VERY HIGH ENERGY GROUND BASED GAMMA RAY TELESCOPY

NIUS Astronomy Nurture Camp 2013

This project is a study of VHE gamma ray astronomy using atmospheric Cherenkov technique. The project involved the study of processes of interaction of gamma rays, formation of extensive air showers, imaging of the Cherenkov radiation and data analysis of the observed data of Crab Nebula and MRK421 using TACTIC at Mt. Abu, India.

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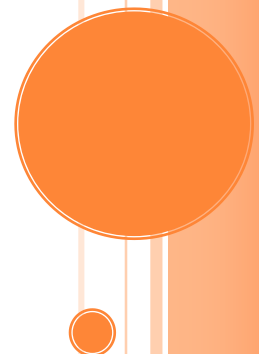Department of Physics,
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I. INTRODUCTION

In order to study the various processes and objects of the universe, electromagnetic radiation and particles emitted from them act as information messenger. But to observe all these radiation and particles directly is very seldom as most of them get deflected or interrupted by interstellar medium or other objects. As gamma rays are very less affected by these interactions, they are a very good source of information about the source object. The direction, energy and temporal spread of these rays reveal the important information about the processes going on at these sources.

In this project, we studied how very high energy gamma rays are observed using ground based telescopes. In Section II, we describe about the sources from which these rays are expected to arrive. The current theories of formation of these sources and classification is discussed.

In Section III, we discuss the various radiation and absorption processes through which gamma rays interact and are relevant to gamma ray astronomy. In Section IV, some of these processes are used to explain the formation of extensive air shower in the atmosphere when gamma rays hit the earth's atmosphere.

In Section V, we discuss the design of the ground based telescopes to capture the Cherenkov telescope emitting from extensive air showers. The telescope details are mentioned and triggering and recording mechanisms are explained. The image processing algorithm is summarised and image parameters are defined.

In Section VI, we discuss the data analysis methods implemented by us on the observed data by TACTIC on Crab Nebulae and MRK421. The important conditions to differentiate the gamma rays from charges cosmic rays have been discussed. The signal estimation and its temporal distribution as also been discussed.

In Section VII, we finally presented the wide scope of the field by describing possible modifications in present techniques and possible verification of currently presented theoretical models of gamma sources.

II. SOURCES OF GAMMA RAYS

We studied about the already known information about the sources of gamma rays and their possible mechanism of emission of gamma rays.

A. Supernova and Supernova Remnants

Supernovae are energetic stellar explosions that are usually triggered in a variety of ways. They play a critical role in high energy astrophysics for many reasons, among them the production of heavy elements, the formation of new stars, and the acceleration of charged cosmic rays. Some are also used as standard candles for measurements of distance on the cosmological scale.

The two important types of supernovae studied in gamma-ray astronomy are –

1) Type Ia – White dwarf stars in binary systems start to gather material from their binary companion by accretion processes or mergers, and their cores attain fusion temperature, resulting in a supernova explosion. All of the stellar mass is ejected, and no core remnant is observed.

2) Type II - By the collapse of the core of a massive star – When a massive star runs out of fuel, it collapses inwards due to its own gravitational force, which is no longer balanced by internal stellar pressure, and the energy released causes a supernova. The core implodes, often resulting in a neutron star or pulsar. The shockwave propagates through the outer layers of the star, and is aided by neutrino emissions from the neutron star. These explosions are observed in star-forming regions such as in the arms of spiral galaxies.

The resultant structure formed is termed a supernova remnant. The shockwave due to the explosion passes through interstellar dust, and the material within the shockwave constitutes the remnant. Supernova explosions typically release energy of the order 10^{51} ergs. SNRs emit in almost all wavelengths upto 100TeV, and gamma ray radiation is generated due to synchrotron radiation and the Inverse-Compton effect. There are more than 250 SNRs observed in the Galaxy and they have dramatically different appearances. There is more than one way in which a supernova explosion can occur and the form of the SNR depends strongly on the nearby interstellar medium.

A hypothesis exists that states that supernovae are the most likely sources of cosmic radiation in the Galaxy (upto energies of 100TeV). We arrive at this hypothesis by simple energy considerations.

It is assumed that cosmic rays fill the Galaxy and the galactic halo, a volume of 1x10^68 cm^3.

Most of the energy is concentrated in the lower energies, at a density of 10−12 erg cm−3 or 0.5 eV cm−3 above 1 GeV. So, the total energy is around 1x10^56 erg.

It is difficult to calculate the loss, and hence the necessary replenishment rate of cosmic rays. One method that is used is to measure the relative abundance of beryllium isotopes produced in the cosmic radiation by spallation (the breakup of heavier nuclei in collisions). This process yields a measure of the average lifetime of a cosmic ray in the galaxy (3x10^7 years). By using

other estimates we improve this estimate to 1.4x10^7 years. this gives us a replenishment rate ~2x10^41 erg/s.

We use this minimum limit to hypothesise a source of cosmic rays that can reach this rate of replenishment. Of the variety of sources in the galaxy, most of them are insufficient either in the frequency of the phenomenon, or in the energy output. However SNRs satisfy this cosmic ray production rate.

Supernovae have an energy output of about 10^52 erg, and a conversion efficiency to cosmic rays of 1% is deemed reasonable. At a frequency of one explosion per 30 years (as observed in similar galaxies to ours), a total output of 10^40 to 10^41 ergs is estimated. This matches our observed cosmic ray production rate.

However, supernova explosions, and subsequently SNRs, do not have sufficiently energetic processes to produce cosmic rays higher than 100 TeV. For this, we must look for other sources in the galaxy.

Acceleration of cosmic rays

The most likely process by which cosmic ray particles are accelerated can be explained by the shockwaves caused due to the supernova which may be persistent for a long time. It is clear through standard models that shockwaves are produced from implosion/explosion and that they propagate into interstellar space and are observed as expanding gas shells. Shock acceleration of relativistic particles is a favourite mechanism for theoretical speculation since it is relatively well understood.

Also there is observational support for the acceleration of particles to super-thermal energies in interplanetary space. There is, however, no direct evidence for shock acceleration in operation at truly relativistic energies and one of the hopes for gamma-ray astronomy is that it will provide the first direct observational evidence of shock acceleration of hadrons up to energies of 100 TeV. There is evidence that this is observed for *electrons* but there is, as yet, not definitive observations of *hadron* shock acceleration.

The supernova explosion ejects the outer layers of the star which propagate into the interstellar medium producing a shock wave. As it moves out, it is resisted by the interstellar medium. For a typical interstellar density of 1 proton cm−3 , it will take about 103 years for 10 M of material moving with a velocity of 5000 km s−1 to sweep up its own mass of interstellar material, this is the characteristic time of the supernova expansion and the time when most of the acceleration occurs.

The Crab nebula is a SNR of a Type II supernova, and is one of the most studied sources of EM radiation in the universe. The apparent size of the Crab nebula is a function of its wavelength. In the radio spectrum, it's size is 4 arc-min diameter, while in the optical spectrum, it's 2 arc-min diameter, and is even smaller in the x-ray spectrum. The emission at all of these

wavelengths exhibits polarization and suggests the presence of synchrotron radiating electrons, which is an accepted method of production of radiation in the Crab nebula.

In the HE region (50 to 500 MeV), the Crab nebula shows two components of almost equal amplitude, one emerging from the pulsar, and one the SNR region surrounding the pulsar.

In the VHE region, normal synchrotron and inverse Compton Effect couldn't separately explain the high energy photons produced, so a new theory was proposed. It postulated that the amorphous radiation from radio to x-rays from the Nebula was due to synchrotron radiation by relativistic electrons, and these same electrons caused Compton-scattering on the photons, boosting them to VHE gamma-ray energies. This matched the hard gamma-ray radiation observed.

The Crab nebula shows some variability in the 1 to 150 MeV range. However, from 300 Gev to 3TeV, the Crab nebula has a steady flux of radiation, and is considered as a standard candle using which telescopes are calibrated.

B.   Active Galactic Nuclie

An active galactic nucleus (AGN) is a compact region at the center of a galaxy that has much higher luminosity, at least in some portion of electromagnetic spectrum. Such excess emission has been observed in Radio, Infrared, Optical, Ultra-violet, X-ray and Gamma Ray wave bands.

A galaxy containing an AGN is called an active galaxy. The radiation from an AGN is believed to be a result of accretion of mass by a ***Super Massive Black hole*** at the center of its host galaxy. AGNs are most the luminous and persistent sources of electromagnetic radiation in the universe, and as such can be used as a means of discovering distant objects.

In the standard model of AGN, some material close to a black hole forms an accretion disc. Dissipative processes in the accretion disc transport matter inwards and angular momentum outwards, while causing the accretion disc to heat up, by a certain kind of viscous effect. The expected spectrum of an accretion disc peaks in the optical-ultraviolet waveband. A large fraction of the AGN's radiation may be obscured by interstellar gas and dust close to the accretion disc.

Some accretion discs produce jets, fast outflows of particles that emerge in opposite directions from close to the disc. The direction of the jet ejection is determined either by the angular momentum axis of the accretion disc or the spin axis of the black hole. The jets have their most obvious observational effects in the radio waveband, where Very Long Baseline Interferometry can be used to study the synchrotron radiation they emit at resolutions of sub-parsec scales. However, they radiate in all wavebands from the radio through to the gamma-ray range via the ***synchrotron*** and the ***inverse-Compton scattering process***, and so AGN jets are a second potential source of any observed continuum radiation. Gamma-ray observations of the AGN alone can provide valuable information on the nature of particle acceleration in the quasar jet, and clues as to how the particles interact with their surroundings.

CLASSIFICATION OF AGNs:

Earlier these objects were empirically discerned by their radio emission, the properties of their optical emission lines, morphological considerations, γ-ray emission and some other properties.

AGN are primarily divided into two groups of spiral and elliptical galaxies. The spiral galaxies are subdivided into Seyfert galaxies (type I and II) based on their optical emission lines. On the other hand, one class of elliptical galaxies with weak radio emission are called Radio Quite Quasars (RQQ), while the other with strong radio emitting objects are further classified on the basis of their optical emission lines. The objects with strong optical emission lines are Radio Quasars (they have two groups: Flat Spectrum Radio Quasars (FSRQs) and Steep Spectrum Radio Quasars (SSRQs)). The second category in this class i.e. objects having weak or no optical emission lines are further classified as Radio Galaxies having no γ-ray emission and the BL Lacerate (BL Lac),named after the prototype of the class BL Lacertae, in constellation Lacerta, objects which have γ-ray emission and also show strong flux variability. The FSRQ which also have γ-ray emission, strong variability and optical polarization, together with BL Lacs form the class of Blazars. All blazars emit γ-rays.

BLAZAR:

A Blazar is an AGN which has one of its relativistic jets pointed toward the Earth so that what we observe is primarily emission from the jet region. The blazar types have differences in the optical emission, as Optically Violently Variable (OVV) quasars and FSRQs have strong emission lines while BL Lacs show weak / no optical lines. These differences are probably due to the amount of cold molecular clouds encountered along the line of sight. They are thus similar to quasars, but are not observed to be as luminous. The visible and gamma-ray emission from blazars is variable on timescales from minutes to days. There are also occasional Flares that are characterized by a high incoming flux of gamma rays. The high variability and broadband emission make long term observations of such blazars very important for understanding their emission mechanisms and other related properties.

