960.863</td>
<td>-0.5° to 27.9°</td>
<td>2.3</td>
<td>12/12</td>
<td>1.11</td>
<td>-2.67(±1.0)</td>
</tr>
<tr>
<td>51961.854</td>
<td>-9.6° to 12.6°</td>
<td>4.2</td>
<td>11/12</td>
<td>1.20</td>
<td>-5.69(±1.5)</td>
</tr>
<tr>
<td>51962.854</td>
<td>-2.5° to 27.0°</td>
<td>2.4</td>
<td>10/12</td>
<td>0.86</td>
<td>-2.31(±1.0)</td>
</tr>
<tr>
<td>51963.875</td>
<td>9.2° to 34.7°</td>
<td>2.2</td>
<td>10/12</td>
<td>0.72</td>
<td>8.60(±0.9)</td>
</tr>
<tr>
<td>51964.833</td>
<td>-0.2° to 20.2°</td>
<td>3.0</td>
<td>12/12</td>
<td>0.82</td>
<td>8.56(±1.4)</td>
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<td>3.0</td>
<td>11/12</td>
<td>1.13</td>
<td>2.00(±1.6)</td>
</tr>
<tr>
<td>51968.837</td>
<td>-3.3° to 19.8°</td>
<td>2.7</td>
<td>12/12</td>
<td>0.89</td>
<td>7.19(±1.3)</td>
</tr>
<tr>
<td>51969.833</td>
<td>-1.6° to 23.7°</td>
<td>2.8</td>
<td>10/12</td>
<td>1.07</td>
<td>5.92(±1.2)</td>
</tr>
<tr>
<td>51990.771</td>
<td>7.0° to 24.1°</td>
<td>2.7</td>
<td>11/12</td>
<td>1.06</td>
<td>2.48(±1.4)</td>
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<tr>
<td>52991.792</td>
<td>4.1° to 23.7°</td>
<td>2.5</td>
<td>11/12</td>
<td>0.83</td>
<td>0.77(±1.3)</td>
</tr>
<tr>
<td>52020.701</td>
<td>-3.0° to 32.2°</td>
<td>2.8</td>
<td>12/12</td>
<td>0.88</td>
<td>5.95(±1.0)</td>
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</table>

Table 6.3: Details of Mkn 421 runs for year 2002

<table>
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<tr>
<th>MJD</th>
<th>Duration (ha)</th>
<th>Trigger rate (Hz)</th>
<th>ndf</th>
<th>normalisation constant</th>
<th>Excess $\gamma$/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>52290.972</td>
<td>1.7° to 10.6°</td>
<td>2.17</td>
<td>5/6</td>
<td>1.17</td>
<td>-8.39(±2.5)</td>
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<tr>
<td>52291.931</td>
<td>1.7° to 10.6°</td>
<td>2.17</td>
<td>5/6</td>
<td>0.87</td>
<td>-7.96(±2.5)</td>
</tr>
<tr>
<td>52342.826</td>
<td>-7.2° to 1.7°</td>
<td>2.54</td>
<td>6/6</td>
<td>1.16</td>
<td>3.10(±2.7)</td>
</tr>
<tr>
<td>52372.750</td>
<td>-2.4° to 28.8°</td>
<td>2.42</td>
<td>10/12</td>
<td>0.76</td>
<td>8.14(±1.0)</td>
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</tbody>
</table>
Table 6.4: Details of Mkn 421 runs for year 2003

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<th>MJD</th>
<th>Duration (ha)</th>
<th>Trigger rate (Hz)</th>
<th>ndf</th>
<th>normalisation constant</th>
<th>Excess γ/\text{min}</th>
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</thead>
<tbody>
<tr>
<td>52649.917</td>
<td>-18.9° to 12.6°</td>
<td>0.97</td>
<td>9/12</td>
<td>0.76</td>
<td>-0.25(±0.5)</td>
</tr>
<tr>
<td>52650.927</td>
<td>-7.8° to 17.4°</td>
<td>1.91</td>
<td>12/12</td>
<td>0.96</td>
<td>-9.87(±0.7)</td>
</tr>
<tr>
<td>52698.854</td>
<td>-22.5° to 40.5°</td>
<td>2.67</td>
<td>11/12</td>
<td>1.01</td>
<td>-8.40(±1.1)</td>
</tr>
<tr>
<td>52702.833</td>
<td>-17.1° to 41.7°</td>
<td>1.13</td>
<td>11/12</td>
<td>0.60</td>
<td>-2.12(±0.5)</td>
</tr>
<tr>
<td>52753.688</td>
<td>3.9° to 27.0°</td>
<td>3.10</td>
<td>17/24</td>
<td>0.91</td>
<td>5.23(±1.4)</td>
</tr>
<tr>
<td>52754.697</td>
<td>1.4° to 29.6°</td>
<td>3.86</td>
<td>22/24</td>
<td>1.00</td>
<td>3.87(±1.5)</td>
</tr>
</tbody>
</table>

Table 6.5: Details of Mkn 421 runs for year 2004

<table>
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<th>MJD</th>
<th>Duration (ha)</th>
<th>Trigger rate (Hz)</th>
<th>ndf</th>
<th>normalisation constant</th>
<th>Excess γ/\text{min}</th>
</tr>
</thead>
<tbody>
<tr>
<td>53054.826</td>
<td>8.6° to 19.0°</td>
<td>5.2</td>
<td>16/18</td>
<td>0.98</td>
<td>-5.4(±2.8)</td>
</tr>
<tr>
<td>53055.854</td>
<td>12.2° to 19.0°</td>
<td>4.3</td>
<td>11/18</td>
<td>0.91</td>
<td>3.8(±2.9)</td>
</tr>
<tr>
<td>53056.833</td>
<td>-18.0° to 25.0°</td>
<td>3.9</td>
<td>13/18</td>
<td>0.98</td>
<td>4.2(±1.2)</td>
</tr>
<tr>
<td>53058.837</td>
<td>-10.1° to 23.2°</td>
<td>4.1</td>
<td>13/18</td>
<td>1.19</td>
<td>-6.0(±1.4)</td>
</tr>
<tr>
<td>53059.854</td>
<td>11.0° to 17.5°</td>
<td>4.9</td>
<td>12/12</td>
<td>0.97</td>
<td>11.8(±3.1)</td>
</tr>
<tr>
<td>53078.795</td>
<td>-5.6° to 25.0°</td>
<td>5.0</td>
<td>20/24</td>
<td>1.32</td>
<td>-16.4(±1.7)</td>
</tr>
<tr>
<td>53081.823</td>
<td>13.8° to 30.0°</td>
<td>4.4</td>
<td>19/24</td>
<td>0.99</td>
<td>-3.2(±2.1)</td>
</tr>
<tr>
<td>53087.750</td>
<td>-14.6° to 20.0°</td>
<td>3.2</td>
<td>15/18</td>
<td>0.81</td>
<td>6.7(±1.2)</td>
</tr>
<tr>
<td>53106.677</td>
<td>-10.9° to 5.0°</td>
<td>2.9</td>
<td>19/24</td>
<td>1.09</td>
<td>-11.4(±1.9)</td>
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Table 6.6: Details of Mkn 421 runs for year 2005

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<th>Trigger rate (Hz)</th>
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<tr>
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<td>18/24</td>
<td>0.53</td>
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<tr>
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<td>22/24</td>
<td>0.72</td>
<td>5.6(±1.4)</td>
</tr>
</tbody>
</table>
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Fig. 6.3: TeV $\gamma$-ray lightcurve of Mkn 421 obtained by PACT during 2000 to 2005 (upper panel). Lightcurve in the lower panel is obtained from the ASM data from Mkn 421 over the same period.

above 1.2 TeV and is shown in figure 6.4. The flux of $\gamma$-rays during the most intense flare and lowest activity state as obtained by Whipple group is also shown in this figure. The dashed line represents the quiescent flux measured in 1995 [95] and solid line represents the flux measured during a flaring state in 2001 [78]. During the period of our observations, there were a few flares in 2000, 2001 and 2004. So our time averaged flux is expected to be between the two extreme limits given by Whipple.

6.1.3 Analysis of Multiwavelength Data

In the early months of 2001 Mkn 421 was in very active state. Simultaneous X-ray, optical and radio data were available for this period. Then in 2003 there was an international multiwavelength campaign from 26th February to 5th March involving $\gamma$-ray and X-ray experiments. Mkn 421 was reported to be in low state during this time. PACT was also part of this observation campaign. But at this time there was an increase in ambient light level at Pachmarhi and it was found that data were noisy. X-ray data were taken by RXTE satellite. Near Infra Red (NIR) and radio data, for this period, were
Fig. 6.4: Integral energy spectrum of Mkn421. The data point (asterix) with error bar represents the time averaged integral flux of Mkn 421 obtained from PACT observation during 2000 to 2005. Dashed line represents the flux measured by Whipple during a low activity state and solid line represents their flux measured during 2001 flaring state.

Analysis of X-ray data

X-ray data obtained using the Rossi X-ray Timing Explorer (RXTE), launched on December 30, 1995 atop a Delta II rocket into low-earth orbit (about 600 km and 23° inclination) were used. There are three instruments on board RXTE: the ASM, the PCA and HEXTE. Total energy range of this satellite is 2-200 keV, as shown in figure 6.5.

The All Sky Monitor (ASM) rotates in such a way as to scan most of the sky every 1.5 hours. It consists of three wide-angle shadow cameras equipped with proportional counters with a total collection area of 90 cm$^2$. The energy range addressed by these detectors is 2-10 keV. Proportional Counter Array (PCA) has five xenon gas proportional counter detectors. They are sensitive to X-rays with energies in the range of 2-60 keV. It has
collection area of 6500 $cm^2$. The High Energy X-ray Timing Experiment (HEXTE) consists of two clusters, each containing four phoswich (NaI/CsI) scintillation detectors. The energy range and collection area of these detectors are 15 - 250 keV and $2 \times 800 cm^2$ respectively.

