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Review Article

Ground-based TeV γ-ray Astronomy in India - Historical Perspective and Recent Developments

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A short historical account of TeV γ-ray astronomy in India is presented. Special attention is given to the development of experimental techniques *vis-a-vis* world-wide development of the field.

Key Words: Gamma-Ray Astronomy; VHE Gamma-Rays; Atmospheric Cherenkov Technique; Cosmic-Ray Origin; Non-Thermal Radiation

Introduction

Earth's atmosphere is opaque to celestial γ-rays as they are copiously absorbed in it. They are detected using instruments onboard spacecraft and high altitude balloons. However, at higher energies these γ-rays can be indirectly detected at ground level. In fact, continuously diminishing intensity with energy (falling energy spectrum), limited detector size (area & weight) and exposure etc. make the ground-based technique the only viable method at energies higher than about 100 GeV.

Very high energy γ-rays and cosmic-rays produce electromagnetic (E-M) cascades in the atmosphere known as Extensive Air Showers (EAS). Relativistic electrons and positrons form the main components of these air showers. The charged particles present in this cascade are responsible for the emission of Cherenkov radiation by air as they propagate down the atmosphere. This radiation is coherent, beamed in the forward direction and can be detected at ground level during moonless clear nights. The effective collection area of over 10^4 m^2 offered by this technique cannot be realized in space as of now. Ground-based γ-ray astronomy is carried out through the detection of Cherenkov radiation produced in the atmosphere by the relativistic charged particles of the E-M cascade initiated by the primary γ-ray. Cosmic-rays constitute the main background of noise limiting the minimum measurable γ-ray flux.

The initial motivation for γ-ray astronomy was to search for sources of cosmic rays which are progenitors of γ-rays. The origin of cosmic rays has been a perplexing issue since its discovery in 1912 by Victor Hess [1]. γ-ray astronomy has its origin in a prophetic paper by Phillip Morrison in 1958 [2], who painted a hopeful picture of the prospects of observing high energy radiation from astrophysical sources in ~ 100 MeV region. However the flux of γ-rays turned out to be woefully much lower than the predictions. The development of the field had to wait for the advent of newer technologies. In regard to ground based observations, it was Cocconi [3] who first proposed to search for γ-ray sources as a narrow-angle anisotropy in the distribution of extensive air showers. Though this idea was not realized in its original form, it stimulated further attempts to use

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angular anisotropy as indirect evidence of presence of γ-ray sources. The detection of Cherenkov radiation in EAS, originally discovered by Galbraith and Jelly in 1952 [4], offered one such possibility. The first dedicated experiment using ground-based atmospheric Cherenkov technique was conducted at Katsiveli, Crimea in 1960-63 with a purely negative result [5]. This technique finally got established with the detection of the Crab nebula by the Whipple group, who pioneered the imaging atmospheric Cherenkov technique [6].

In India ground-based γ-ray astronomy was pioneered by a group from the Tata Institute of Fundamental Research (the TIFR group) led by Prof. B.V. Sreekantan and P.V. Ramanamurthy who plunged into this field as early as 1969. Another group from Bhabha Atomic Research Centre (the BARC group), led by Dr. H. Razdan and late Dr. C.L. Bhat also actively pursued this field.