UNIFIED THEORY:

The appearance of active galactic nuclei (AGN) depends so strongly on orientation that our current classification schemes are dominated by random pointing directions instead of more interesting physical properties. Light from the centers of many AGN is obscured by optically thick circumnuclear matter, particularly at optical and ultraviolet wavelengths. In radio-loud AGN, bipolar jets emanating from the nucleus emit radio through gamma-ray light that is relativisticaly beamed along the jet axes. Blazar is a SMBH with its jet nearly or completely pointed towards us. In some other viewing angle it appears as a Radio galaxy or as a seyfert galaxy.
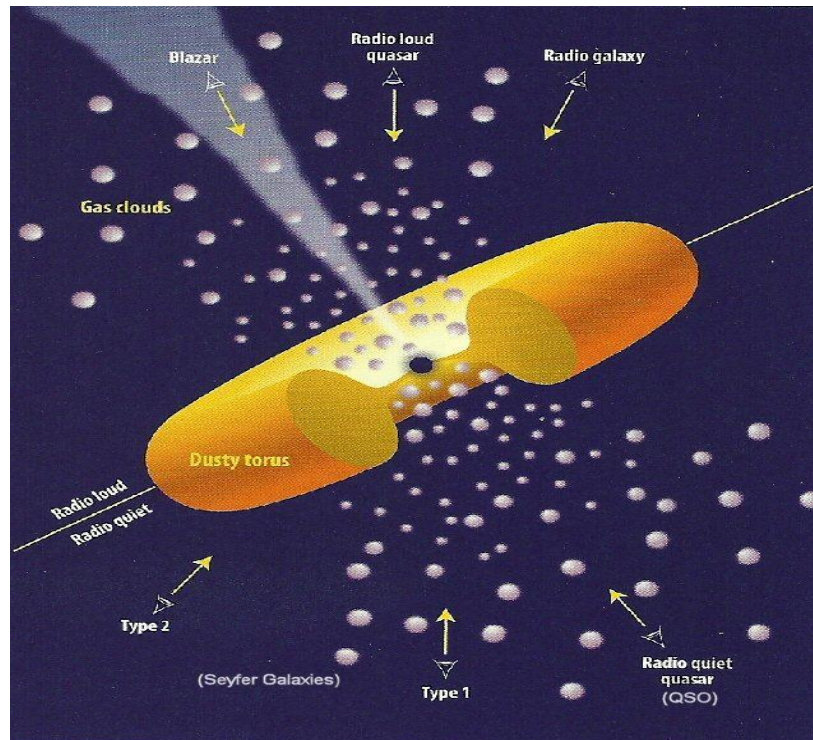
An artistic view of unified scheme
Image courtesy: http://universe-review.ca/F05-galaxy01.htm

Source of Energy:

Although the Super-Massive Black Hole at the center of AGN is a very great source of energy, we have no clear understanding about how energy is being extracted from it and how the jets of relativistic particles are formed in the vicinity of the black hole.

The observation of HE and VHE gamma rays from blazars is strong and independent evidence that the radiation in blazars is produced in relativistic jets and that the jets make a small angle with the line of sight. The low energy component is generally agreed to be due to Synchrotron radiation.

But in explaining the high energy component there is no general consensus and many models have been proposed to explain the origin of the high energy component.

Markarian421*:*

Markarian421 under study is a blazar, located in the constellation Ursa Major, estimated to be at a distance from us of around distance of $\sim$ 134.1 Mpc (H = 71 km s-1 Mpc-1 , Ωm = 0.27, $\Omega\lambda$ = 0.73). It was first determined to be a very high energy gamma ray emitter, found to be emitting radiation in the TeV energies, in 1992 by M. Punch at the Whipple Observatory, and an extremely rapid outburst in very high energy gamma rays (15-minute rise-time) was measured in 1996 by J. Gaidos at Whipple Observatory. It is one of the closest blazars to Earth, making it one of the brightest quasars in the night sky. It is suspected to have a super massive

black hole (SMBH) at its center due to its active nature, and has a companion galaxy (Markarian 421-5) that is fueling the gas jets observed pointing away from the galaxy.

It has been seen that the TeV γ-ray emission from Mrk421 is highly variable with variations of more than one order of magnitude and occasional flaring doubling time of as short as 15 minutes.

C.   Compact Binary Systems

Most of the stars in our galaxy are associated with other stars making multiple star systems which are orbiting around each other. Half of the stars in the stellar population occur in some kind of binary association. The compact binary system consists of a compact star generally a neutron star or black hole and a normal massive star called the companion star. The compact star accretes mass from the companion star. They are known for the powerful emission of temporally and spectrally variable X-ray radiation.

D.   Gamma Ray Bursts

GRBs are flashes of γ-rays associated with the extremely energetic explosions in distant galaxies. They are the most luminous electromagnetic emissions occurring in the Universe in any wavelength band and perhaps the brightest phenomenon since the big bang. Bursts can last from milliseconds to nearly an hour, although a typical burst lasts a few seconds and typically (1051 - 1054) ergs s−1 are released within this time.

E.   Young Open Star Clusters

Star clusters which are groups of stars are of two types. One is the globular clusters which are tight groups of hundreds of thousands of very old gravitationally bound stars, while other is the open clusters, a more loosely clustered group of stars, generally contain less than a few hundred members, and are often very young. The particles can be accelerated to extreme energies by means of shock created by the collision of winds of these massive young stars.

F.   Star forming galaxies

These young galaxies are characterized with an exceptionally high star formation rate as compared to the normal galaxies. High star formation and supernova rate in starbust galaxies enhances the energy density of energetic nonthermal particles - mostly electrons and protons which are Fermi accelerated in the sites of SNRs.

III. RADIATION AND ABSORPTION PROCESSES

Observing gamma ray showers involves usage of earth's atmosphere where these rays undergo various process to form Extensive Air Showers. Following is a brief description of the processes involved:-

A. Pair Production

Gamma ray photons in dense medium undergo pair production process. In intense electric field of the nucleus of atoms, the gamma ray photon gets annihilated to form a pair of an electron and a positron flying away in almost same direction as the gamma ray at relativistic speeds.
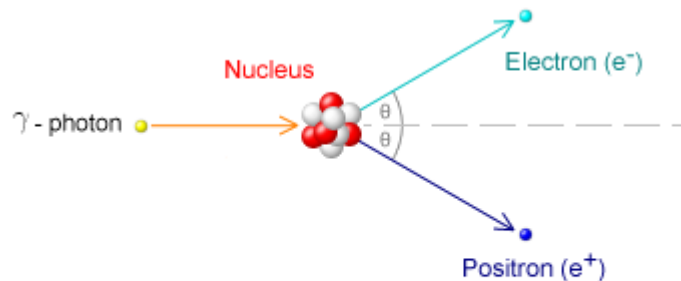
$$E_o > 2m_0c^2, \text{ where } m_0 \text{ is}$$
the electron rest mass

Image Courtesy: www.relativitycalculator.com

The energy of gamma ray is transferred to the pair with very less loss and hence the information about direction and energy of the gamma ray is transferred.

B. Electron Bremsstrahlung

When charged particle moves in the electric field of a nucleus, it undergoes deflection. This in a way causes it to decelerate and hence it emits electromagnetic radiation whose energy is proportional to the acceleration of the particle in the field.
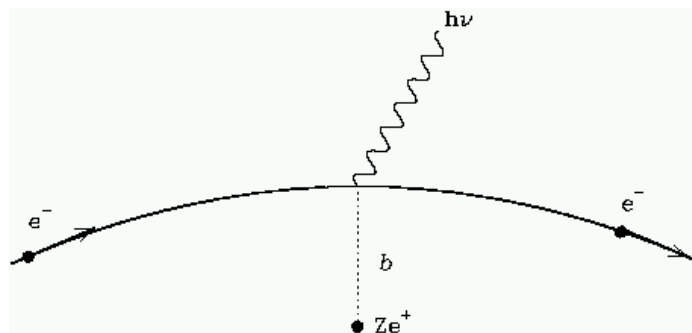
Image courtesy: www.astro.utu.fi

Cosmic electrons in SNRs and Interstellar Medium undergo bremsstrahlung and emit gamma rays. The gamma rays that result from bremsstrahlung have energies of the same order as the incident electron. The spectral index for the power law expression remains same for the electron the emitted radiation.

C.   Cherenkov Radiation

When a charged particle travels through a medium, it disturbs the neutrality of surrounding molecules due to polarization. The polarization switches on and off as the particles passes which causes the molecule to radiate electromagnetic radiation. When particle traverses with a speed greater than speed of light in that medium, the emitted wavefronts interfere with each other constructively and get squeezed in temporal dimension causing a very small but bright flash of electromagnetic radiation.
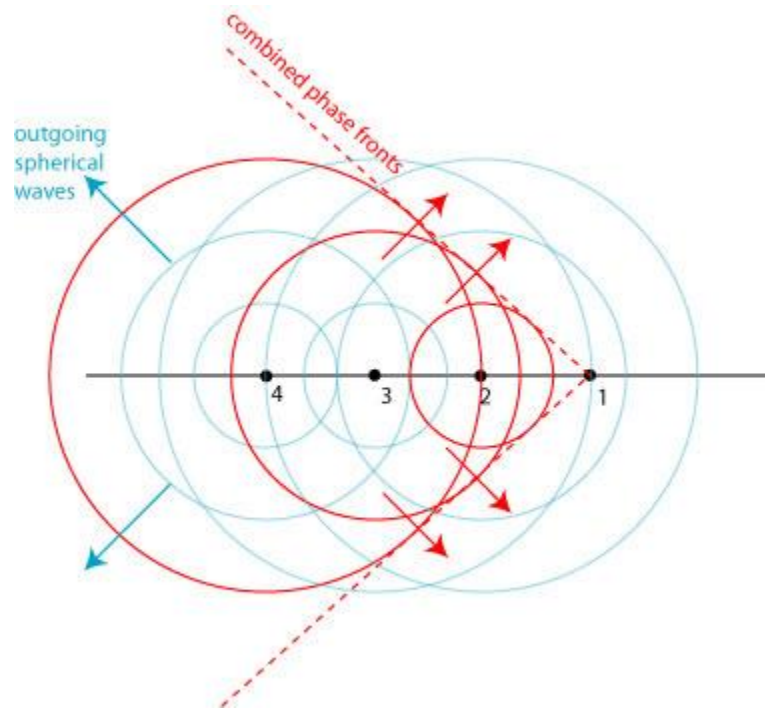
Image Courtesy: www.skullsinthestars.com

This radiation generally lie in shorter wavelengths of the optical region. The emitted photons carry very less energy and practically does not slow down the charged particle. The angle which this Cherenkov light makes with velocity of the charges particle is known as Cherenkov angle and is equal to $\cos^{-1}(c/vn)$.

D.   Pion production

Protons can produce π mesons either in inelastic collisions with matter or interacting with ambient radiation, e.g. the microwave background. Both charged (π + , π −) and neutral pions (π0) are produced with the same probability in the nucleonic cascades and are the lightest ($m_{\pi 0}$ = 135 MeV , $m_{\pi +} = m_{\pi -}$= 140 MeV) mesons.
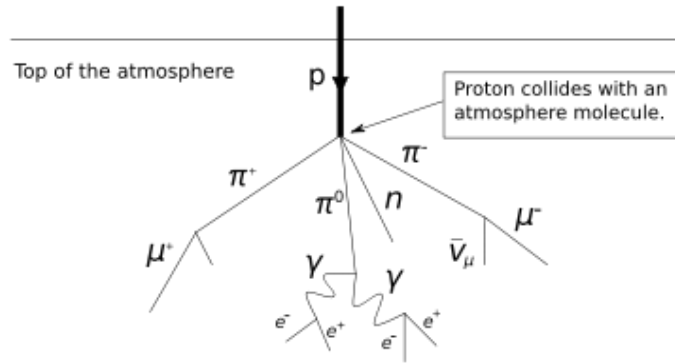
Image Courtesy: www.newworldencyclopedia.org

Neutral pions with a mean life of 0.83×10^{-16} s $\times \gamma_\pi$ (where γ_π is the Lorentz factor of the pion) decay into gamma rays.