Data sets for year 2001 and 2003 were extracted\(^2\) from observation IDs 60145 and 80172 respectively. First set of data were collected during March-April 2001 when Mkn421 was in flaring state. The second set was collected during 26th February to 5th March 2003. Mkn421 was in quiescent state at this time. We have analyzed Standard 2 PCA data which has a time resolution of 16s with energy information in 128 channels. Even though observations were carried out with PCU 0 and PCU 2, we have used only PCU 2 data. This is because PCU 0 has lost its front veto layer at the beginning of Epoch 5 (May, 2000). So the data from this detector are more prone to contamination by events caused by low-energy electrons entering the detector. Data from all the layers of PCU 2 are added. Data reduction is done with FTOOLS (version 5.3.1)\(^3\) distributed as part of HEASOFT (version 5.3). For each of the observations, data were filtered using standard procedure given in the RXTE Cook Book \(^4\). Lightcurves for source were

\(^2\)http://heasarc.gsfc.nasa.gov/W3Browse
\(^3\)http://heasarc.gsfc.nasa.gov/docs/software/lheasoft
\(^4\)http://heasarc.gsfc.nasa.gov/docs/xte/recipes/cook_book.html
extracted by running *saextrct* command on data files. This program allows extraction of lightcurves in the specified energy range. Background data is synthetically produced by ftool *pcabackest* by matching the background conditions of observations with those in various model files. These model files contain actual background observations sorted by quantities such as the position of the spacecraft with respect to the South Atlantic Anomaly. The outputs of *pcabackest* were put through *saextrct* and background lightcurves and spectra were obtained. For extraction of background, model appropriate for bright sources (*pca_bkgd_cmbrightvle_eMv20031123.mdl*) was used for the 2001 data since source was in high state during that period. For 2003 data, when source was in low state, model appropriate for faint sources (*pca_bkgd_cmfaintl7_eMv20030330.mdl*) was used. In figures 6.6, 6.7 & 6.8 the X-ray lightcurves from PCA data is shown in three different energy bands 2-9 keV, 9-20 keV and 20-60 keV for Mkn 421. Top panels show lightcurve for 2001 and bottom panels for 2003. We have found that during flare in 2001 count rates in different energy bands are 5-6 times higher in comparison with the quiescent state in 2003.

![Lightcurve Image]

Fig. 6.6: PCA light curve, in energy range 2-9 keV, for Mkn 421. *upper panel* For 2001 and *lower panel* for 2003.

Spectral analysis of PCA data was carried out using XSPEC [12]. Using
saextract pha files were created for source and background. In spectral analysis it is necessary to know the detector response to X-ray photons which depends on two factors. Firstly, absorption/transmission of X-rays by detector windows and collimator. Secondly, interaction of these photons in
the detector volume. Response matrices were generated using ftool pcarsp. Each of the X-ray data sets consists of several subsets. For 2003 we have taken the entire data set. Data for year 2001 were collected over the period from 19th March to 1st April. Since our main aim was to compare the data corresponding to quiescent and flaring state, we picked up only those subsets from 2001 data set which have count rates $\geq 100 \, cts \, s^{-1} \, PCU^{-1}$. Spectral data from both the data sets were fitted by cutoff power law with line of sight absorption. The line of sight absorption was fixed to neutral hydrogen column density at $1.38 \times 10^{20} \, cm^2$ [27]. We have added a 1% systematic uncertainty for spectral analysis which is common practice. Each subset was analysed separately following this procedure. Also, all subsets for given observation period were combined and fitted. The best fit photon indices for 2001 and 2003 data were obtained as $2.05(\pm 0.03)$ and $2.40(\pm 0.03)$. Cutoff energies were found to be about $24.9(\pm 0.26) \, keV$ and $23.9(\pm 2.4) \, keV$ respectively. Figures 6.9 & 6.10 show the folded spectrum for Mkn 421 and figures 6.11 & 6.12 show the unfolded spectrum for the combined data sets of 2001 and 2003. In figure 6.13 photon index of each subset, is plotted against flux for 2001 and 2003. It is found that as flux increases photon index decreases i.e. spectrum hardens as flux increases.

![Folded spectrum of Mkn 421 for 2001. Residuals are shown in the bottom panel.](image)

Fig. 6.9: Folded spectrum of Mkn 421 for 2001. Residuals are shown in the bottom panel.
Fig. 6.10: Folded spectrum of Mkn 421 for 2003. Residuals are shown in the bottom panel.

Fig. 6.11: Unfolded spectrum of Mkn 421 for 2001.
Chapter 6. Results

Fig. 6.12: Unfolded spectrum of Mkn 421 for 2003.

Fig. 6.13: Cross plot of flux vs photon index, indicating hardening of spectra with increase in flux.

Optical and NIR Observations

For the 2001 flare, simultaneous optical data taken by WEBT\(^5\) (whole Earth Blazar Telescope) collaboration [98]. They have used 60 cm KVA-telescope

\(^5\)a large collaboration among optical institutes involved in blazar monitoring studies (see http://astro.fmarion.edu.webt/)
at La Palma during this period. During 2003 campaign Near InfraRed (NIR) data was taken by a 1.2 m telescope at Gurushikhar observatory, Mount Abu, India. Photometry in the J-band was done using a NIR imager/spectrometer with a $256 \times 256$ HgCdTe NICMOS 3 array. The instrument was used in the imaging mode with a $2 \times 2$ arcmin$^2$ field. Mkn 421 was observed continuously on all nights between 25th February to 5th March 2003 [64].

Radio Observations

We have used radio data applied by Dr. T. Hovatta for 2001 and 2003 periods. These data were taken by Metsähovi radio telescope at 22 and 37 GHz. The details about the radio data are given in [99].

6.1.4 Spectral Energy Distribution

The X-ray and $\gamma$-ray emission from TeV blazars is commonly attributed to the Synchrotron Self Compton (SSC) model. In this mechanism a population of high-energy electrons in jet emits synchrotron radiation, followed by inverse Compton scattering of synchrotron photons to TeV energies. In figures 6.14 & 6.15 SEDs for Mkn 421 for 2001 and 2003 are shown. We have used the time averaged flux of $\gamma$-rays obtained from PACT observations in the SED of 2003 as shown by a square symbol with error bar in figure 6.15. During the multiwavelength campaign in 2003 this source was at quiescent state. Mkn 421 was at low state during most of the PACT observation from 2000 to 2005, and hence the time averaged flux is expected to be consistent with the quiescent state of Mkn421. In the SED plot of 2001 square symbol represents the time averaged flux obtained after combining only those runs which are simultaneous with the X-ray observations. Fits involving X-ray data with a simple one zone SSC model are shown by solid lines. The SSC code$^6$ used for this purpose is developed by [77]. This code computes the synchrotron and inverse Compton emission, and corrects the emitted photon spectrum for Synchrotron Self-Absorption and internal absorption.

$^6$The SSC code is freely available at http://jelley.wustl.edu/multiwave.
due to pair production processes. This model assumes a spherical emission volume of radius $R$, that moves with a bulk Lorentz factor $\Gamma$ towards the observer. The radiation is Doppler shifted by a factor

$$\delta_j = \left[ \Gamma \left( \frac{1 - \beta \cos \theta}{1 + \beta \cos \theta} \right) \right]^{-1}$$

where $\beta$ is the bulk velocity of the plasma in units of the speed of the light and $\theta$ is the angle between the jet axis and the line of sight in the observer frame. The emission volume is filled with an isotropic non-thermal electron population and a randomly oriented magnetic field $B$. The energy spectrum of the electrons in the jet is described by a broken power law with low-energy ($E_{\text{min}}$ to $E_b$) and high-energy ($E_b$ to $E_{\text{max}}$) indices $p_1 = 2$ and $p_2 = 3$, respectively ($p_i$ is from $dN/dE \propto E^{-p_i}$; $E$ is the electron energy in the jet frame). This code takes into account the attenuation of the VHE $\gamma$-rays by the diffuse infrared background as modeled by MacMinn & Primack [120]. Best fit parameters of SEDs for year 2001 and 2003 are listed in tables 6.7 & 6.8. $w_e$ is the electron density. Even though this one zone SSC model fits X-ray to $\gamma$-ray data satisfactorily it underestimates radio and optical fluxes. This model thus suggests that the low-energy radio-to-optical emission is dominated by emission from regions other than those emit the bulk of the X-rays and $\gamma$-rays. Introduction of additional electron components improves the fit at lower energy emissions, as suggested by Krawczynski et al. SED components of radio and optical emissions are shown by dotted and dashed lines in figures 6.14 & 6.15 respectively. Best fit parameters to optical and radio data for 2001 and 2003 are also listed in tables 6.7 & 6.8. SEDs corresponding to high and low states MKn 421 is shown in the figure 6.16 for comparison. It is seen that SED parameters vary greatly at higher energies but weakly at lower energies.

### 6.1.5 Study of Correlated Variability between X-ray and NIR data

Correlation between X-rays and TeV $\gamma$-rays is well established. In HBLs correlation between high energy and low energy emissions is not yet established. Correlation study was carried out between X-ray and NIR data collected during multiwavelength campaign. Figure 6.17 shows the light
Table 6.7: Best fit parameters for SED 2001

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<th>Optical</th>
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<td>15</td>
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<tr>
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<td>0.005</td>
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<tr>
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<td>0.00019</td>
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Table 6.8: Best fit parameters for SED 2003

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<td>R(m)</td>
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curve for PCA (in two energy bands 2-9 keV and 9-20 keV) and NIR data, with 5 minutes binning. The cross-correlation between two data sets is de-
Fig. 6.16: Comparison between SEDs of 2001 and 2003. There are significant changes in SED parameters at higher energy emission compared to that at low energy emissions.