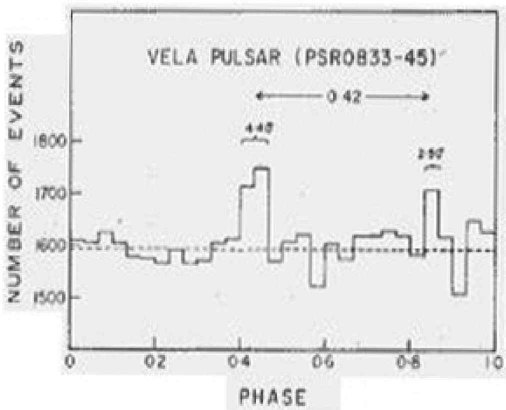
Over the years the concerned groups have improved the sensitivity of their setups and lowered the γ-ray energy threshold by constantly upgrading their telescopes. At present an array of 24 telescopes operates at Pachmarhi to detect Cherenkov showers through wave-front sampling technique while another 4 element array operates at Mt. Abu and uses the imaging technique for the detection of γ-rays. The threshold energy of primary γ-rays that trigger these set-ups is about 1 TeV. Till recently only a few γ-ray sources were detected at these energies where as the satellite-based EGRET has detected about 270 sources at energies below 10 GeV. With the advent of new ground based systems of high sensitivity the number of TeV sources detected has increased substantially during the last few years. Efforts are also being made world-wide to reduce the energy threshold of ground-based set-ups to a few tens of GeV. In this direction, plans are being implemented for new generation experiments in India using the high altitude and low night sky background of a site in the Himalayas to advantage. A 7 element wavefront sampling telescope, HAGAR (High Altitude GAmma Ray telescope), has been recently commissioned at Hanle (32^o.8N, 78^o.9E, 4200m altitude) and work on the 21 m diameter Cherenkov imaging telescope, MACE (Major Atmospheric Cherenkov Experiment), has also been initiated there. The MACE telescope which will have a trigger threshold of ~30 GeV is scheduled to be fully operational in 2015.

Early History

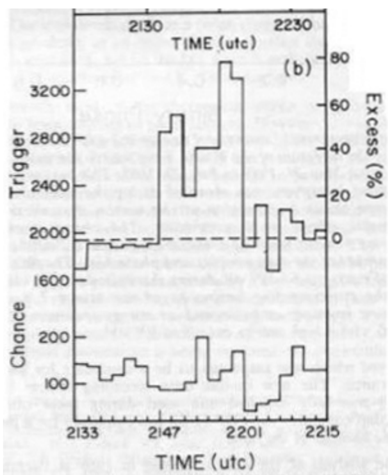
The TIFR group started the field of ground-based γ-ray astronomy in India in 1969, soon after the announcement of the discovery of pulsars in 1968. Pulsars were proposed to be the site of origin of high energy cosmic rays and hence the sources of ultra high energy γ-rays. They searched for pulsed emission of γ-rays from 6 pulsars with the same periodicities as observed at radio frequencies [7]. The Cherenkov light was detected by 2 large search light mirrors (f/ 0.45 mirrors of 90 cm dia) which focused it onto fast (56 AVP) photo-multipliers (PMT) placed at their foci as shown in Fig. 1(a). The full field of view of each mirror was 3^o. The approximate collection area of high energy γ-rays was 3×10^4 m^2 and the threshold energy of detection ~10 T eV. The mirrors, mounted on an orienting platform, tracked each pulsar for about

(a) Mukurthi (b) Ooty (c) Pachmarhi

Fig. 1: Early compact arrays



(a) Phasogram of events from Vela pulsar



(b) Burst from Her X-1

Fig. 2: Results from the Ooty and Pachmari arrays

Fig. 3: Set-up of 6 telescopes at Gulmarg

Fig. 4: One of the telescopes of PACT array (2 of the remaining 24 telescopes are seen in the background)