The $\pi^\pm$ mesons have a mass of 139.6 MeV/c2 and a mean lifetime of 2.6×10^{-8} s. They decay due to the weak interaction, producing mu mesons and gamma rays. μ meson then further decay into electrons and positrons.

E.   Compton Scattering

The scattering of a photon off an unbound electron is known as Compton scattering. It is the dominant interaction of a gamma ray in the energy region from a few hundred keV to 10 MeV in most materials and is the basis of the Compton telescope. Hence, it is most important when the photon energy is of the

order or greater than the rest mass of the electron. Initially, our assumption is that the electron is at rest or that we are working in the rest frame of the electron.

In the Compton process, a high energy photon imparts its energy to an electron, and slows down.

Compton scattering

$v' < v$
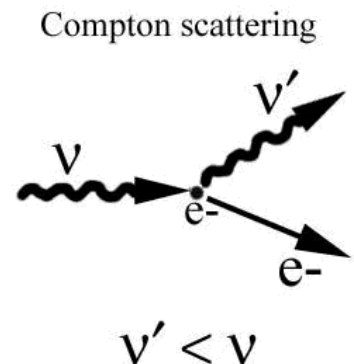
Electron is initially at rest
e- gains energy

Image courtesy: venables.asu.edu

F.   Inverse Compton Scattering

The inverse Compton process is the collision of a high energy electron with a low energy photon, and is very important in astrophysical systems. It is physically the same as Compton. To the observer in the frame of the electron, the stationary electron scatters an energetic photon. Since the scattered photon acquires considerable energy this can be seen as a form of photon 'energy boosting'. It is the dominant mechanism by which VHE gamma rays are produced by electrons in astrophysical sources such as plerions and AGN.

In the inverse process, a low energy photon is accelerated to very high speeds.
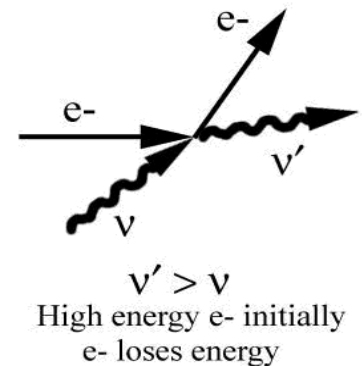
Image courtesy: venables.asu.edu

G.   Synchrotron Radiation

When high-energy particles are in rapid motion, including electrons forced to travel in a curved path by a magnetic field, synchrotron radiation is produced. Synchrotron radiation is also generated by astronomical objects, typically where relativistic electrons spiral (and hence change velocity) through magnetic fields. Two of its characteristics include **non-thermal power-law spectra**, and **polarization**.

A class of astronomical sources where synchrotron emission is important is the pulsar wind nebulae. **Crab Nebula**, in the constellation Taurus, is well known to contain a pulsar at its heart. Pulsed emission gamma-ray radiation from the Crab has recently been observed up to ≥25 GeV probably due to synchrotron emission by electrons trapped in the strong magnetic field around the pulsar. Polarization in the Crab nebula at energies from 0.1 to 1.0 MeV illustrates a typical synchrotron radiation.
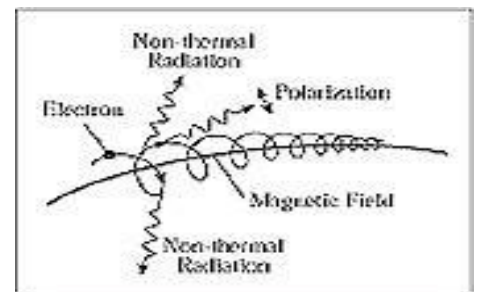
Image courtesy: ase.tufts.edu

H.   Photon-photon pair production

High energy gamma rays get absorbed in a low energy photon background by the process of photon-photon pair production.

The cross-section of the process maximizes when

$$E\gamma \, h\nu(1 - \cos\theta) \sim 2(m_e c^2)^2 = 0.52(\text{ MeV})^2$$

This process is responsible for attenuation of gamma rays due to Extra galactic Background Light.
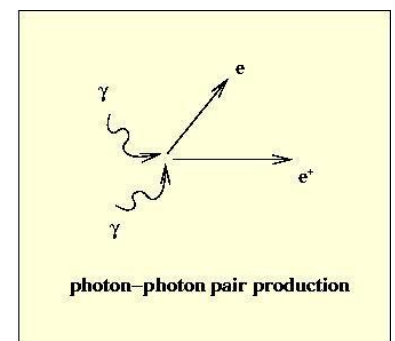
Image Courtesy: www.physics.adelaids.edu.au

IV. FORMATION OF EXTENSIVE AIR SHOWER

As the gamma ray struck the earth's atmosphere, it undergoes pair production forming electron and positron. Mean distance that the gamma ray travels before undergoing pair production is $\frac{9}{7}\chi$. This occurs at an altitude of 20km. The resultant electron and positron pair carries the total energy of the incident gamma ray. After traversing about a radiation length, these positrons and electrons undergo bremsstrahlung to emit gamma rays which further undergo pair production after another radiation length. In this way, a shower of charged particles falling down at a small angle to the initial direction of incident gamma ray is formed. This shower is known as Extensive Air Shower. The process continues down through the atmosphere with the number of charges particles increasing till their energy drops to a point where ionization losses and radiation losses become equal. This point is known as the shower maximum. From this point onwards, the cascade of charged particles dies off.
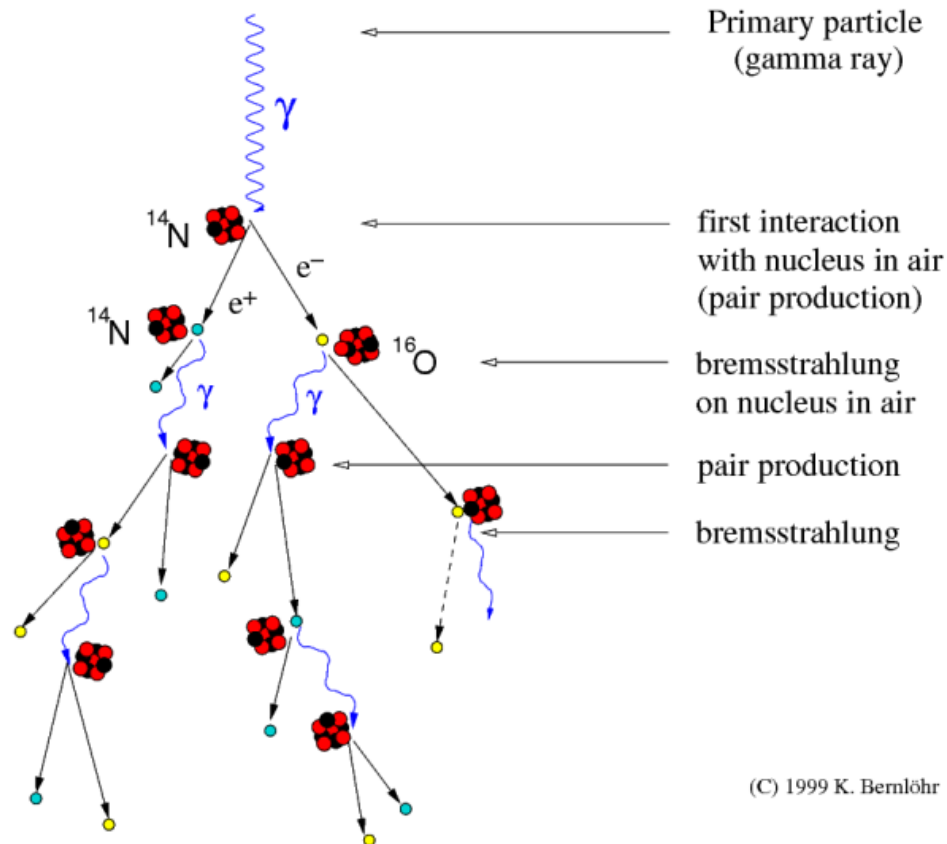
Image Courtesy: www.mpi-hd.mpg.de

All electrons and protons moving at relativistic speeds in the atmosphere emit Cherenkov radiation. This Cherenkov radiation can be easily detected using simple light detectors and hence can be used to generate an image of the shower. The shower retains the original direction of the gamma ray as when the shower is back traced, it converges to the point of origin of shower where the incident gamma ray

underwent pair production. Hence the original direction of the gamma ray can be easily traced to determine the source of the gamma ray in the sky. Further, the number of Cherenkov photons emitted is directly proportional to the initial energy of gamma ray revealing more information about the source. The Cherenkov light arrives at the detector within a span of a few nanoseconds, so the time of arrival of the incident gamma ray can also be recorded to a high precision.
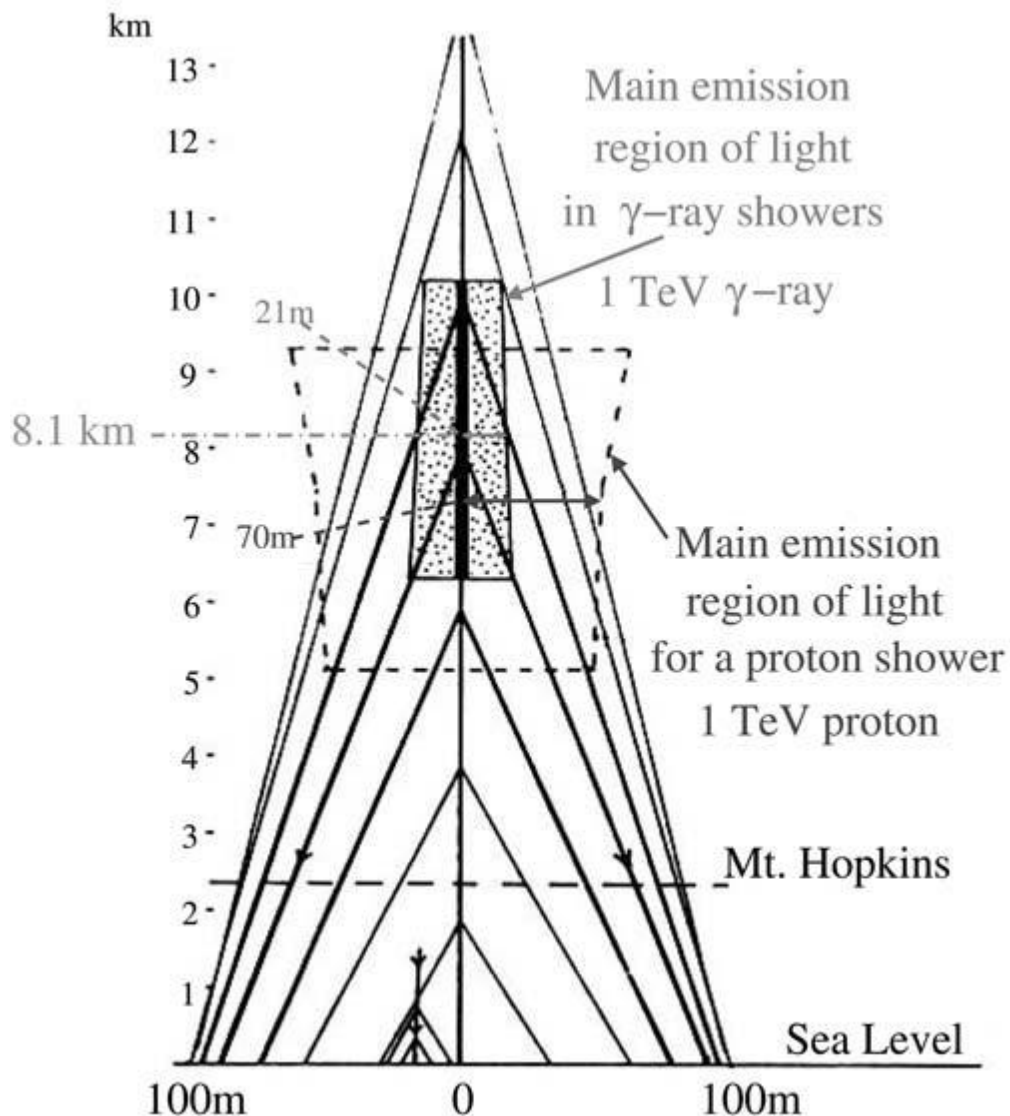
Image Courtesy: Hillas A M 1996 *Proc. 'TeV Gamma-ray Astrophysics' (Heidelberg) (Space Sci. Rev. 75)* ed H J Volk and F A Aharonian (Dordrecht: Kluwer) p 17

The incoming Cherenkov light can be considered to be coming from three regions. 25% comes from the shower top upto the altitude of 10km. The Cherenkov angle decreases with the altitude and hence the light appears as a focused annulus of radius about 120m on ground. 50% of the light comes from a cylinder of radius 21 m and length 4km centered at the shower maximum. Remaining 25% of the light comes from the region of shower upto the altitude of 6km. This light falls close to the shower axis and is vulnerable to large fluctuations due to very few surviving charged particles in this region.