Defined as

\[
P_{xy}(L) = \frac{\sum_{K=0}^{N-L-1}(x_{K+L} - \bar{x})(y_{K} - \bar{y})}{\sqrt{\sum_{K=0}^{N-1}(x_{K} - \bar{x})^2 \sum_{K=0}^{N-1}(y_{K} - \bar{y})^2}} \quad \text{for } L < 0 \quad (6.1)
\]

and

\[
P_{xy}(L) = \frac{\sum_{K=0}^{N-L-1}(x_{K} - \bar{x})(y_{K+L} - \bar{y})}{\sqrt{\sum_{K=0}^{N-1}(x_{K} - \bar{x})^2 \sum_{K=0}^{N-1}(y_{K} - \bar{y})^2}} \quad \text{for } L \geq 0 \quad (6.2)
\]

But these functions do not take into account data gaps if any. Like any other astronomical time series these two data sets are also too sparse and unevenly sampled. There are two approaches for dealing with the gaps in the data: interpolation and discrete binning. Interpolation becomes unreliable when there is significant power on time scales smaller than the typical gap size, as in this present case. In the other approach correlation function can be measured without interpolating in the temporal domain. This method is called Discrete Correlation Function (DCF) \[28\]. This method avoids the problem of spurious correlations at zero lag due to correlated errors.
is defined in the following way: For two discrete data trains, \( a_i \) and \( b_j \), unbinned discrete correlation function is defined as

\[
UDCF_{ij} = \frac{(a_i - \bar{a})(b_j - \bar{b})}{\sqrt{(\sigma_{a}^2 - e_a^2)(\sigma_{b}^2 - e_b^2)}}
\]

(6.3)

for all measured pairs \((a_i, b_j)\). Each of these is associated with the pairwise lag \( \Delta t_{ij} = t_i - t_j \). The parameter \( e_f \) is the measurement error associated with the data set. Binning this result in time allows to measure \( DCF(\tau) \) function directly. Averaging over the \( M \) pairs for which \( \tau - \Delta \tau / 2 \leq \Delta t_{ij} < \tau + \Delta \tau \),

\[
DCF(\tau) = \frac{UDCF_{ij}}{M}
\]

(6.4)

The \( DCF(\tau) \) is not defined for a bin with no points. The drawback of \( DCF \) is that if the sample distribution is very skewed then measured correlation will be erroneous. To avoid this problem \( z \)-transformed discrete correlation function (ZDCF) [10] is used. The ZDCF makes use of the Fisher’s \( z \)-transform of the correlation coefficient. It’s main advantage over \( DCF \) is that it is more efficient in dealing with any correlation present. The ZDCF involves three steps. Firstly, all possible pairs of observations \((a_i, b_j)\) are sorted according to their time-lag \( t_i - t_j \) and binned into equal population bin. Secondly, each bin is assigned its mean time lag and the intervals above and below the mean that contain \( 1 \sigma \) of each point. Finally, the correlation coefficient of the bins are calculated and \( z \)-transformed. The ZDCF between X-ray and NIR is plotted in figure 6.18 against delay. ZDCF function suggests that X-ray variability lags the NIR variability by \( \sim 3 \) days. But this correlation is rather weak, only \( \sim 50\% \). Whereas ZDCF between two energy bands of X-ray data shows that there is no lag between them and they are highly correlated.

### 6.2 Markarian 501

Markarian 501 is the second HBL type blazar detected at TeV energies. It is also a nearby source (\( z=0.033 \)) like Mkn 421. Unlike Mkn 421 initially it

\(^7\)ZDCF code is freely available at http://www.weizmann.ac.il/home/tal/zdcf2.html
Fig. 6.17: Light curve for NIR data (top panel) and PCA data for energy range 2-9 keV (middle) and for energy range 9-20 keV (bottom) with 5 minutes binning.

Fig. 6.18: ZDCF distribution, between NIR and PCA data in 2-9 keV energy range (top), between NIR and PCA data in 9-20 keV energy range (middle) and between PCA data in 2-9 keV energy range and PCA data in 9-20 keV energy range (bottom).

was not detected by EGRET. Mkn 501 was first detected by Whipple observatory based on 66 hours of data in 1995 [95]. This was a very significant detection because it was first detected by ground based experiments at VHE
energies and later detected at lower energies by EGRET. In 1995, flux level from the source was small (∼ 8% of the Crab), initial detection had 8.4σ significance. A confirming detection of VHE γ-rays from Mkn 501 was provided by the HEGRA CT1 detector [49]. Based on 147 hours of data taken in 1996, a 5.2σ signal was obtained. In 1995 and 1996, this source was in low state, with no emission observed above 0.5 times the Crab flux. In 1997, Mkn 501 entered a very active phase. The VHE emission from it increased dramatically. Ground based observations by Whipple [51], HEGRA [31], CAT [41], TACTIC and Telescope array [15] showed that the source underwent a series of rapid flares in 1997 as shown in the figure 6.19. Peak count rates were as much as five times the level of the Crab. Subsequently it was also detected by EGRET. The high flux of VHE emission from Mkn 501 in 1997 has permitted extraction of detailed energy spectrum. The differential energy spectrum is given by [32] as:

$$dN/dE \propto E^{-1.92\pm0.03_{stat}\pm0.20_{syst}}\exp[-E/6.2\pm0.4_{stat}(−1.5 + 2.9)_{syst}]$$

where $E$ is in units of TeV.

### 6.2.1 Multiwavelength Observations

Simultaneous observations of Mkn 501 made by instruments at many wavelengths including VHE γ-ray measurements are of great importance. First multi-wavelength observations were carried out in 1997, when the source was in a very active state. These multi-wavelength observations revealed for the first time, clear correlations between its VHE γ-ray and hard X-ray emission, like that of Mkn 421. During this observing period Mkn 501 was one of the brightest blazars ever observed at 50-150 keV energies.

**Spectral Energy Distribution (SED)**: Figure 6.20 shows the SED of Mkn 501 derived from contemporaneous multi-wavelength observations and an average of non-contemporaneous archival measurements. Solid line in the figure represents the flux measured during 1997 flare at different wavelengths simultaneously. Dotted line represents the quiescent flux obtained from archival data. It is clearly seen that the energy corresponding to the
peak of the X-ray and $\gamma$-ray flux shifts towards higher energies as flux increases.

### 6.2.2 Observation of Mkn 501 using PACT

Mkn 501 was observed using PACT since 2000. Total $\sim 47$ hours of on-source data were collected for Mkn 501. Based on preliminary checks some data were rejected which includes data of year 2000 and 2002. In those two years data were taken with 2 sectors pointing towards the source and other 2 sectors pointing towards the background region simultaneously. Therefore these data were rejected for the reason mentioned in section 5.1. Approximately 27 hours of data were retained. These data were analysed following methods in chapter 4. After applying post analysis cuts $\sim 21$ hours data remained. Details of these runs are summarized in tables 6.9 & 6.10. Values in the first column is the MJD corresponding to the mid point of the source run. Duration for each run, in hour angle, is given in the second
Fig. 6.20: Spectral Energy Distribution of Mkn 501 from contemporaneous and archival data. This figure is taken from [126].

column. Trigger rates, as observed during source runs, are listed in column three. Fourth column gives number of degrees of freedom. Normalisation constants and excess $\gamma$-ray rates are listed in fifth and sixth column respectively. Lightcurve obtained from 2003 and 2004 data for Mkn 501 is shown in figure 6.21.

During the PACT observation period this source was in low state. It was much weaker than the Crab. PACT sensitivity is such that to detect any
Table 6.9: Details of Mkn 501 runs for year 2003

<table>
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<th>ndf</th>
<th>normalisation constant</th>
<th>Excess $\gamma$/min</th>
</tr>
</thead>
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<td>10/12</td>
<td>1.02</td>
<td>-3.16(±0.5)</td>
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<td>-5.3° to 15.1°</td>
<td>3.4</td>
<td>23/24</td>
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<td>-5.8° to 15.0°</td>
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<td>23/24</td>
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<td>1.20</td>
<td>-3.11(±1.3)</td>
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Table 6.10: Details of Mkn 501 runs for year 2004

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<th>Trigger rate (Hz)</th>
<th>ndf</th>
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<td>3.3</td>
<td>20/24</td>
<td>1.06</td>
<td>-5.39(±2.4)</td>
</tr>
<tr>
<td>53140.839</td>
<td>-14.9° to 20.0°</td>
<td>3.6</td>
<td>20/24</td>
<td>1.00</td>
<td>2.44(±1.3)</td>
</tr>
<tr>
<td>53141.854</td>
<td>-13.2° to 8.0°</td>
<td>2.6</td>
<td>18/24</td>
<td>0.81</td>
<td>10.15(±1.5)</td>
</tr>
<tr>
<td>53144.840</td>
<td>-10.2° to 25.0°</td>
<td>3.4</td>
<td>16/24</td>
<td>0.92</td>
<td>1.71(±1.2)</td>
</tr>
<tr>
<td>53145.867</td>
<td>6.1° to 36.0°</td>
<td>2.9</td>
<td>15/24</td>
<td>0.95</td>
<td>1.66(±1.1)</td>
</tr>
<tr>
<td>53148.861</td>
<td>8.6° to 35.0°</td>
<td>2.9</td>
<td>20/24</td>
<td>1.20</td>
<td>-8.40(±1.4)</td>
</tr>
</tbody>
</table>
source at 5\(\sigma\) significance, with flux level 0.5 times that of the Crab, would require \(\sim 200\) hours. Hence we have estimated 3\(\sigma\) upperlimit on TeV \(\gamma\)-ray flux for Mkn 501 in the following way. Overall average excess \(\gamma\)-ray rate for Mkn 501 was found to be \(-1.6\pm0.43\) per minute. Again average zenith angle coverage of Mkn 501 at Pachmarhi is 30°. Energy threshold and collection area of PACT at this angle is 1.2 TeV and \(1.8\times10^5\) m\(^2\) respectively. Thus upperlimit is estimated to be \(1.22\times10^{-11}\) \(\gamma\) cm\(^{-2}\) s\(^{-1}\) (\(\geq\) 1.2 TeV) as shown in the figure 6.22. In this figure dashed line represents the quiescent flux detected in 1995 [96] and solid line represents the flux level detected during the flare in 1997 [51] from Mkn 501 by Whipple group.