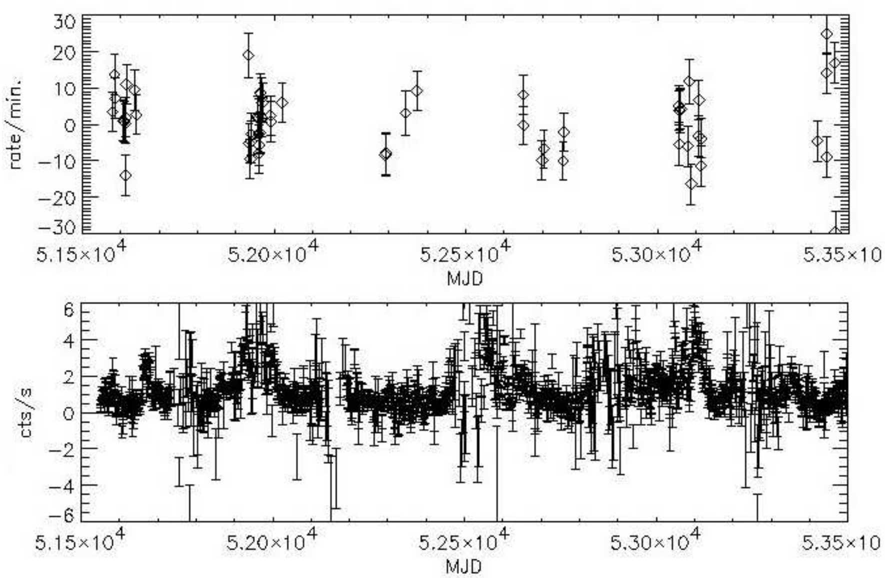


Fig. 5: PACT results on daily average γ-ray rate per minute for Mrk 421 (*upper panel*) and daily average X-ray photon rate per second obtained by the All Sky Monitor (ASM) on board RXTE satellite (*bottom panel*) for circa 2000 to 2005

an hour when it was close to its meridian transit. Observations were made on clear moonless nights in the years 1969 and 1970 at Mukurthi located at an altitude of 2200 m above mean sea level in the Nilgiri Hills in South India. Not having found any significant flux of γ-rays from any source they placed upper limits on the flux of γ-rays of the order of 10^{-11} photons per cm^2 *per s* [8].

This activity was revived after a hiatus of 5 years with more number of mirrors and improved detection methods. For 10 years, an array of Cherenkov telescopes with a total mirror area of about 20 m^2 was operated in and around Ooty (now called Udhagamandalam) in South India (76°.71E, 11°.42N, 2300 m altitude). A photograph of the set-up is shown in Fig. 1(b). This set-up was moved in the year 1986 to Pachmarhi (22°.47N, 78°.43E, 1075 m altitude) in the state of Madhya Pradesh, in central India, where the sky conditions for night sky observations are better than at Ooty (Fig. 1(c)). A very systematic search for pulsed emission of γ-rays was made on a number of isolated pulsars [9] and X-ray binaries [10] using these set-ups at Ooty and Pachmarhi. Crab, Vela (Fig. 2(a)), PSR0355+54, Geminga and Her X-1 (Fig. 2(b)) showed positive signals on several occasions [11, 12, 13, 14, 15, 16, 17].

The BARC group started observing the night sky in the mid seventies at Gulmarg in North India (34°.5N, 74°.3E, 2743 m altitude) using two bare faced PMTs (EMI 9545B) separated by 1 m and pointing vertically upwards to the sky (which may be likened to a wide angle telescope with a viewing angle of 50° w.r.t. zenith) in the drift scan mode. In this mode the telescope is kept stationary, and the sky is scanned as the Earth rotates. They reported [18] a non-random component in the arrival times of cosmic ray events for time separation of < 40 s. Later following the TIFR group, they too installed [19] a similar set-up at Gulmarg, consisting of 6 equatorially mounted parabolic search light mirrors of 0.9 m diameter divided into 2 banks of 3 mirrors each. This set-up which is shown in Fig. 3 was operated during 1984-89. Using this system they observed a few X-ray binaries (Cyg X-3, Her X-1, 4U0115+63), pulsars (Geminga, PSR 0355+54) and cataclysmic variables (Am Her) and other sources [20, 21, 22]. More details of the historic account of the above activities are documented in literature [23, 24].