V.   IMAGING OF CHERENKOV RADIATION

The Cherenkov radiation coming from the Extensive Air Shower is collected by the ground based telescopes to get the image of the shower and hence information about the incident gamma ray.

A.   Atmospheric Cherenkov Technique Telescope details

The telescope is a simple combination of a light collecting system using a mirror reflector, a light detecting system at its focal plane and fast pulse counting electronic system attached to it.

Atmosphere, though out of control regime, plays a crucial role in this technique as it acts as a large calorimeter. The gamma rays end up in Extensive Air Showers which can be detected by ground based detectors.

Generally Davis-Cotton design is implemented to collect the Cherenkov radiation from the extensive air shower. The tessellated arrays of spherical mirror of same focal length provides larger mirror collection area.
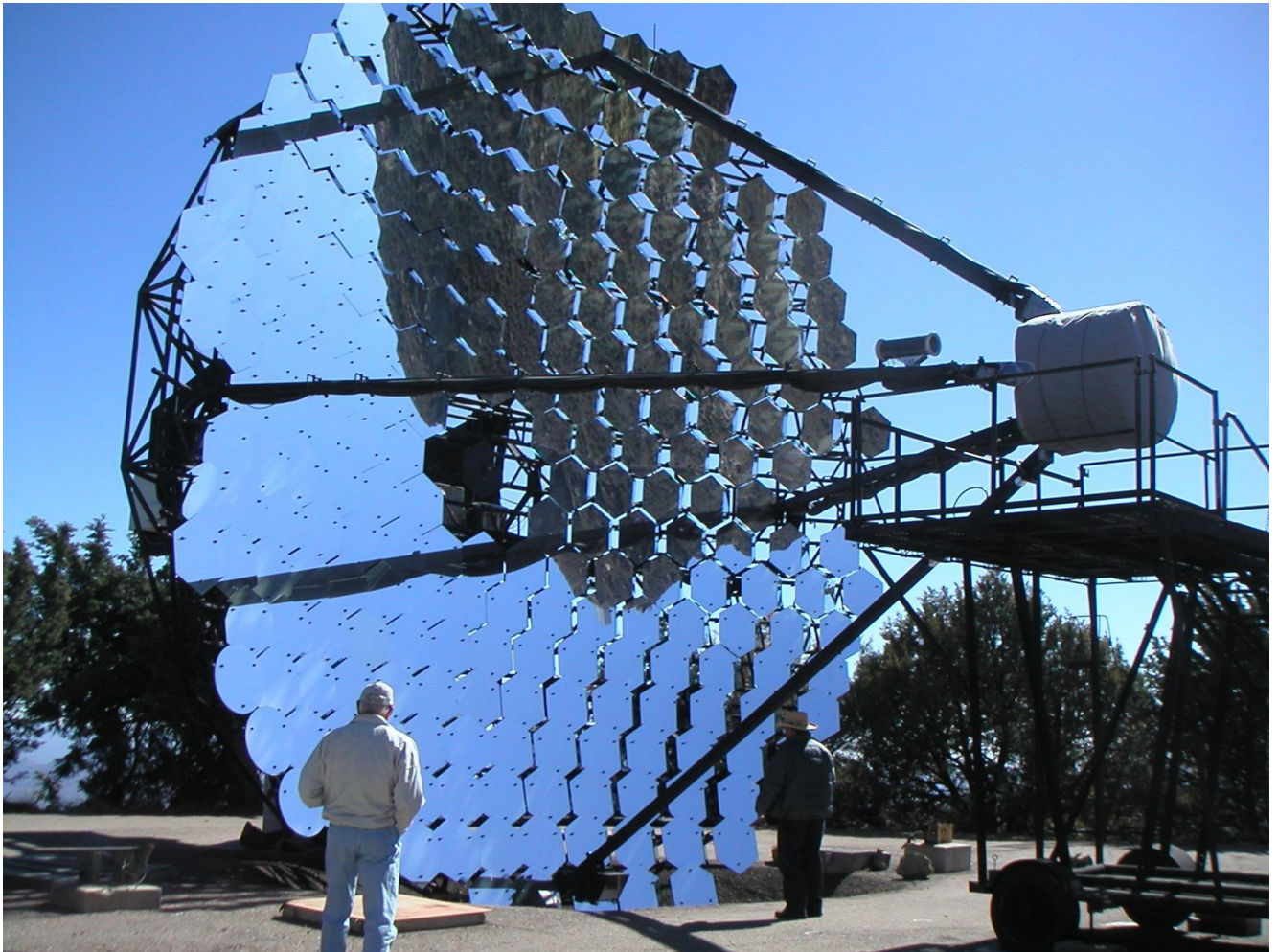
Image Courtesy: www.classicalarchives.com

The actual collection area of the telescope is however different than the mirror collection area and is very large. The whole area from which Cherenkov radiation can be recorded is the actual collection area of the telescope. The mirror collection area however determines the minimum energy gamma ray that it can observe.

Image courtesy: http://en.wikipedia.org/wiki/Photomultiplier
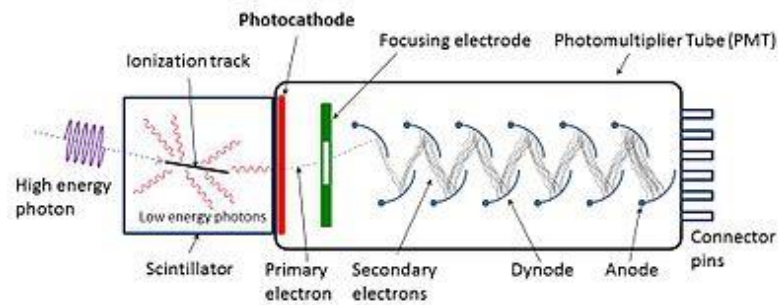
On the focal plane, there is generally an array of Photo Multiplier Tubes to detect the light signals. PMT works on the principle of photoelectric effect. The falling light emits photoelectrons at the photocathode plate. These primary electrons are focused to pass through many channels which multiply their number by around 4 each time they pass through them. Hence, in the end, $10^5 - 10^6$ electrons reach the collector pin and generate a small pulse of current.
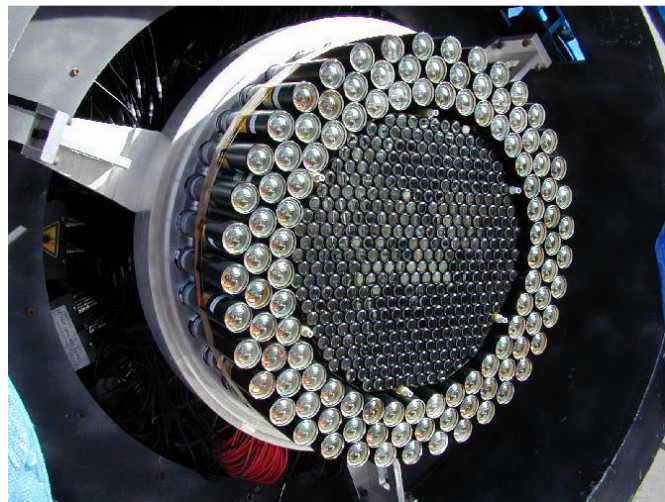
The 490 pixel camera of the Whipple Observatory made up of individual photomultipliers.
Image courtesy: T.C. Weeks Very High Energy Gamma Ray Astronomy, pg. 34

An array of such PMTs is used to capture the image of the Cherenkov light pulse. They have a quantum efficiency of around 15%. Drawback of using PMTs is that they get easily damaged by bright light.

B.   Triggering and recording
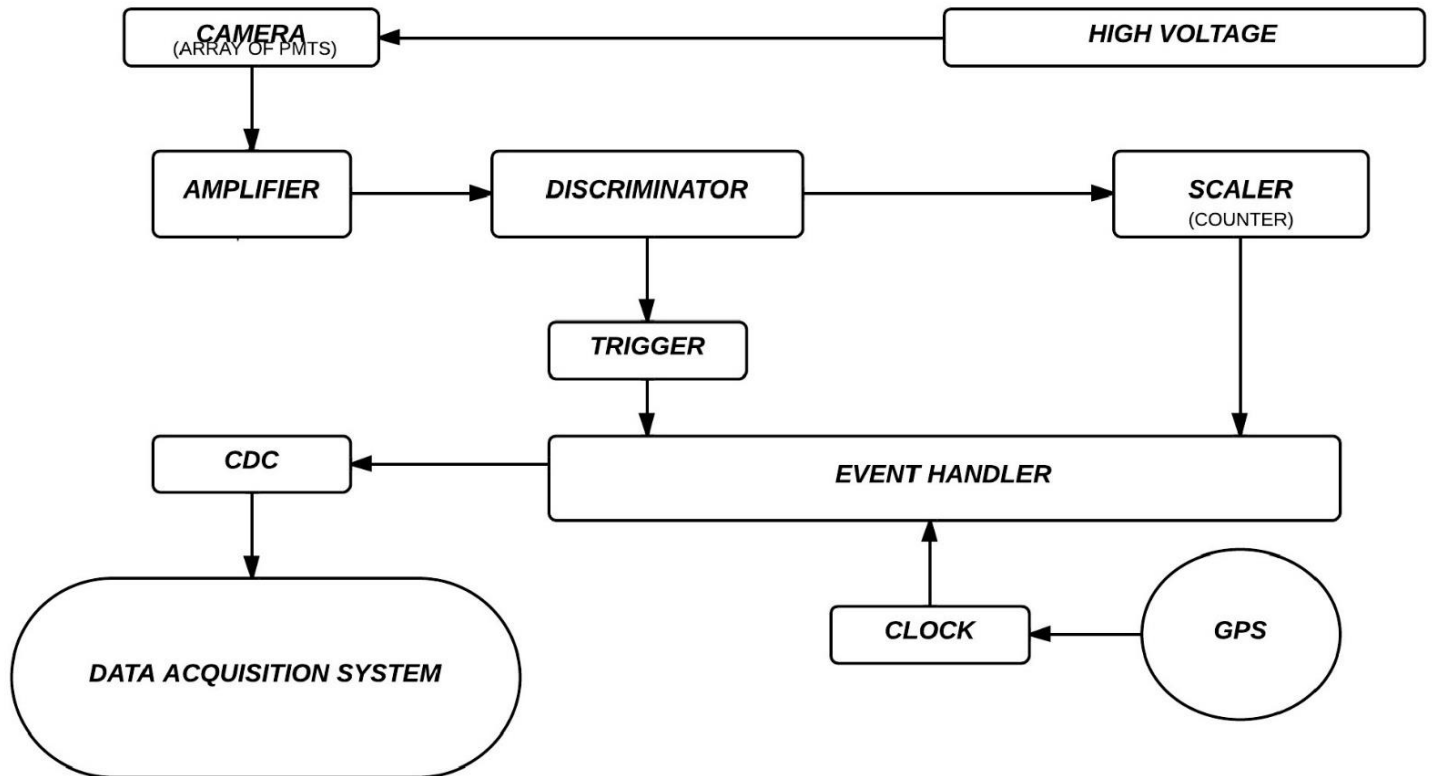
The pulse from the amplifier is fed into a discriminator circuit. The Discriminator then converts any analog pulse over a certain threshold into digital pulses and provides output for the scaler and the Trigger Generator Module. Then the Trigger Generator Module checks the configurations of signals detected in surrounding pixels and by predefined algorithms *decides* whether the received pulse is a part of an event or not. Then it *triggers* the Event Handler to record the event. Event Handler now clubs the Data from *scaler*, which measures the intensity of pulse, with time of event from a GPS clock.