![Mkn 501 Spectrum](image)

**Fig. 6.22:** Integral energy spectrum of Mkn 501. The arrow pointing downwards represents the 3\(\sigma\) upperlimit on the flux of TeV \(\gamma\)-rays from this source obtained by PACT. Dashed line represents the flux measured by Whipple during a low activity state and solid line represents their flux measured during 1997 flaring state.

### 6.3 1ES1426+428

Blazar 1ES1426+428 is situated at a distance of \(z=0.129\). This source is of interest primarily because its high redshift. The flux of very high energy \(\gamma\)-rays from extragalactic objects (BL Lacs in particular) is likely to be affected by absorption due to the \(\gamma-\gamma\) collision and pair production
processes during their propagation in the inter galactic medium. VHE $\gamma$-rays collide with the diffuse extragalactic IR (Infra Red) background radiation and get attenuated. As a result energy spectrum gets modified. This source was not detected by EGRET. Three different groups, Whipple [69], HEGRA [35]and CAT [60] have reported significant VHE $\gamma$-ray detection from 1ES1426+428. It is a weak source (typically 6 % of the Crab). Its synchrotron peak in SED plot is located at higher energies than any other TeV blazars and is classified as an extreme HBL [55]. X-ray observation of 1ES1426+428 during 1999 with the BeppoSax instrument revealed that peak of its synchrotron spectrum occurs at $>100$ keV, leading to the prediction of observable TeV flux from this source. Recently the VERITAS group [93] detected this source at $5.8\sigma$ level of significance based on 44.4 hours of observation. The energy spectrum of 1ES1426+428 shows flattening at energies above 1 TeV that is consistent with the expected signature of absorption by the extragalactic background light. The differential energy spectrum between 250 GeV and 1 TeV is well described by a steep power law with a spectral index $3.50\pm0.15$. HEGRA group [7] has seen this source with significance of $7.5\sigma$ based on 260.1 hours of observation in years 1999-2000 and 2002.

6.3.1 Observation of 1ES1426+428 Using PACT

We have observed this source using PACT since 2002. A total of $\sim65$ hours of data were collected on this source which spans 4 years. Based on preliminary checks data in year 2003 were rejected (for the same reason for which Mkn 501 data were rejected for year 2000 and 2002) and approximately 40 hours of data were retained. After applying post analysis cuts $\sim24$ hours of data were remained. Details of these runs are given in the following tables 6.11,6.12 & 6.13. Lightcurve of 1ES1426+428 is shown in the figure 6.23.

Considering the facts that this source is situated farther in distance (4 times compared to Mkn 421 or Mkn 501) and the sensitivity of PACT, very long duration observations are required to detect significant excess from 1ES1426+428. Even for Whipple, whose sensitivity is much better com-
Table 6.11: Details of 1ES1426+428 runs for year **2002**

<table>
<thead>
<tr>
<th>MJD</th>
<th>Duration (ha)</th>
<th>Trigger rate (Hz)</th>
<th>ndf</th>
<th>normalisation constant</th>
<th>Excess γ/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>52349.910</td>
<td>-8.5° to 27.0°</td>
<td>3.3</td>
<td>11/12</td>
<td>1.34</td>
<td>-9.97(±1.3)</td>
</tr>
<tr>
<td>52351.924</td>
<td>-0.6° to 25.0°</td>
<td>3.5</td>
<td>11/12</td>
<td>1.07</td>
<td>-5.66(±1.5)</td>
</tr>
<tr>
<td>52353.910</td>
<td>-10.5° to 1.1°</td>
<td>2.2</td>
<td>6/6</td>
<td>0.99</td>
<td>-7.13(±2.4)</td>
</tr>
<tr>
<td>52376.819</td>
<td>-21.0° to 33.2°</td>
<td>2.0</td>
<td>6/6</td>
<td>1.21</td>
<td>-10.51(±1.0)</td>
</tr>
<tr>
<td>52377.819</td>
<td>-10.7° to 29.7°</td>
<td>2.1</td>
<td>6/6</td>
<td>1.41</td>
<td>1.42(±1.3)</td>
</tr>
<tr>
<td>52379.826</td>
<td>-2.3° to 1.4°</td>
<td>1.8</td>
<td>6/6</td>
<td>0.57</td>
<td>-7.97(±2.9)</td>
</tr>
</tbody>
</table>

Table 6.12: Details of 1ES1426+428 runs for year **2004**

<table>
<thead>
<tr>
<th>MJD</th>
<th>Duration (ha)</th>
<th>Trigger rate (Hz)</th>
<th>ndf</th>
<th>normalisation constant</th>
<th>Excess γ/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>53088.899</td>
<td>-4.4° to 24.9°</td>
<td>3.3</td>
<td>12/12</td>
<td>0.96</td>
<td>7.35(±1.1)</td>
</tr>
<tr>
<td>53089.897</td>
<td>3.6° to 25.0°</td>
<td>2.6</td>
<td>17/24</td>
<td>0.99</td>
<td>-0.13(±1.4)</td>
</tr>
<tr>
<td>53110.868</td>
<td>12.8° to 25.0°</td>
<td>4.1</td>
<td>18/18</td>
<td>0.87</td>
<td>6.80(±2.4)</td>
</tr>
<tr>
<td>53115.826</td>
<td>0.0° to 21.6°</td>
<td>4.0</td>
<td>23/24</td>
<td>0.95</td>
<td>-9.34(±1.8)</td>
</tr>
<tr>
<td>53116.823</td>
<td>-6.5° to 10.3°</td>
<td>4.2</td>
<td>20/24</td>
<td>0.94</td>
<td>19.42(±2.1)</td>
</tr>
<tr>
<td>53116.868</td>
<td>11.2° to 30.0°</td>
<td>4.3</td>
<td>23/24</td>
<td>1.08</td>
<td>-14.97(±2.0)</td>
</tr>
<tr>
<td>53117.868</td>
<td>13.7° to 30.5°</td>
<td>3.5</td>
<td>22/24</td>
<td>0.95</td>
<td>-2.52(±1.8)</td>
</tr>
</tbody>
</table>

Table 6.13: Details of 1ES1426+428 runs for year **2005**

<table>
<thead>
<tr>
<th>MJD</th>
<th>Duration (ha)</th>
<th>Trigger rate (Hz)</th>
<th>ndf</th>
<th>normalisation constant</th>
<th>Excess γ/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>53443.920</td>
<td>-5.2° to 20.1°</td>
<td>4.4</td>
<td>16/24</td>
<td>1.17</td>
<td>-8.3(±1.6)</td>
</tr>
<tr>
<td>53444.924</td>
<td>4.5° to 20.0°</td>
<td>2.8</td>
<td>24/24</td>
<td>1.05</td>
<td>-26.3(±2.5)</td>
</tr>
<tr>
<td>53470.851</td>
<td>-2.6° to 11.7°</td>
<td>3.8</td>
<td>10/12</td>
<td>0.99</td>
<td>11.9(±1.6)</td>
</tr>
</tbody>
</table>
pared to PACT, it is a very weak source and near the threshold of their sensitivity. Therefore we have estimated flux upperlimit for this source from our observations. The average excess event rate was obtained as $-4.0 \pm 0.47$ per minute. Average zenith angle coverage for this source is also $\sim 30^\circ$. Thus we have obtained $3\sigma$ upperlimit on VHE $\gamma$-ray flux as $1.34 \times 10^{-11}$ photons cm$^{-2}$ s$^{-1}$ ($\geq 1.2$ TeV). This is shown in figure 6.24 as an arrow pointing downwards, along with result from Whipple group.

Fig. 6.23: Lightcurve of 1ES1426+428 as obtained from PACT data.

Fig. 6.24: $3\sigma$ upperlimit on VHE $\gamma$-ray flux for 1ES1426+428 as estimated from PACT observation is shown by arrow pointing downwards in the figure, solid line represents the integral flux measured by Whipple for $\sim 45$ hours of observation.
6.4 Blazar ON231 (or W COMAE)

ON231 (or W COMAE) is a LBL type of blazar. For this type of sources peak of the first hump, in their SEDs, lies at lower energies. Peak of the second hump occurs at X-ray energies and therefore significant TeV γ-ray emission is not normally expected from this type of objects. However, observations by EGRET revealed a hard power law spectrum (photon spectral index \( \alpha = 1.73 \pm 0.18 \)) extending up to about 10 GeV with no sign of any cutoff [65]. Because of its hard spectrum it was thought that ON231 may also be detected at energies up to few hundreds of GeV. Also, this source provides an excellent test to distinguish between leptonic and hadronic blazar jet models. According to leptonic models γ-ray emission will cutoff sharply above 100 GeV. In contrast, hadronic models may allow for significant emission above 100 GeV. But Whipple group [70] even after repeated observation has not detected this source above 300 GeV (threshold energy). STACEE, whose energy threshold is less than 100 GeV, also has not detected any significant excess from this source [48, 86].

6.4.1 PACT observation of ON231

We have observed this source in the year 2003 and 2004. A total of 17 hours data were collected on ON231. No run was rejected either based on preliminary checks or post analysis cuts. All the runs were analysed following the procedure in chapter 4. Results are summarized in tables 6.14 and 6.15. Lightcurve of ON231 is shown in the figure 6.25. Overall excess γ-ray rate was found to be -5.6±0.64 per minute, consistent with no evidence for emission of γ-rays. We have estimated 3σ upperlimit on γ-ray flux for this source. ON231 transits almost through zenith at Pachmarhi latitude.