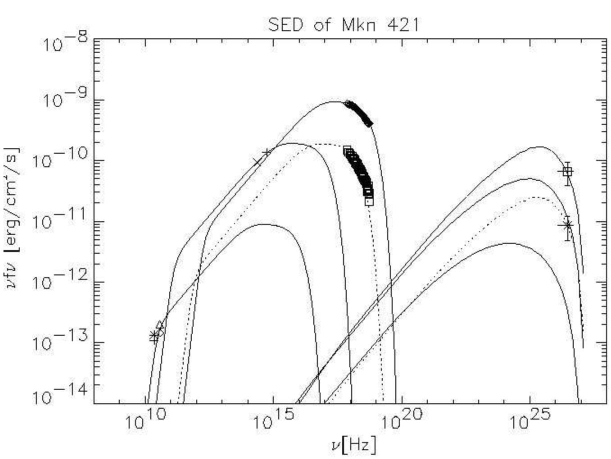


Fig. 6: SED of Mrk421 during 2001 (*flare state*) and 2003 (*quiescent state*). SSC fits for both these states are shown by *solid* and *dotted* lines respectively. Three one-zone SSC models are used to fit X-ray optical and radio data in each case

Present Set-Ups

The detection of atmospheric Cherenkov showers was initially carried out using 2 complimentary methods. In one method, the lateral distribution of Cherenkov photons is sampled while in the other method, the image of Cherenkov light in the atmosphere is obtained at the focal plane of the telescope with an array of photo detectors, essentially sampling the longitudinal development of the shower. The former method is known as the wave-front sampling method while the later is referred to as the imaging technique. The new generation of ground-based set-ups like HESS, MAGIC, CANGAROO and VERITAS adopt both these techniques by forming an array of imaging telescopes. Such telescopes sample both longitudinal and lateral development of the shower and have become powerful tools in the exploration of very high energy γ-ray universe [25].

1 PACT, the Wave-Front Sampling Array at Pachmarhi

The upgraded Pachmarhi Array of Cherenkov

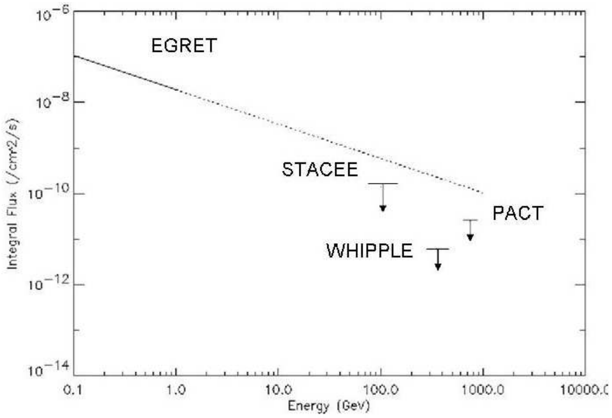


Fig. 7: 3σ Upper limits on the flux of TeV -rays from ON231 as obtained by PACT, Whipple, STACEE groups. The *solid line* is the energy spectrum as measured by EGRET and the *dotted line* is the extrapolation of GeV spectrum to TeV energy

independently steerable (±45° in E-Wand N-S directions). The movement of telescopes is remotely controlled by an automated telescope orientation system [27]. High voltages of individual PMTs are controlled through a computerized automated rate adjustment and monitoring system. The array is divided into 4 sectors of 6 telescopes each with an independent data acquisition system for each sector. The analog signals from 7 PMT's of a telescope are linearly added to form a telescope trigger pulse. A coincidence of any 4 telescope pulses initiates the data recording in each sector. A real time clock (RTC) synchronized with a GPS clock records the absolute arrival time (up to μs) of the Cherenkov flash. Data regarding 'timing' and 'amplitude' (Charge) of PMT