The Data about the event is the sent to a CDC (charge digital converter) that converts the pulse intensities into a sensible number. This number is now recorded as raw data in the Data Acquisition System waiting to be further processed.

C.   Image Processing

After getting the number of photons in each PMT (pixel) detected for each event, we need to process this numbers to identify the image of the extensive air showers in the array. In case of TACTIC, a 12-bit number is received from each PMT. The image processing involves three processes:-

1.   Calibration

No matter how uniform the manufacture process is made, the PMTs inherently have different sensitivity and hence give different values of photon count for same light intensity. Hence we need to normalize the number of counts from each pixel such that they represent light intensity on same scale.
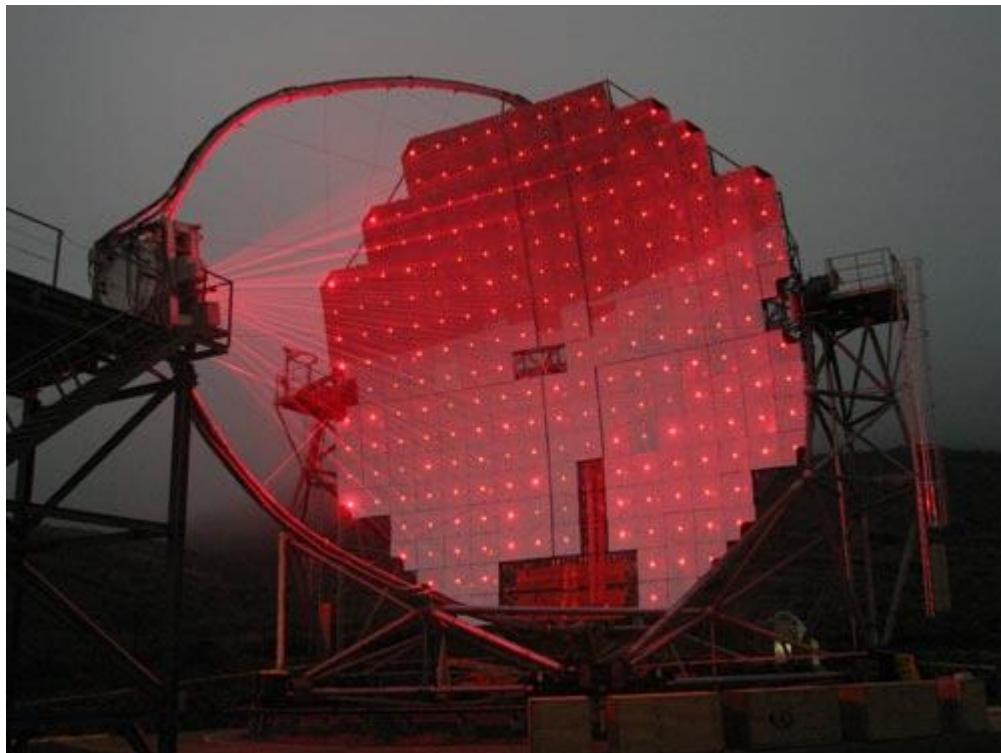
Image courtesy: www.newscientist.com

This is done by using a artificial monochromatic source of light (Laser) falling uniformly on all the PMTs and measuring their response to it. Then we can find a conversion factor for each PMT such that we get the same no. of counts from each PMT for the uniform light falling on it. These conversion factors are then used to normalize the counts from each pixel to get the actual light intensity variation over the focal plane of the telescope.

2.   Night Sky Background noise removal

Since Cherenkov light lie in the optical region, it causes the problem of the noise as earth's atmosphere is very transparent to the optical region. Apart from artificial sources and moon which can be avoided by selection of place and time, the light from the

stars in the night sky is a source of noise which cannot be avoided at all. Hence this background needs to be removed during image processing only.

This is done by pointing the telescope to a place in sky where there is no gamma source and a predetermined number of events are captured (about 2000). These events are used to make a distribution for each pixel of the array and a mean and standard deviation for each pixel is calculated. Say the ith pixel has this offsource data mean μ_i and standard deviation σ_i.

Now, for each even recorded in the observation, from each ith pixel count, its μ_i is subtracted and if the data goes to negative value, we simply equate it to zero.

$$N_{i,new} = N_{i,recorded} - \mu_i$$

3.   Image Identification (Peel subtraction)

After removing the noise as much as we could, we finally locate the interested part of the pixel array, which have taken the image of the extensive air shower. This is done by a two level cleaning process using the following conditions:-

i.   Picture Threshold: All the pixels which have their count value greater than $6\sigma_i$ (where σ_i is the standard deviation calculated from data of off source observation) are taken as the image pixels.

ii.   Boundary Threshold: All pixels which have a pixel of above class in neighbor and have their count value greater than $4\sigma_i$ are also taken as the image pixel.

All other pixels, which do not fall in any of the above category are not considered as image pixel and are made zero. Hence, we get an image of the extensive air shower in the form of a bunch of pixels with number of counts proportional to light intensity at that spot.

D.   Image Parameterization

After image processing, the image needs to be parameterized to analyze it. Following parameters are defined for the obtained image:-

1.   Size (S)

The overall light content of the image is parameterized by the total number of normalized CDC counts contained in it. To the first approximation, the size is proportional to the energy of the primary particle.

2.   Length (L)

The RMS angular size equal to the semi-major axis of the ellipse, and this is related to the longitudinal development of the shower. This parameter gives a measure of the angle subtended by the shower.

3.   Width (W)

The RMS angular size equal to the semi-minor axis of the ellipse and related to the lateral development of the shower.
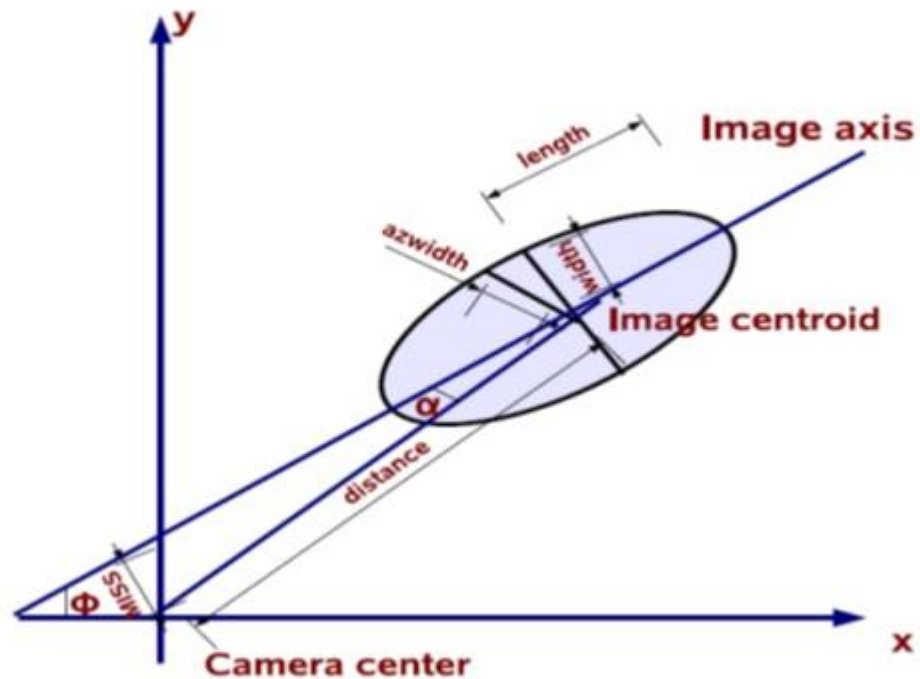
Image Courtesy: TeV Gamma-Ray Observations of Mrk421 and H1426+428 with TACTIC
Imaging Telescope, K. K. Yadav

4.   Distance (D)

The distance from the centroid of the image to the center of the field of view of the camera. This parameter gives information about the impact point of the shower i.e. a crude measure of core distance for a γ-ray shower. It is also viewed as the angle between the shower axis and the line joining the shower maximum and the telescope.

5.   Alpha (α)

The angle between the image axis (i.e. shower axis) and the line joining the image centroid and the camera center (source position). It is basically the angle between shower axis and the optical axis of the telescope and hence is an orientation parameter. As events with small alpha point towards the source position, it is one of the most powerful parameters for the γ-hadron separation. Gamma ray showers usually have a small value of alpha, while hadron showers have a random probability distribution for alpha

6.   Asymmetry (As)

It is a measure of the symmetric shape of the image. The γ-ray images should have tails which preferentially point away from the source position. This is due to the development of the air-shower. Towards the source, the density of photons is higher, and this results in a higher image density towards the center.

7.   Concentration or Frac2 (F2)

Ratio of the two largest pixel signals to the sum of all the signals. It represents the degree of light concentration and hence is a measure of the compactness of the image.

8.   Miss (M)

The perpendicular distance of the major axis of the image from the center of field of view of the camera. It is a measure of the shower orientation.

9.   Azimuthal Width

The RMS angular size along a line, which is perpendicular to the line joining the image centroid to the center of field of view. It is a measure of both the shape and the orientation of the image.

10.   Azimuthal Angle (ϕ)

It is the angle made by the image's major axis with the defined x-axis of the camera.

11.   Number of Pixels

Total number of PMTs left after the image cleaning which have non-zero count values and are part of the image is the no. of the pixels of the image. It helps in determining the credibility of the image obtained.