Energy threshold and collection area of PACT for vertical showers are 750 GeV and \( 1.4 \times 10^5 \) m\(^2 \) respectively. Using this collection area upperlimit on γ-ray flux is estimated as \( 2.50 \times 10^{-11} \) photons cm\(^{-2} \) s\(^{-1} \) (\( \geq 750 \) GeV) and is shown in the figure 6.26, along with other results.
### Table 6.14: Details of ON231 runs for year 2003

<table>
<thead>
<tr>
<th>MJD</th>
<th>Duration (ha)</th>
<th>Trigger rate (Hz)</th>
<th>ndf</th>
<th>normalisation constant</th>
<th>Excess $\gamma$/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>52758.708</td>
<td>-11.8° to 22.8°</td>
<td>2.9</td>
<td>20/24</td>
<td>0.84</td>
<td>2.82(±1.1)</td>
</tr>
<tr>
<td>52759.715</td>
<td>-8.8° to 26.5°</td>
<td>3.2</td>
<td>21/24</td>
<td>0.95</td>
<td>-9.98(±1.4)</td>
</tr>
<tr>
<td>52760.702</td>
<td>-13.9° to 24.9°</td>
<td>3.7</td>
<td>22/24</td>
<td>1.03</td>
<td>-4.35(±1.3)</td>
</tr>
<tr>
<td>52761.715</td>
<td>-5.4° to 28.2°</td>
<td>3.9</td>
<td>23/24</td>
<td>0.96</td>
<td>-12.08(±1.5)</td>
</tr>
</tbody>
</table>

### Table 6.15: Details of ON231 runs for year 2004

<table>
<thead>
<tr>
<th>MJD</th>
<th>Duration (ha)</th>
<th>Trigger rate (Hz)</th>
<th>ndf</th>
<th>normalisation constant</th>
<th>Excess $\gamma$/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>53084.802</td>
<td>-15.8° to 20.0°</td>
<td>4.2</td>
<td>20/24</td>
<td>1.13</td>
<td>-9.4(±1.5)</td>
</tr>
<tr>
<td>53084.865</td>
<td>18.8° to 30.0°</td>
<td>4.5</td>
<td>20/24</td>
<td>0.94</td>
<td>-0.7(±2.5)</td>
</tr>
<tr>
<td>53085.865</td>
<td>19.0° to 30.0°</td>
<td>3.6</td>
<td>19/24</td>
<td>0.93</td>
<td>5.2(±2.2)</td>
</tr>
</tbody>
</table>

---

**Fig. 6.25:** Lightcurve of ON231 obtained from PACT observations.

### 6.5 Discussion and Conclusions

Mkn 421 was observed most extensively by PACT. Out of four blazars we have observed using PACT only Mkn 421 was reported to be in flaring state (by other experiments) on few occasions between 2000-2005. We have obtained average integral flux for this source by combining all the data.

We have attempted a multiwavelength study of Mkn 421. We have estimated time averaged integral flux of TeV $\gamma$-rays by combining all the data from 2000 to 2005. This time averaged integral flux agrees well with the best fit SSC parameters obtained from X-ray data in 2003. Since the source was at low state during this period, the time averaged flux from PACT is
expected to be consistent with the quiescent state flux of Mkn 421.

Also, we have attempted a comparative study of 2 states of Mkn 421, flaring and quiescent. In March-April 2001 source was in very active state and in February-March 2003 it was in low state. Peak position of SED of 2001 is at higher energy compared to that of 2003, suggesting that peak positions shifts towards higher energy as flux increases. This is consistent with spectral hardening reported here based on spectral analysis of X-ray data. There are significant changes in SSC parameters for these two data sets at X-ray and γ-ray energies. One zone SSC model cannot fit all data including radio and optical. Introduction of additional zones improves the fit at lower energies. But there was almost no change for SSC parameters at lower energies during quiescent and flaring state of Mkn421. The lack of correlation between high-energy emission and low-energy emission suggests that the low-energy radio to optical radiation is dominated by emission from regions other than those that emit the bulk of the X-rays and γ-rays. There may be different population of electrons located in physically separated regions and may have different spectral energy distributions (e.g., $E_{\text{max}}$).
Blazejowski et al. have carried out similar study on SED of Mkn 421 with multiwaveband data collected over the period 2003-2004. They have divided the entire data set into three groups depending on X-ray count rates as low, medium and high and each set was fitted with one zone SSC model. High energy emissions, i.e., X-ray and VHE $\gamma$-ray, were fitted nicely by this model. At low energy emissions, i.e., radio and optical, fit was improved with the introduction of additional zones. There is reasonable agreement between the best fit SSC parameters obtained here and that obtained by them.

We have looked for correlations between X-ray and NIR data, collected during multiwavelength campaign in 2003. It seems that NIR variability leads the X-ray variability by $\sim 3$ days, but the observed correlation is only $\sim 50\%$. According to relativistic jet model [?] the central engine produces a jet consisting of relativistic, magnetized plasma that flows outward at speeds close to that of light. This is a simplistic description and here it is expected that X-rays originate from region of jet close to the central engine and lower frequency emission originate from regions successively down the jet as plasma moves away from the central engine. It is normally expected based on this model that any variation in high-frequency emission would lead corresponding variation at lower frequencies.

There could be some shocks in this jet. This is called shock-in-jet model [121] as shown in figure 6.27. These shocks could be moving or stationary. Also there could be more complications like turbulence, multiple shocks and also bending of jets. In shock-in-jet model there could be forward as well as reverse shocks. Shock accelerates particles and there could be frequency stratification at shock front. This means that high frequency emission is emitted only from a thin sheet behind the shock front and thickness of this sheet increases as frequency decreases. This frequency stratification was invoked to explain the general trend of more rapid variations at higher frequencies seen in many of the blazars. Simulations done by Marscher and Travis [83] show rapid flickering in light curves at higher frequency and significant damping of this flickering at lower frequencies. This model also predicts higher frequency variations leading lower frequency ones. So ac-
According to these models X-ray should lead NIR.

However some authors have indicated reversal of trend i.e. NIR leading X-ray. In case of 3C279, X-ray emission is found to lag behind optical by 15 days. But this source is of LBL type. In LBL type of blazars relativistic electrons present in the jet emit synchrotron emission at optical/IR energies. Then these optical photons due to inverse Compton scattering produce X-rays. As a result peak position of X-ray flare could be delayed relative to that of optical. But Mkn 421 is of HBL type. Also from SSC parameters it was seen that there was no correlation between high energy emission and low energy emission in case of Mkn 421. Moreover observed correlation between X-ray and NIR was weak and data stretch is also short, just 6 days. To get any meaningful result, larger data stretch is required.

**A MODEL FOR THE INNER JET**

![Diagram of inner jet model](image)

Fig. 6.27: Innerjet model. This figure is taken from [126].

For remaining three blazars, Mkn 501, 1ES1426+428 and ON231 data collected using PACT are much less than Mkn 421. Mkn 501 is a nearby blazar like Mkn 421 but throughout PACT observation period this source was in quiet state with flux level much below the Crab flux. It would require very long observation to detect significant excess from this source compared to ~ 47 hours of data collected by PACT. Flux level of 1ES1426+428 was also very low during PACT observation. Moreover this source is situ-
ated at high redshift so there is attenuation in TeV $\gamma$-rays by extragalactic background light. Even Whipple and HEGRA groups could detect $\gamma$-ray emissions from this source only with very long observations. Thus we have estimated $3\sigma$ upperlimits on VHE $\gamma$-rays from these two sources. ON231 is a LBL type of source, but because of its hard spectrum at X-ray energies it was thought that Tev $\gamma$-rays may be detected from this source. But so far no experiment has detected this source in GeV/TeV energies. Our estimate of $3\sigma$ upperlimit on $\gamma$-ray flux from this source is consistent with other observations.

In short more multiwavelength observations are needed to constrain the models proposed for the emission of radiation from blazars.
Chapter 7

Systematic Errors, Summary and Future Prospects

In this chapter, in section 7.1, systematic errors of PACT are described in details. In section 7.2, results of 4 blazars are summarized. Future prospects are discussed in section 7.3.

7.1 Systematic Errors

Success of any ground based Cherenkov telescope, whether using imaging technique or wavefront sampling technique, depends on how well it can distinguish $\gamma$-rays against an overwhelming background of cosmic rays. It is necessary therefore to improve signal to noise ratio by rejecting most of the cosmic rays. We could not reject cosmic rays efficiently in the present analysis. This is partially due to limitations of the setup and partially related to data quality. Systematic errors are introduced in the estimation of arrival direction, in rejection of background showers, as well as in the estimation of $\gamma$-ray flux and energies. These are elaborated below.

7.1.1 Arrival angle estimation

Errors due to plane front approximation

Cherenkov shower front from air shower is spherical in shape. In analysis procedure it was approximated by a plane front. Normal to this plane front is assumed to be the direction of the source. To examine the effects of this
approximation, a spherical front was generated originating from a point 9 km above the PACT array and the relative arrival times of photons at the telescopes were simulated in accordance with the typical core distance distribution of triggers. These relative times of arrival were fitted with a plane front and the direction of the shower axis was obtained. Resulting space angle distribution is shown in the upper panel of figure 7.1. This distribution peaks at about 0.6°. Whereas it was expected to peak very close to 0°. Lower panel of the same figure shows the variation of space angle as a function of distance of shower core from the centre of the array. Fitted space angle increases with the core distance. Because of this reason estimation of shower direction will be erroneous. This error will be minimum for showers landing within or very near the array. Since most of the triggers are generated by showers with cores landing at some distance from the array centre, there is error in the estimate of the shower direction resulting from plane front approximation and it is of the order of 0.5°-1.0° typically for vertical showers.

Figure 7.2 shows the distribution of fitted space angles for a sample of simulated γ-ray showers with detailed detector response. This distribution peaks at about 0.7°-0.8°, even though incident showers are perfectly vertical, mainly due to core distance effect.