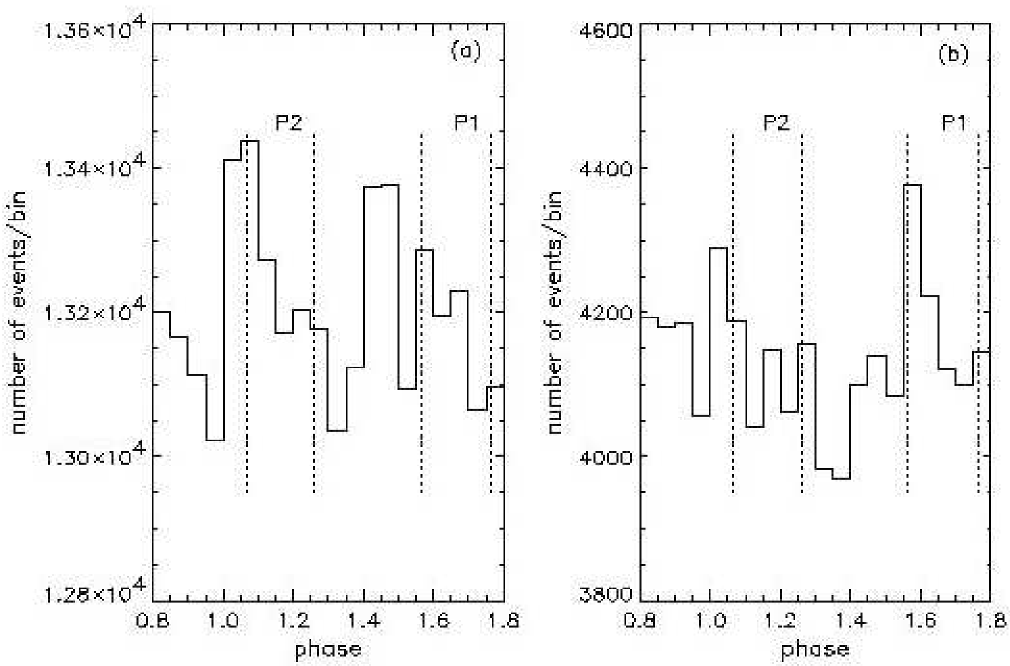


Fig. 8: Phase histogram for Geminga pulsar events (a) space angle (ψ) < 2.5° and (b) ψ < 1.0°

Telescopes (PACT) was comissioned in the year 2001. It consists of 25 Cherenkov telescopes arranged as a 5×5 matrix spread over an area of 80m × 100m [26]. Each telescope consists of 7 parabolic F/1 mirrors of 90 cm diameter made from 6mm thick float glass. Each mirror is viewed by a fast PMT (EMI 9807B) at its focus with 3° field of view. The total reflector area of each telescope is 4.45 m^2. Each telescope is on an equatorial mount and is pulses are recorded for each event together with telescope information using a CAMAC based system operating on a Gnu/Linux platform. Digital informations like the arrival time of photons at the telescopes, trigger status, event arrival times etc. from all 4 sectors are also recorded in the central control room. A portion of PACT is shown in Fig. 4. PACT has an energy threshold of ~ 800 GeV for γ-rays incident in the vertical direction and the