VI. DATA ANALYSIS

A.   Obtaining Gamma Domain

1.   Length cuts

If the length of the image is too small then it may correspond to an electronic cascade. Hence a lower limit is put. If the mage length is loo large then it may correspond to cosmic ray because the spread of γ-ray is small. Hence an upper cut also exists.
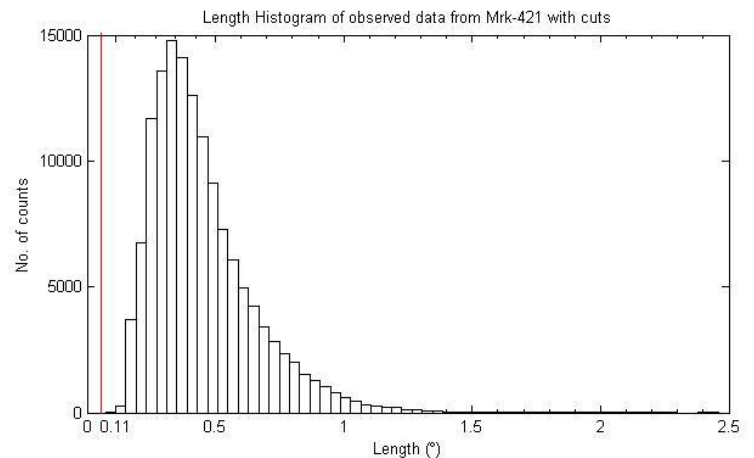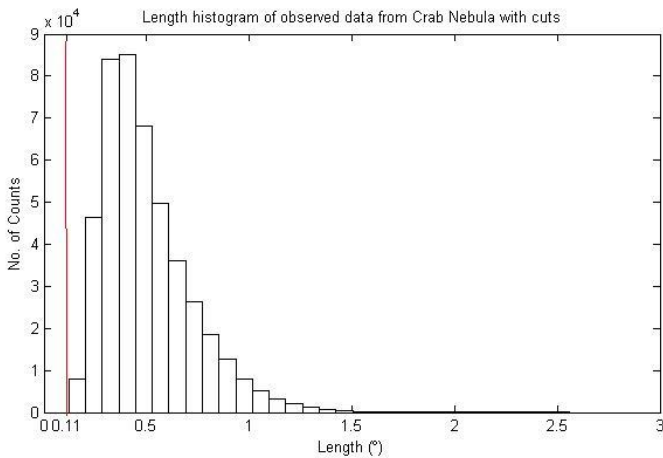
Following cuts were applied to observed data:-

Crab-	Lower cut-0.11	Upper cut-0.0.1+0.052*log(size)
Mrk421-	Lower cut-0.11	Upper cut-0.235+0.265*log(size)

2.   Width cuts

If the width of the image is too small then it may correspond to electronic cascade. Hence a lower cut is put. If the image is too large then it corresponds to a cosmic ray because the spread of a γ-ray is small. Hence a upper cut must also exist.
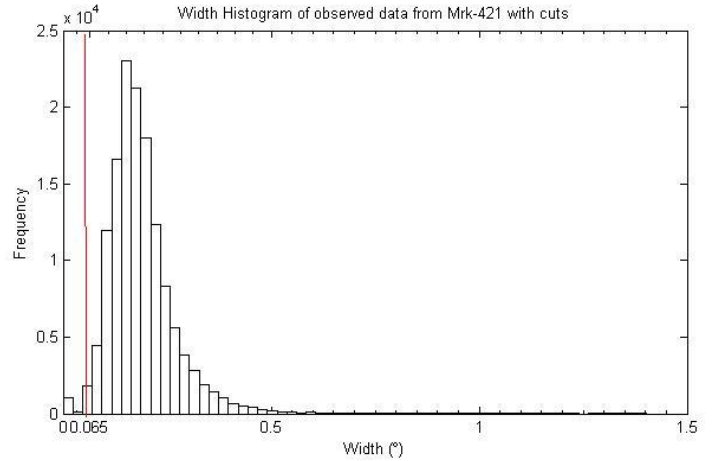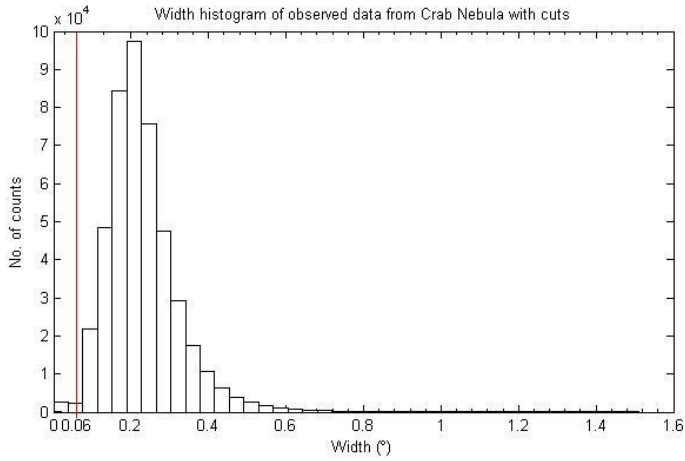
Following cuts were applied to observed data:-

Crab-   Lower cut- 0.06   Upper cut- 0.085+0.016*log(size)
Mrk421-   Lower cut- 0.065   Upper cut- 0.085+0.012log(size)

3.   Length and Width Ratio

Since the cascades due to gamma rays is more compact with respect to cosmic ray cascades, we can comfortably apply a lower cut to select gamma rays preferably.
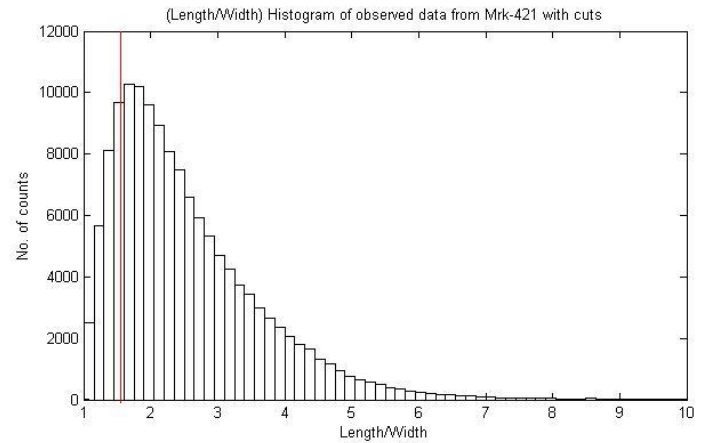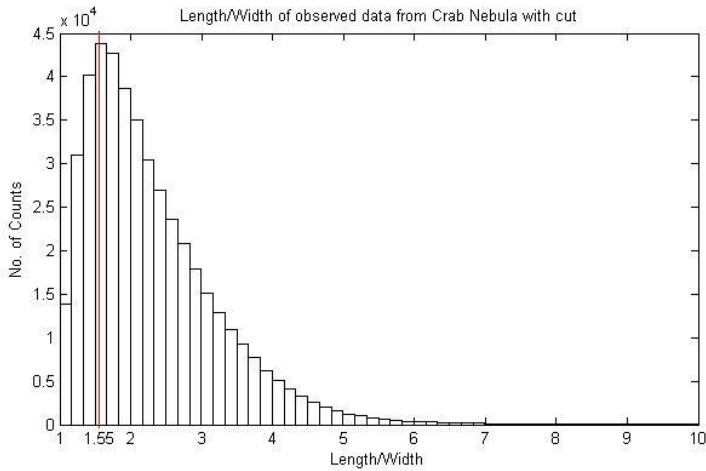
Following cuts were applied to observed data:-

Lower cut-   Crab- 1.55   Mrk421- 1.55

4.   Size cuts

Very small size of the image implies a weak signal. Weak signal increases the uncertainty of the cascade to be a gamma or cosmic ray generated or a cascade at all. Hence a lower cut is applied on the size of the image.
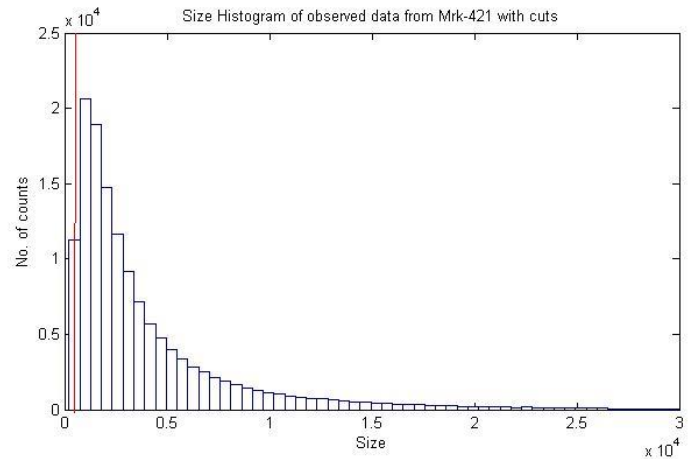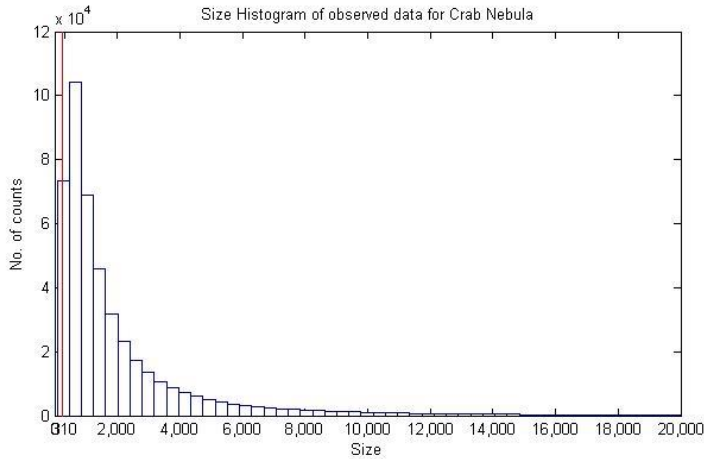
Following cuts were applied to observed data:-

Lower cut-   Crab- 310   Mrk421- 485

5.   Distance cuts

If the image is too close to the centre of the camera the γ-ray shower is pictured as a almost circular image. Under such conditions it becomes difficult to differentiate b/w a γ-ray and a cosmic ray. Therefore a lower cut is put on this parameter. If the distance is too large then some of the information may be lost. So even an uppercut exists which depends on the zenith angle.
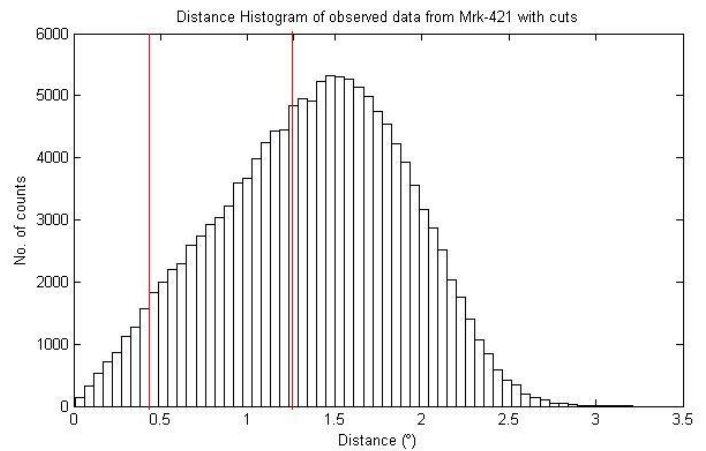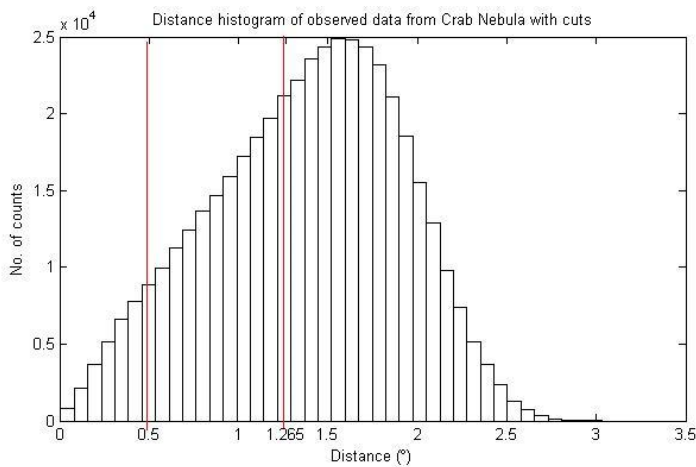
Following cuts were applied to observed data:-