Situation is further complicated in the case of cosmic ray showers due to their isotropic nature. Figure 7.3 shows fitted space angle vs core distance for gamma rays and for three sets of proton showers i.e. proton showers incident in vertical direction (θ=0°), isotropic proton showers incident within zenith angle of 1.5° (θ ≤1.5°) and within 3° (θ ≤3°). For isotropic proton showers fitted space angle will also depend on the incident angle. In the case of vertical proton showers space angle seems to vary with core distance as in the case of gamma ray showers. But this dependence is smeared in the case of isotropic showers. This is because for isotropic proton showers fitted space angle also depends on the incident angle. As a result error on fitted space angle does not show clear core distance dependence.
Fig. 7.1: (a) Space angle distribution for plane wavefront fitting of spherical wavefront, (b) space angle vs distance of array center from shower core.

Fig. 7.2: Space angle distribution of gamma-ray initiated showers incident vertically. Monte Carlo simulations include the detector response.

**Problems with conical and spherical front fitting**

We showed that plane wavefront approximation has limitations. This is because plane wavefront fit gives direction of the normal to the spherical
Fig. 7.3: Space angle from plane front approximation vs core distance for (a) gamma rays, (b) protons incident vertically, (c) protons incident within $1.5^\circ$ and (d) protons incident within $3^\circ$.

front at the position of the detector array instead of direction of shower axis. One possible improvement is to revise the shower front fitting algorithm by using either conical front or spherical wavefront.

Experiments like CELESTE [25, 57] and STACEE [90] have used spherical front approximation. In CELESTE all telescopes are tilted towards shower maximum at a height of about 11 km in the direction of source. Thus the radius of curvature of shower front is fixed to 11 km. Using arrival times of shower front at various telescopes, positions of telescopes and radius of curvature of shower front, the time of arrival of Cherenkov front ($T_i$) is calculated for each telescope. $\chi^2$ minimization is done between these individual $T_i$’s and their average ($T^0$). Differentiating this $\chi^2$ expression with respect to location of shower maximum ($x,y$), analytical expressions for $x$ and $y$ are obtained. This algorithm apparently gives position of shower maximum accurate to $\approx 15 \, m$. Such an algorithm can not be adopted for PACT observations because in case of PACT radius of curvature of shower is not fixed. So we have additional parameter to minimize. Also we need to
incorporate core location in this algorithm. In case of CELESTE, tilting of telescopes towards shower maximum along with narrow field of view (0.5°) ensures that shower core lies inside the array at the cost of collection area, which is not the case for PACT.

Themistocle [40, 105] experiment used conical fit for their data. It involves six parameters: \( X, Y \) coordinates of impact point, \( u, v \) direction cosines of incident shower, cone angle (\( \theta \)) and time \( T \) when apex hits the ground as shown in figure 7.4. Themistocle array was much larger compared to PACT. Their array was spread within an area of \( 280 \times 190 \, \text{m}^2 \) as opposed to \( 80 \times 100 \, \text{m}^2 \) of PACT. Also energy threshold of Themistocle was 3 TeV and at these energies shower front is conical rather than spherical. For PACT however, shower front is closer to spherical shape. For Themistocle by imposing the condition of 12 out of 18 telescopes triggering it was ensured that shower core lies inside the array for most of the events. On the other hand, in the case of PACT, majority of the triggers are due to shower core landing outside the array. By imposing a condition of 18 out of 24 telescopes etc, the core could be brought nearer.

![Spatial sampling of the conical Cherenkov light wave-front by a 2D detector array](image)

Fig. 7.4: Schematic diagram of a shower with conical front.

**Algorithm for spherical front fit**: Shower core may lie anywhere around the array centre or origin of coordinate system. In figure 7.5 shower maxi-
mum is given by \((x_R, y_R)\) at an altitude of \(R\) w.r.t. ground. Shower core hits the ground at \((x_c, y_c)\). Here we calculate delay between arrival of shower front at core and at individual telescopes and minimize \(\chi^2\). So delay at telescope \(i\) is given by

\[
\begin{align*}
  c(t_i - T_0) &= \sqrt{(x_R - x_i)^2 + (y_R - y_i)^2 + (R - z_i)^2} - \sqrt{(x_R - x_c)^2 + (y_R - y_c)^2 + R^2} \\
  \text{(7.1)}
\end{align*}
\]

where telescope location is given by \((x_i, y_i, z_i)\) and arrival time of shower front at this telescope is \(t_i\). \(T_0\) denotes arrival time of shower front at core. \(\chi^2\) is given by

\[
\chi^2 = [2Rc(t_i - T_0) + 2Rz_i + 2x_R(x_i - x_c) - x_i^2 + x_c^2 + 2y_R(y_i - y_c) - y_i^2 + y_c^2]^2 \\
\text{(7.2)}
\]

Partial derivatives of \(\chi^2\) wrt six parameters \((T_0, x_c, y_c, x_R, y_R, R)\) are given by

\[
\frac{\partial \chi^2}{\partial T_0} = -4Rcf \\
\text{(7.3)}
\]
\[
\frac{\partial \chi^2}{\partial x_c} = -4(x_R - x_c)f 
\] (7.4)

\[
\frac{\partial \chi^2}{\partial y_c} = -4(y_R - y_c)f 
\] (7.5)

\[
\frac{\partial \chi^2}{\partial x_R} = 4(x_i - x_c)f 
\] (7.6)

\[
\frac{\partial \chi^2}{\partial y_R} = 4(y_i - y_c)f 
\] (7.7)

\[
\frac{\partial \chi^2}{\partial R} = 4c(t_i - T_0 + z_i)f 
\] (7.8)

where

\[
f = 2Rc(t_i - T_0) + 2Rz_i + 2x_r(x_i - x_c) - x_i^2 + x_c^2 + 2y_R(y_i - y_c) - y_i^2 + y_c^2
\] (7.9)

Setting all partial derivatives equal to 0, six equations can be obtained which are to be solved simultaneously to get analytical expressions for six parameters. These equations are fairly complicated and solving them simultaneously is nontrivial task. At this stage of the thesis this work is incomplete.

### 7.1.2 Rejection of background showers

**Separation using arrival direction**

It was thought earlier that space angle distribution of gamma ray showers will be narrower compared to proton showers and it will be possible to impose tighter cuts on the space angle and thereby reject more cosmic ray showers. Figure 7.6 shows the space angle distribution for plane front fit to proton showers within 3°. Space angle distributions obtained from γ-ray and proton initiated showers were compared as shown in figure 7.7. It was found that gamma ray and proton space angle distributions were almost overlapping. Thus not many cosmic rays are rejected just by off-axis cut.
Density parameters

Efficacy of various parameters based on density fluctuations and timing jitter was tested earlier for gamma hadron separation. Based on simulations it was suggested that these parameters can give moderate discrimination
against cosmic ray showers \cite{22, 20}. However, when the response of the
detector setup was also simulated, these distributions broadened and looked
almost alike for proton and \( \gamma \)-ray initiated showers. For example, figure 7.8
shows the distribution of parameter MDF (Medium Density Fluctuation)\(^{1}\)
without and with detector response. In this figure it is seen that gamma ray and proton MDF distributions look somewhat separated before applying detector response (upper panel), but get merged after applying detector response (lower panel). This merging is to a large extent due to night sky background photons and photoelectron conversion. These processes add their own fluctuations, smearing out the fluctuations arising from differences in kinematics of gamma ray and cosmic ray showers. Therefore these parameters can not be used for rejection of cosmic rays on event by event basis, unless the night sky background is reduced considerably.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure7.8.png}
\caption{Distribution of medium range density fluctuations (MDF) for gamma rays (solid line) and protons (dotted line). Upper panel is without detector response and lower panel is with detector response.}
\end{figure}

\(^{1}\)Medium Density Fluctuation is defined as the ratio of the RMS variations of the total number of photons detected in each of the telescope of the array to the average number of photons incident on the telescope
7.1.3  Estimation of primary energy of the shower

ADC is a measure of Cherenkov photon density at various locations in Cherenkov pool and hence is expected to be proportional to the energy of the primary. However, for any gamma ray shower or cosmic ray shower, density depends on core distance. So lower energy shower falling closer to the array and higher energy one landing away from the array will give similar densities and hence similar ADC values. Figure 7.9 shows mean ADC per telescope vs energy for a sample of gamma ray showers as obtained from detector simulation program. For any given energy there is a large spread in ADC values. Hence it is difficult to estimate gamma ray energy based on ADC value alone unless core distance is known.

![Fig. 7.9: Avg(ADC) per telescope vs Energy for gamma ray showers](image)

In the case of cosmic ray showers there is further complication due to their isotropic nature. Here significant number of triggers arises from showers which are slightly inclined with respect to the source direction. For these inclined showers only fraction of the Cherenkov cone falls within 3° mask of the telescopes and this fraction depends on inclination angle of shower axis with respect to the pointing direction. Hence even for a given core distance, ADC value could be same for lower energy shower along pointing
direction and higher energy shower inclined to the pointing direction. In other words, the measured photon density depends upon the core distance as well as incident angle of the shower. Figure 7.10 shows average ADC value per telescope vs primary energy for proton showers.

To summarise, based on ADC value alone, it is not possible to estimate energy of the primary on a shower by shower basis, unless core distance is known by some other means.

### 7.1.4 Estimation of flux of $\gamma$-rays

**Sensitivity**

For Crab like source, having energy spectrum of $\frac{dJ}{dE} \propto E^{-2.49}$ at 1 TeV, $5\sigma$ sensitivity of PACT for 50 hours of observations without any rejection of cosmic ray showers is estimated to be $2.93 \times 10^{-11} \text{ ph/cm}^2/\text{s}$. Earlier it was assumed that based on angular resolution of $\sim 0.1^\circ$ of PACT, it will be possible to reject $99\%$ of the recorded cosmic ray showers. With further rejection based on GHS parameters it was expected that we can achieve total rejection of $99.75\%$ of cosmic rays retaining about $44\%$ of gamma rays. However, we have seen above that it was not possible to have much of
off-axis rejection and also GHS parameters are ineffective after considering detector response. The cuts used here led to only 15% of rejection of proton showers. Assuming this modest rejection of cosmic ray showers and assuming negligible rejection for gamma rays, sensitivity is estimated to be $2.71 \times 10^{-11} \text{ph/cm}^2/\text{s}$.