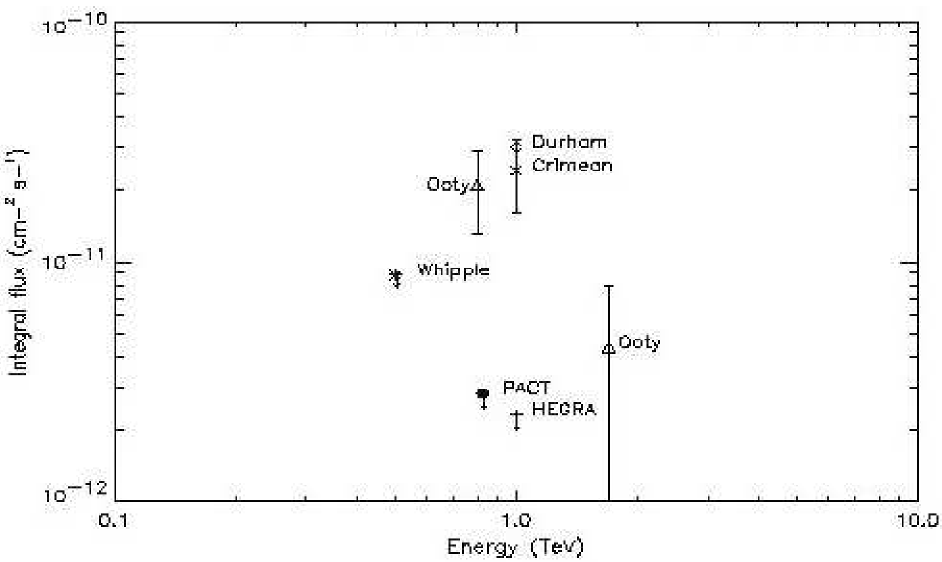


Fig. 9: Prior results on the pulsed flux of γ-rays from Geminga pulsar and the PACT results

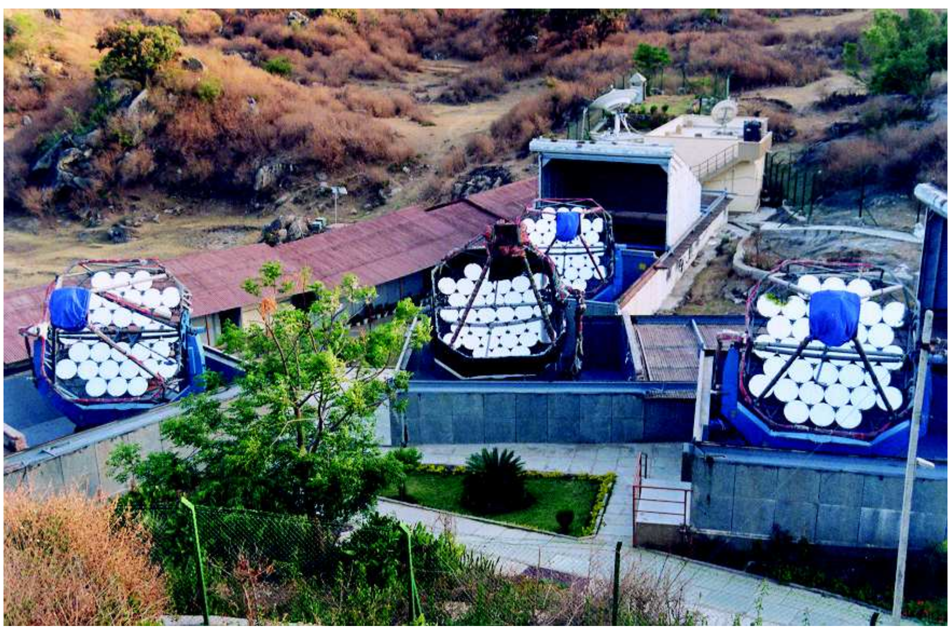


Fig. 10: The 4 element Imaging Telescope system TACTIC at Mt Abu

to obtain the direction of arrival of shower for each event. Thus 'space angle' between the direction of arrival of the shower and the source direction is obtained for each event. Cuts are applied on the number of telescopes with valid 'timing' data as well on the quality of fit parameter (using χ^2 for the fit).

Observations on AGNs like Mrk 421, Mrk 501, 1ES 1426+428, ON 231 etc. were carried out using PACT [28, 29]. The PACT result on daily average γ-ray rate per minute is shown for Mrk 421 in Fig. 5 along with daily average X-ray photon rate per second obtained by the All Sky Monitor (ASM) on board RXTE satellite for circa 2000 to 2005. The Spectral Energy Distribution (SED) of Mrk421 during flaring and quiescent states were studied in detail. A comparison of SEDs during these two states of Mrk421 is shown in Fig. 6.

corresponding collection area is ~10^5m^2. The observations are usually carried out in a stretch first either ON-source and followed by OFF-source region or *vice versa* during the same night. The OFF-source region is chosen to have the same declination as that of the source but offset in RA such that same zenith angle range is covered for both ON-source and OFF-source runs. Typical run duration is about 1 to 3 hours. Data with all telescopes pointing to the zenith is used for calibration purposes. The relative time of arrival of Cherenkov photons is fitted to a plane shower front

Three one-zone SSC models are used to fit X-ray, optical and radio data in each case. The TeV upper limits of ON231 as obtained by PACT and other telescopes are depicted in Fig. 7.