Crab-   Lower cut- 0.5   Uppercut- 1.27*(cos(zenith angle))^0.95
Mrk421-   Lower cut- 0.5   Upper cut- 1.27*(cos(zenith angle)^0.88

6.   Frac2 cut

The cosmic ray cascades emit their secondary products at a wider angle in comparision to gamma ray EAS. Hence, the gamma ray cascades are more compact than cosmic ray cascades.
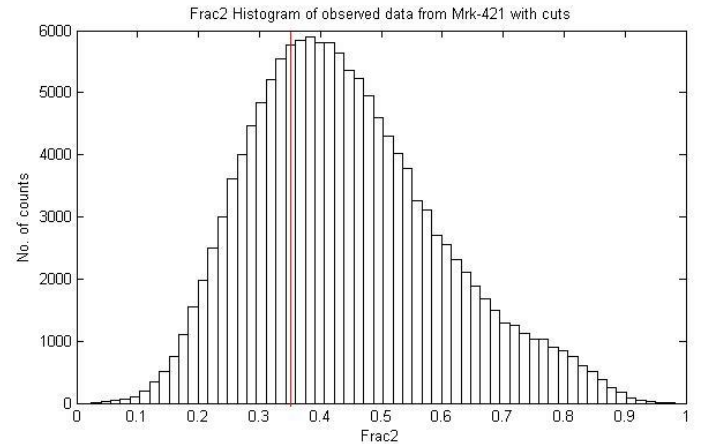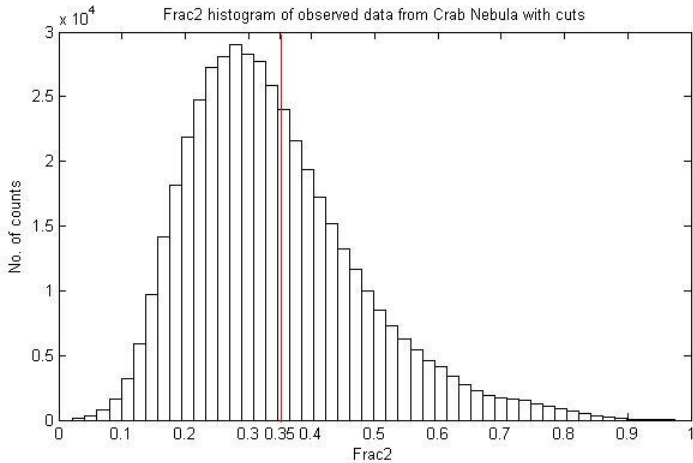
Following cuts were applied to observed data:-

Lower cut-   Crab- 0.35   Mrk421- 0.38

7.   Number of Pixels

If the number of pixels of an image is too less, it is most probably something less rather than a cascade. Hence we apply a lower cut on this parameter to ensure that a meaningful image is studied.
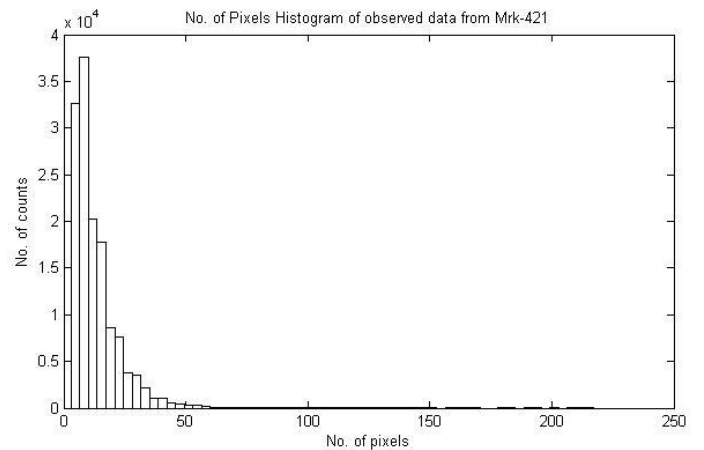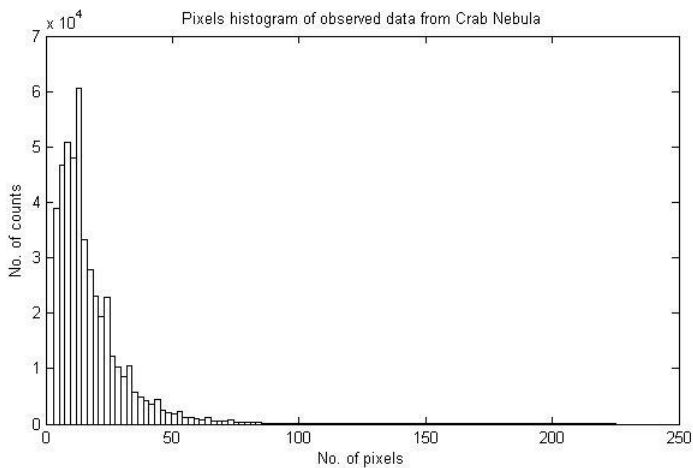
Following cuts were applied to observed data:-

Lower cut-   Crab- 4   Mrk421- 4

8.   Asymmetry cut

The γ-ray images should have tails which preferentially point away from the source position. Thus there must be a lower cut for asymmetry. This cut also depends upon the size if the image.
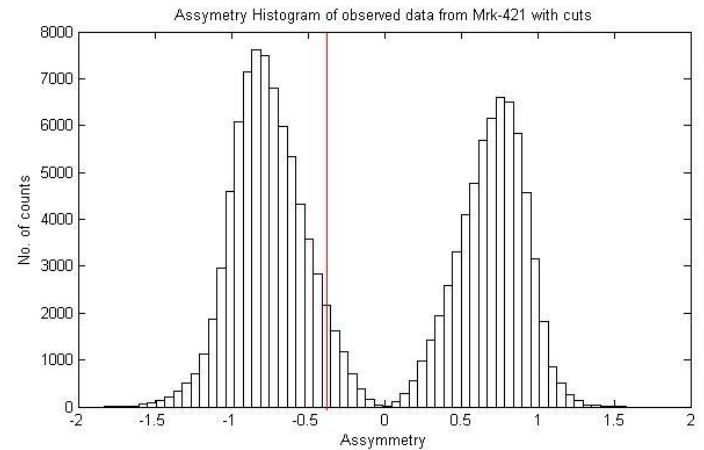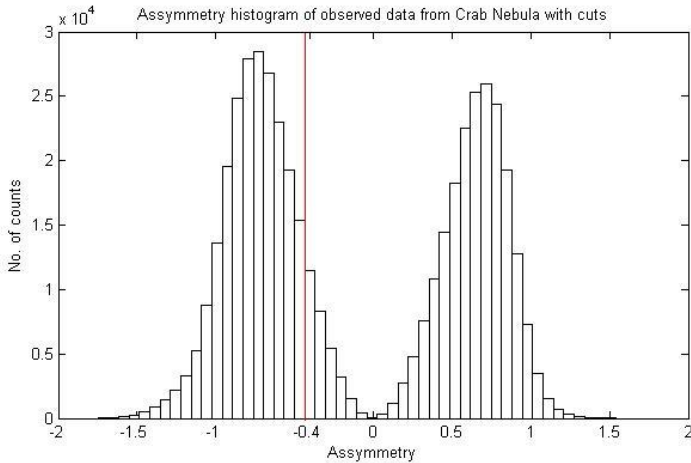
Following cuts were applied to observed data:-

Crab-   Lower cut- -0.4 if size > 360   -1.3 if size < 360
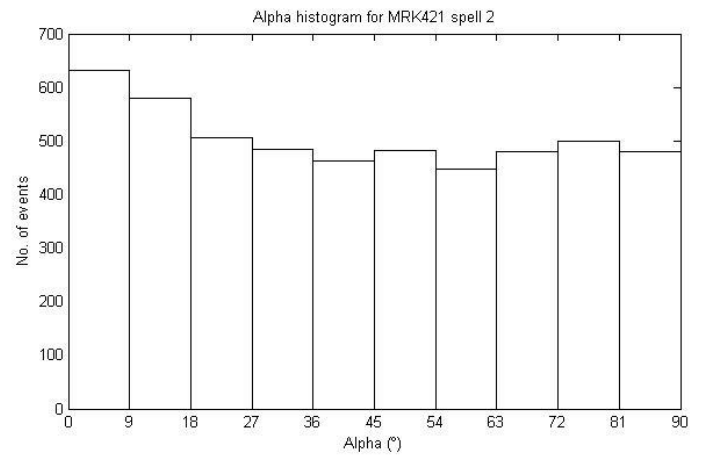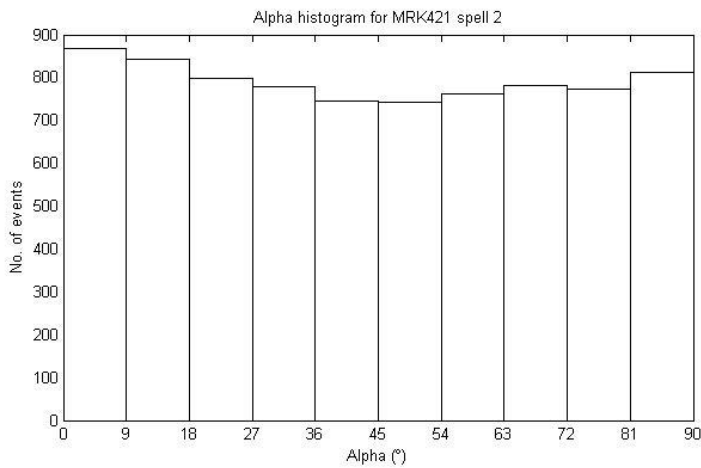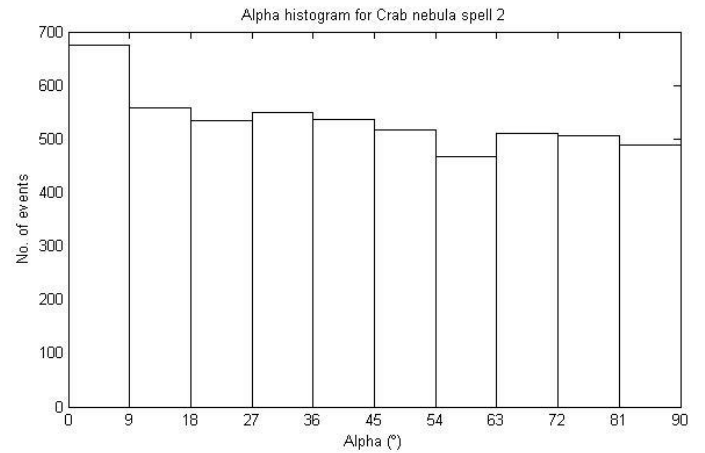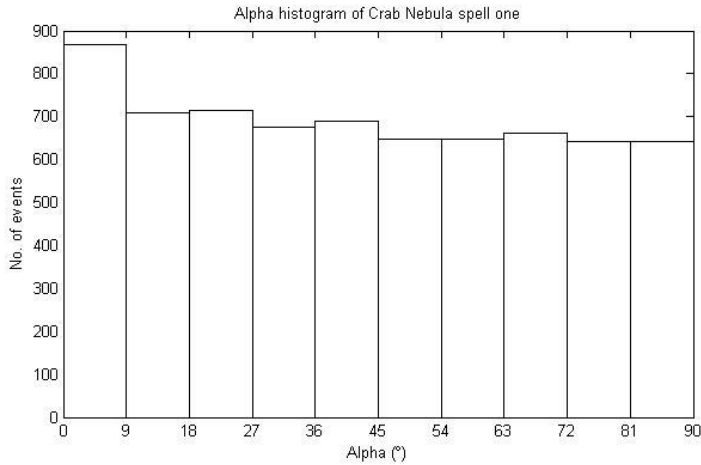Mrk421-   no cuts applied

9.   Alpha cut

Since we preferably point our telescope to the source, the alpha angle for the gamma rays coming from the source must have small alpha of their cascade images taken by the telescope. Hence during signal estimation, we take cascades with alpha less than 18 degrees only.