Figure 7.11 shows sensitivity of PACT in terms of observation duration required as a function of source flux in Crab units to detect the source at the level of $5\sigma$ for the following three conditions.

1. Without cosmic ray rejection we need to observe source like crab for 49 hours with equal observation duration for background.

2. With 15% rejection of cosmic rays, over and above the rejection due to hardware trigger, required observation duration of source is 41 hours.

3. If rejection of 99.75% cosmic rays retaining 44% of gamma rays is possible, then the observation time needed to detect Crab is one hour.

**Normalization constant**

Source and background space angle distributions are normalized using $2.5^\circ$-$6.5^\circ$ region while estimating $\gamma$-ray signal in most of the cases. This region is expected to be devoid of gamma rays and hence should normalize for differences in sky conditions between ON and OFF runs. Gamma ray signal is estimated as excess of source events in $0^\circ$ to $2.5^\circ$ region using the following equation,

$$\text{excess events} = \sum_{i=0}^{2.5} (S_i - c_k B_i)$$  \hspace{1cm} (7.10)

It is clear from this equation that excess will be more when $c$ is underestimated and will be less when $c$ is overestimated, as shown in the figure 7.12. Ideally $c$ should be very close to 1. The figure 7.13 shows a cross plot of flux vs normalization constants for all Mkn 421 runs. The population

\footnote{The actual ratio of cosmic ray to $\gamma$-ray is 1000:1. But because of the 4/6 trigger logic used in the experiment about 60% of cosmic rays are rejected at the trigger level.}
Fig. 7.11: PACT sensitivity in terms of observation duration required for detection of source at $5\sigma$ level vs source flux in Crab units without cosmic ray rejection (dotted line), with 15% cosmic ray rejection (dashed line) and with 99.75% cosmic ray rejection retaining 44% of gamma rays (solid line)

of data in second and fourth quadrants indicate this effect of normalization constant introduces systematic errors in estimation of $\gamma$-ray signal.

Fig. 7.12: Variation of excess with normalization constant.
Fig. 7.13: Excess rate vs normalization constant for all Mkn 421 runs from 2000-2005

Tests with fictitious sources

Some of the source vs background runs showed deficit rather than excess and also occasionally there were runs with huge excess and deficit. Main reason for this large excess/deficit was mismatch of space angle distributions between source and background runs, like peak positions of the space angle distributions, width of the distributions etc. Mismatch in space angle distributions can arise due to difference in night sky conditions during source and background runs. To check the stability of background runs some tests were carried out. For this purpose two background runs were taken with Mkn 421 declination in one night followed by similar runs on next night. This exercise was done thrice in 2004-2005 observation season. Results are given in table 7.1 and 7.2. In table 7.1 comparison is done between background runs which were taken on the same night and in table 7.2 comparison is done between background runs taken on consecutive nights. In most cases it was seen that there was a mismatch in space angle distributions between background runs taken either in the same night or in the consecutive nights.

Similar exercise was carried out with vertical runs. For each year from
Table 7.1: Comparison of background runs taken with Mkn 421 declination on the same nights.

<table>
<thead>
<tr>
<th>Run no.</th>
<th>excess rate/min</th>
<th>comparison of space angle distributions</th>
</tr>
</thead>
<tbody>
<tr>
<td>674 vs 675</td>
<td>-16.0</td>
<td>mismatch</td>
</tr>
<tr>
<td>676 vs 677</td>
<td>-10.8</td>
<td>mismatch</td>
</tr>
<tr>
<td>694 vs 695</td>
<td>0.4</td>
<td>similar</td>
</tr>
<tr>
<td>696 vs 697</td>
<td>-30.8</td>
<td>mismatch</td>
</tr>
<tr>
<td>740 vs 741</td>
<td>10.4</td>
<td>mismatch</td>
</tr>
<tr>
<td>742 vs 743</td>
<td>12.4</td>
<td>mismatch</td>
</tr>
</tbody>
</table>

Table 7.2: Comparison of background runs taken with Mkn 421 declination on the consecutive nights.

<table>
<thead>
<tr>
<th>Run no.</th>
<th>excess rate/min</th>
<th>comparison of space angle distributions</th>
</tr>
</thead>
<tbody>
<tr>
<td>674 vs 676</td>
<td>14.7</td>
<td>mismatch</td>
</tr>
<tr>
<td>674 vs 677</td>
<td>8.5</td>
<td>similar</td>
</tr>
<tr>
<td>675 vs 676</td>
<td>17.4</td>
<td>mismatch</td>
</tr>
<tr>
<td>675 vs 677</td>
<td>3.7</td>
<td>similar</td>
</tr>
<tr>
<td>740 vs 742</td>
<td>15.2</td>
<td>mismatch</td>
</tr>
<tr>
<td>740 vs 743</td>
<td>19.9</td>
<td>mismatch</td>
</tr>
<tr>
<td>741 vs 742</td>
<td>5.2</td>
<td>similar</td>
</tr>
<tr>
<td>741 vs 743</td>
<td>15.7</td>
<td>mismatch</td>
</tr>
</tbody>
</table>
2000 onwards, two vertical runs were selected. Each vertical run was split into two halves and each half was analysed following procedure mentioned in chapter 3 and space angle distributions were obtained for each half treating them as source and background runs. Comparison was done between these distributions and results are summarized in table 7.3. For vertical runs also it was found that in most of the cases space angle distributions did not match. Since telescopes are stationary in these runs, mismatch could be due to changing sky conditions. To quantify the mismatch, in space angle distributions, we have shown the various moments of the space angle distributions in table 7.4 for two runs, Run # 670 & 739.

To see whether this mismatch in space angle distributions is indeed due to changing sky conditions we divided vertical run # 670 and split it into 4 smaller segments of 35 minutes each. For each of these segments space angle distributions are obtained and results are given in 7.5. It is found that

### Table 7.3: Comparison of vertical run space angle distributions.

<table>
<thead>
<tr>
<th>Year</th>
<th>run no.</th>
<th>excess rate/min</th>
<th>comparison of space angle distributions in first and second half</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>048</td>
<td>-7.41</td>
<td>mismatch</td>
</tr>
<tr>
<td></td>
<td>053</td>
<td>-2.47</td>
<td>similar</td>
</tr>
<tr>
<td>2001</td>
<td>173</td>
<td>32.74</td>
<td>mismatch</td>
</tr>
<tr>
<td></td>
<td>223</td>
<td>-7.43</td>
<td>similar</td>
</tr>
<tr>
<td>2002</td>
<td>328</td>
<td>-6.50</td>
<td>similar</td>
</tr>
<tr>
<td></td>
<td>346</td>
<td>1.90</td>
<td>similar</td>
</tr>
<tr>
<td>2003</td>
<td>414</td>
<td>-2.82</td>
<td>similar</td>
</tr>
<tr>
<td></td>
<td>470</td>
<td>10.32</td>
<td>similar</td>
</tr>
<tr>
<td>2004</td>
<td>618</td>
<td>67.60</td>
<td>mismatch</td>
</tr>
<tr>
<td></td>
<td>670</td>
<td>11.90</td>
<td>mismatch</td>
</tr>
<tr>
<td>2005</td>
<td>730</td>
<td>5.45</td>
<td>similar</td>
</tr>
<tr>
<td></td>
<td>739</td>
<td>5.53</td>
<td>similar</td>
</tr>
</tbody>
</table>
### Table 7.4: Moments of both the halves of two vertical runs.

<table>
<thead>
<tr>
<th>Run no.</th>
<th>Mean</th>
<th>Variance</th>
<th>Skewness</th>
<th>Kurtosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 670 - 1st half</td>
<td>1.91</td>
<td>4.52</td>
<td>6.90</td>
<td>77.26</td>
</tr>
<tr>
<td>Run 670 - 2nd half</td>
<td>2.22</td>
<td>11.24</td>
<td>7.26</td>
<td>71.59</td>
</tr>
<tr>
<td>Run 739 - 1st half</td>
<td>2.73</td>
<td>7.69</td>
<td>4.05</td>
<td>31.40</td>
</tr>
<tr>
<td>Run 739 - 2nd half</td>
<td>2.61</td>
<td>5.60</td>
<td>3.11</td>
<td>19.67</td>
</tr>
</tbody>
</table>

### Table 7.5: Comparison between different segments of vertical run 670. Duration of each segment is of 35 minutes

<table>
<thead>
<tr>
<th>Segments</th>
<th>Rate per minute</th>
<th>Normalization constant</th>
<th>Comparison of space angle distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>seg.1 v seg.2</td>
<td>2.65</td>
<td>0.85</td>
<td>similar</td>
</tr>
<tr>
<td>seg.1 v seg.3</td>
<td>9.20</td>
<td>0.85</td>
<td>mismatch</td>
</tr>
<tr>
<td>seg.1 v seg.4</td>
<td>11.60</td>
<td>1.17</td>
<td>mismatch</td>
</tr>
<tr>
<td>seg.2 v seg.3</td>
<td>-0.50</td>
<td>1.08</td>
<td>similar</td>
</tr>
<tr>
<td>seg.2 v seg.4</td>
<td>-6.2</td>
<td>1.44</td>
<td>mismatch</td>
</tr>
<tr>
<td>seg.3 v seg.4</td>
<td>-6.9</td>
<td>0.77</td>
<td>mismatch</td>
</tr>
</tbody>
</table>

space angle distributions matches for consecutive segments. Also, as the separation between segments increases these distributions deviates, suggesting that smaller time gap between source and background runs give better result.
7.2 Summary

This thesis deals with the observational study of four blazars Mkn 421, Mkn 501, 1ES1426+428 and ON231, based on observations carried out over the period 2000 to 2005 using Pachmarhi Array of Cherenkov Telescopes in the $\gamma$-ray window. For Mkn 421 we have also attempted a multiwaveband study by using other contemporaneous data. An introduction has been given about TeV blazars and we have briefly described the motivations for carrying out observational studies for these extragalactic objects. We have explained the atmospheric Cherenkov technique and in particular wavefront sampling technique. A detailed description about the experimental setup of PACT has been given. Monte Carlo simulations carried out for PACT have been discussed. After that analysis procedure of PACT data is described followed by results of the four blazar observations carried out using PACT.

Out of the 4 sources we have maximum coverage for Mkn 421. Total $\sim$ 200 hours of data were collected on this source. After applying cuts approximately 100 hours of data were analysed. To have better signal to noise ratio all the data were added and time averaged integral flux for Mkn 421 was obtained as $4.45(\pm1.9) \times 10^{-12} \ \gamma \ cm^{-2} \ s^{-1}$ above 1.2 TeV. Moreover since Mkn 421 was in low state during most of the PACT observation from 2000 to 2005 the time averaged flux is expected to be consistent with the quiescent state of Mkn421. We have also carried out multiwavelength study for this source involving $\gamma$-ray, X-ray, optical and radio data on two occasions corresponding to high and low states of Mkn 421. We have analysed the X-ray data, taken by RXTE satellite, for these two periods. First set of data was collected during March-April 2001 when Mkn421 was in flaring state. The second set was collected during February-March 2003 when this source was in quiescent state at this time. For both the occasions simultaneous optical/NIR and radio data were available. We have obtained SED plot using $\gamma$-ray, X-ray, optical/ NIR and radio data for these two data sets and fitted them with Synchrotron Self-Compton (SSC) model. We found that single zone SSC model does not fit all the data together. To fit data at lower energies multizone emissions are needed.
We have also looked for correlations between X-ray and NIR data, collected during multiwavelength campaign in year 2003. It was found that NIR variability leads the X-ray variability by $\sim 3$ days. But the correlation was only of the order of 50%. But according to various models, e.g., relativistic jet model, shock in jet model, higher frequency variations should lead the lower frequency ones. Since our data stretch was very short (only $\sim 6$ days), thus we can not draw any meaningful conclusion from our result.

Other blazars which we have observed are Mkn501, 1ES1426+428 and ON231. We have not seen any significant $\gamma$-ray flux from any of these sources. Mkn 501 was in quiet state during the PACT observation period from 2000 to 2005 and was much weaker than the Crab. Therefore it would require very long observation duration to detect significant excess from this source. Thus we have estimated $3\sigma$ upperlimit on $\gamma$-ray flux for Mkn 501 as $1.22 \times 10^{-11} \gamma\text{ cm}^{-2} \text{ s}^{-1} (\geq 1.2 \text{ TeV})$. 1ES1426+428 is a distant blazar. It would require a very long exposure to detect significant excess from this source, because of the absorption of VHE $\gamma$-rays in the intergalactic space by the extragalactic background light. WHIPPLE has seen excess from this source after long observation duration. PACT is less sensitive than this experiment. Also amount of data collected on this source were much less than what is actually required. So we have given upperlimit on $\gamma$-ray flux for this source which is $1.34 \times 10^{-11} \gamma\text{ cm}^{-2} \text{ s}^{-1} (\geq 1.2 \text{ TeV})$. ON231 is a LBL type blazar and till date TeV $\gamma$-rays are detected only from HBL blazars. But, observations by EGRET have shown a hard power law energy spectrum extending upto about 10 GeV with no sign of any cutoff for this source. Because of its hard spectrum it was thought that ON231 may be detected at higher energies and hence is a potential TeV $\gamma$-ray source. No experiment has detected significant excess from ON231 above 100 GeV so far. The $3\sigma$ upperlimit on $\gamma$-ray flux from ON231 is estimated to be $2.50 \times 10^{-11} \gamma\text{ cm}^{-2} \text{ s}^{-1} (\geq 750 \text{ GeV})$. 
7.3 Scope for Improvements and Future Prospects

There exists a gap in the spectral coverage between the previous generation of Cherenkov telescopes (Whipple, HEGRA, PACT etc) and that of the satellite based detector (e.g. EGRET) as seen in the figure 7.14, in the energy region between 10 GeV and 300 GeV. Therefore the major thrust in the γ-ray astronomy at present is to cover this unopened window. Lowering of energy threshold will also enable the study of spectral cutoffs in blazars and will also allow addressing issues regarding pulsed emission from pulsars. In recent times HESS collaboration [38] has achieved energy threshold of 100 GeV, based on stereoscopic technique, using an array of imaging telescopes. MAGIC, another imaging telescope, using a very large size light collector is expected to reduce the energy threshold to 30 GeV [3, 84]. Similarly experiments like CELESTE, STACEE etc have used large number of light collectors (using solar power plants) to achieve lower energy threshold. Alternatively it is possible to achieve lower energy threshold with modest size experiment carried out at higher altitude. In figure 7.15 it is shown that as the height increases the Cherenkov photon density increases near the shower core. These features effectively reduce the energy threshold of the experiment operated at higher altitude.

A new Gamma Ray Observatory, called HIgh-altitude Gamma Ray Observatory or HIGRO,3 [75] comprising an array of wavefront sampling telescopes and a large stereo imaging Cherenkov telescope is being set up at the high altitude astronomical site at Hanle (latitude 32.8° North, longitude 78.9° East and altitude 4200 m), in the Ladakh region of northern India. The main motivation, for this experiment is the low energy threshold of few tens of GeV and hence overlaping observations with satellite based detectors. The atmospheric attenuation of Cherenkov photons at Hanle altitude is ∼ 14% as compared to ∼ 50% at sea level. The Cherenkov photon density near the shower core at Hanle is higher by a factor 4-5 [56] compared to that at the sea level for showers of same energy.

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3It is a collaboration of Bhabha Atomic Research Center, Mumbai; Indian Institute of Astrophysics, Bangalore and Tata Institute of Fundamental research, Mumbai
At present, a 7 telescopes array, called High Altitude GAmma Ray observatory or HAGAR [53] is being set up at Hanle. HAGAR is based on wavefront sampling technique like PACT. These seven telescopes will be in the form of a hexagon, as shown in figure 7.16, with a spacing of 50 m between telescopes. Each of the 7 telescopes will have 7 para-axially mounted...
parabolic mirrors of diameter $\sim 0.9$ m with a photomultiplier tube fitted at the focus of every mirror. Telescope structure is based on Alt-Azimuth design. Energy threshold of HAGAR is estimated to be, defined as the peak of the differential trigger rate distribution, $\sim 60$ GeV for vertically incident showers. Sensitivity of HAGAR would be such that it will detect the Crab at $5\sigma$ level without any hadron rejection in $\sim 2$ hours compared to that of 50 hours for PACT. In figure 7.17 sensitivity of HAGAR is compared with present and future $\gamma$-ray telescopes. Figure 7.18 shows the photograph of the first telescope of HAGAR commissioned in June, 2005. Commissioning of remaining telescopes is underway. All 7 telescopes are expected to be operational by middle of 2007.

This will be followed by the Major Atmospheric Cherenkov Experiment (MACE) [75] telescope. This experiment is planned to be a system of two high resolution imaging Cherenkov telescopes operating in a stereoscopic mode. Energy thresholds for single MACE element is estimated to be $\sim 15$ GeV and $\sim 25$ GeV at zenith angles $10^\circ$ and $30^\circ$ respectively. The first element will be operational by 2010. Figure 7.19 shows the schematic diagram of the MACE telescope.
Fig. 7.17: Sensitivity of HAGAR, without any cosmic ray rejection, is compared with present and future $\gamma$-ray telescopes.

Fig. 7.18: Photograph of one of the telescopes installed at Hanle
In May, 2007 NASA will launch the Gamma-ray Large Area Space Telescope (GLAST). This satellite experiment will operate in the energy range 10 keV to 300 GeV. Sensitivity of this experiment would be much better compared to that of EGRET. Thus overlapping observations of HAGAR and MACE with the GLAST could enhance our understanding of the AGN’s and other celestial sources.
Appendix A

Appendix

A.0.1 Event data format for sectors :

- word 0 : station no.
- word 1 : event no. (LSB)
- word 2 : event no. (MSB)
- word 3 : data size (119 words)
- word 4-8 : RTC time
- word 9 : latch
- word 10-33 : 12 channel scalers, two words for each scaler channel
  1 : triggers
  2 : recorded events
  3 : Cumulative no. of monitoring interrupts
  7-12 : Royal Sums 1-6
- word 34-73 : 16 ch TDC module : individual mirror TDC
- word 74-81 : spare
- word 82-117 : 12 ch ADC module : indiv mirror ADC’s
- word 118 : check_sum=sum of words 0:117
A.0.2 Event data format for main station:

- word 0: station no.
- word 1: event no. (LSB)
- word 2: event no. (MSB)
- word 3: data size (52 words)
- word 4-8: RTC time
- word 9,10: latch
- word 11-20: scalers
  11: station 1 triggers
  12: station 1 recorded events
  13: station 2 triggers
  14: station 2 recorded events
  15: station 3 triggers
  16: station 3 recorded events
  17: station 4 triggers
  18: station 4 recorded events
  19: main station triggers
  20: main station recorded events
- word 21-50: TDCs
  21-32: royal sum 11, 12,...,16
  33-44: royal sum 21, 22,...,26
  45-50: royal sum 31, 32,...,36
- word 51: check sum=sum of words 0:50
A.0.3 Monitor data format for sectors:

- word 0: station Flag (1111 for Sector #1, ..., 4444 for Sector #4)
- word 1: monitor record no.
- word 2: data size (57)
- word 3-7: RTC time
- word 56: spare

A.0.4 Monitor data format for main station:

- word 0: station Flag (7777)
- word 1: monitor record no.
- word 2: data size
- word 3-7: RTC time
- word 8-19: RS11, ..., RS16, RS21, ..., RS26
- word 20-23: spare
- word 24-35: RS31, ..., RS36, RS41, ..., RS46
- word 36-39: spare
- word 40: spare
Bibliography