B.   Signal estimation

The signal that is obtained from the source (Mrk-421) is estimated by a series of processes, and by finding the no. of gamma ray counts, we find the significance of the signal. If the significance is greater that 5σ (where σ is the standard deviation of the data), then our signal is accepted, and is said to have a sufficient accuracy.

For removing the cosmic background noise, we apply a series of cuts on the image parameters, which are obtained through Monte-Carlo simulations, and have been discussed in Section VI.A

Once these cuts are applied, the alpha values of the accepted events are plotted on a histogram against frequency (no. of events per bin). Alpha values are divided in 10 bins, each of 9° length, and the no. of events per bin is noted.

Alpha histogram of Crab Nebula spell one

Alpha histogram for Crab nebula spell 2

Alpha histogram for MRK421 spell 2

Alpha histogram for MRK421 spell 2

From the histogram, it is apparent that the first two bins have higher no. of counts compared to the other bins. For gamma ray events, the alpha values are small, as they point towards the camera center, and as such would lie within the first two bins. Also, alpha values for cosmic ray showers have an equal probability distribution and would be present equally in all bins.

We define N_{on} as the no. of events in the first two bins. N_{on} contains both the observed gamma ray counts and the cosmic ray events.

$$N_{on} = \sum_{i=1}^{2} bin(i)$$ where bin(i) is the no. of events in the ith bin.

We define N_{cosmic} as the average no. of cosmic ray events per bin. For doing this, it is presumed that for values of alpha between 27 degree ([4th] bin) and 81 degree (9th bin), only cosmic rays are present.

$$N_{cosmic} = \frac{\sum_{i=4}^{9} bin(i)}{6} = \frac{N_{cosmic\ total}}{6}$$

N_{off} is defined as the total no of cosmic ray events in the first two bins.

$$N_{off} = 2N_{cosmic} = \beta . N_{cosmic\ total} \qquad \text{where ß is the normalisation factor.} \quad \beta = \frac{1}{3}$$

So, the total no. of gamma ray events, $Excess = N_{on} - N_{off}$
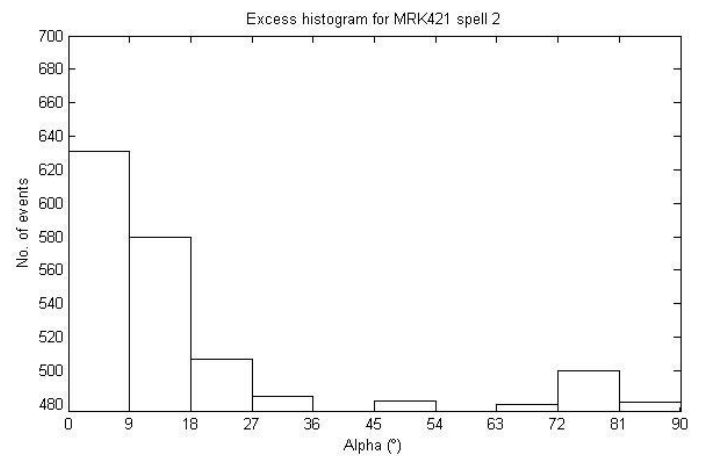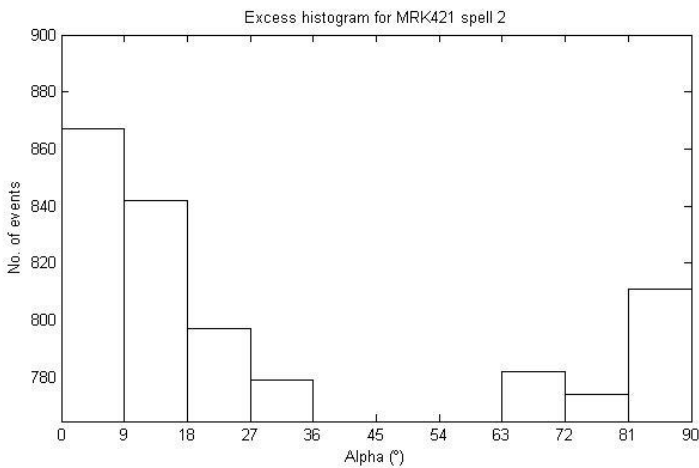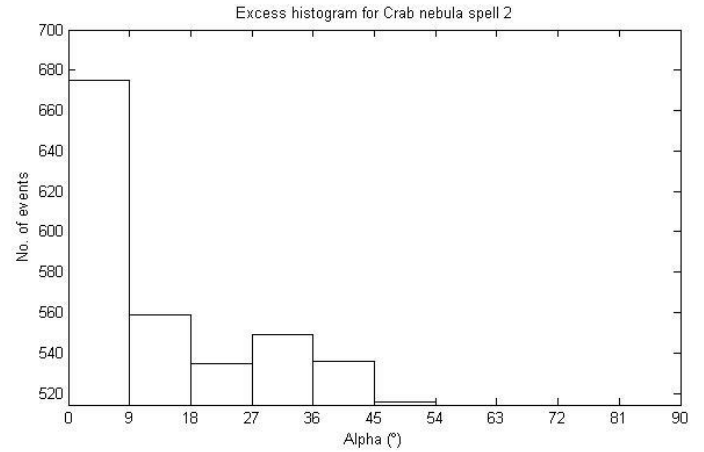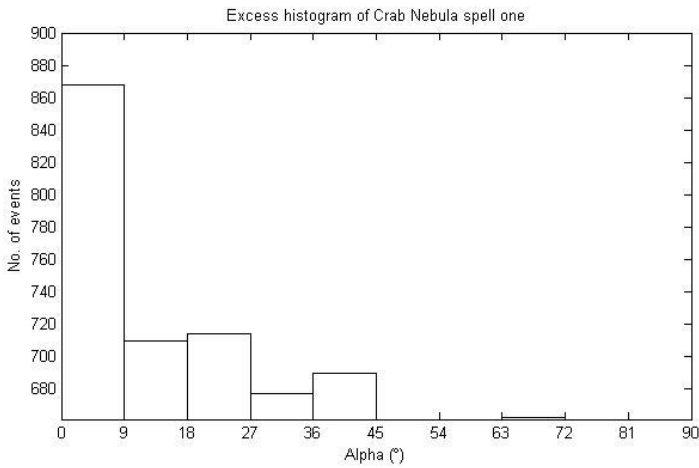
Also, the error in N_{on}, $\Delta N_{on} = \sqrt{N_{on}}$

And the error in N_{off}, $\Delta N_{off} = \sqrt{N_{off}}$

We define the significance of our observation, $N_\sigma = \dfrac{Excess}{\sqrt{(\Delta N_{on})^2 + \beta . (\Delta N_{off})^2}}$

If our significance, N_σ is greater than 5, then the observation has some meaning, and it has sufficient accuracy. This shows that the signal is not due to fluctuations in the cosmic ray background, but is due to our gamma source. We claim detection at this point.

For the data observed, we found following sigma values:-

Crab Nebula: Spell1: 5.6845   Spell2: 5.1708
MRK421:   Spell1: 3.8214   Spell2: 6.6251

C. Light Curve

Temporal distribution of the flux of the gamma ray source reveals important information about the source. To get this temporal distribution, the number of excess events or photons per hour are plotted against the mean Modified Julian Date of the observations. This plot is known as Light Curve for the source.
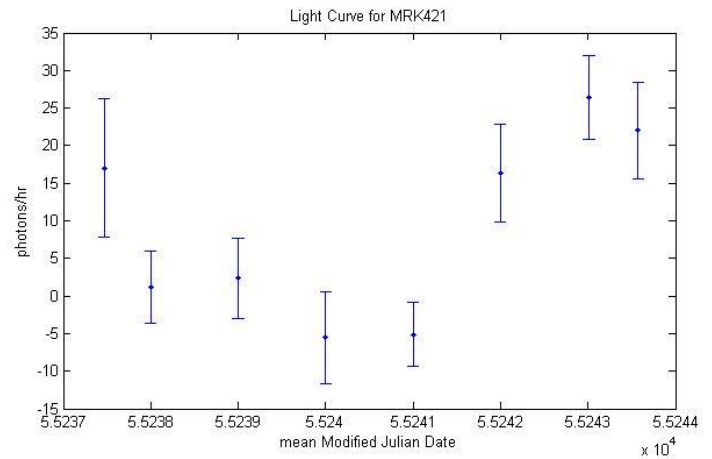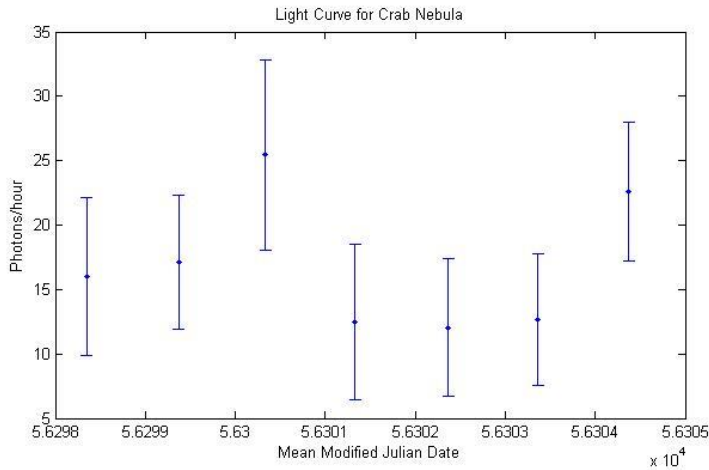
The light curves shows that Crab Nebula is a steady source of gamma rays while MRK421 shows high variations (flares) in gamma ray emission. This can be attributed to the difference in the emission process of the gamma rays in the two sources.

VII.   FUTURE SCOPE OF THE PROJECT

Gamma ray telescopy is a vast and emerging field and cannot be encapsulated in a two weeks project. As the time goes one, new and larger telescopes are being installed all around the globe which are expected to observe more gamma ray sources.

One field where we are currently not satisfied with the present telescopy method is the image processing part. It is believed that with more analysis more efficient ways of cleaning the image captured by the camera can be devised.

Further, the new arriving telescopes (e.g. MACE) requires rebuilding the data analysis packages to ensure efficient use of them and lowering the energy threshold for detection of incident gamma rays.

Along with present methods for modeling the images obtained of the cascades and filtering gamma ray EAS images from them, Artificial Neural Networks are expected to produce better results with more development of the algorithm.

The flux density curves obtained using these telescopes provides good information about the Extra galactic Background Light present it universe due to its effect on the gamma rays. As the astronomy in this field is developing, more bleak and distant gamma ray sources (Z=0.56 & Z=0.61) have been found forcing us to rethink on our models which earlier predicted shorter gamma horizons for the universe.

Further, the gamma ray telescopy is providing necessary data to verify the various models explaining the mechanisms of energy extraction from the compact objects in Active Galactic Nuclie. The telescopy is able to estimate more parameters about these objects like size of particles in jets, angular momentum, density of surrounding cold material etc.

VIII.   ACKNOWLEDGEMENT

IX. BIBLIOGRAPHY

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