Search for TeV γ-rays from Geminga Pulsar was carried out during the six year period spanning 2000-2006 using the PACT [29]. No evidence for pulsed emission of γ-rays was seen in the long stretch of data at a threshold energy of 825 GeV. The light curve of Geminga pulsar is shown in figure 8 and the flux

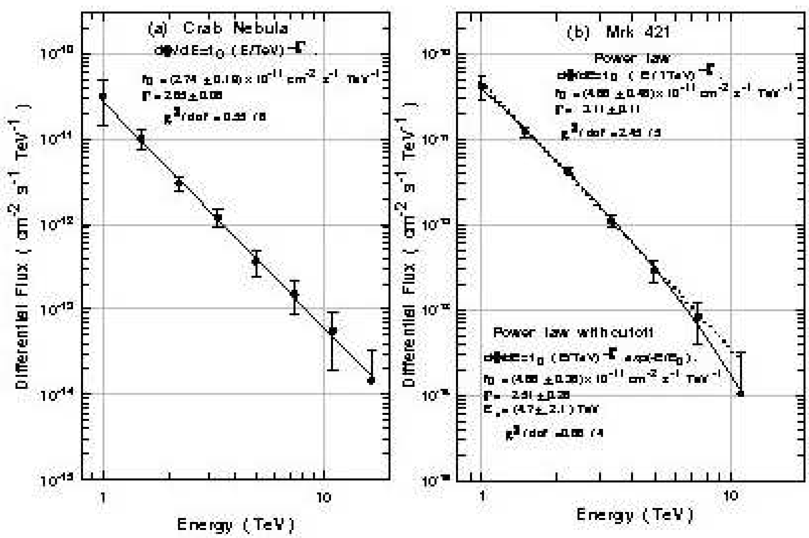


Fig. 11: (a) The differential energy spectrum of the Crab nebula as measured by the TACTIC telescope. (b) Differential energy spectrum of Mrk 421 for the data collected during Dec. 27, 2005-Feb 07, 2006

upper limits in Fig. 9.

2 TACTIC, the Imaging Telescope at Mt. Abu

The BARC group also moved to a better site than Gulmarg and set up an imaging telescope called TACTIC (TeV Atmospheric Cherenkov Telescope with Imaging Camera) at Mt Abu (24^o.62N, 72^o.75E, 1257 m altitude) in 1997. The 4 element array, shown in Fig. 10, is arranged in a triangular configuration (one element at the centroid and 3 elements at the vertices of an equilateral triangle of side 20 m). The telescope deploys a F/1 type tracking light collector of ~9.5 m^2 area made up of 34 x 0.6 m diameter, front coated spherical glass facets which have been pre-aligned to produce an on-axis spot of ~0^o.3 diameter at the focal plane. The central imaging telescope uses a 349-pixel, PMT (ETL 9083UVB) based imaging camera with a uniform pixel resolution ~0^o.3 and a field of view ~6^o x 6^o to take a fast snapshot of the atmospheric Cerenkov events produced by an incoming cosmic-ray particle or a γ-ray photon with an energy above 1 TeV. The focal plane instrumentation of the vertex elements is designed to study the intensity variation of the Cherenkov events and aid in the segregation of the gamma-ray events from an overwhelmingly large number of cosmic-ray events. The back end signal processing hardware of the telescope is based on in-house developed medium channel density NIM and CAMAC modules. The data acquisition and control system of the telescope has been designed around a network of PCs running the QNX (version 4.25) real-time operating system. The innermost 121 pixels (11 × 11 matrix) are used for generating the event-trigger based on the 3 Nearest Neighbor Non-Collinear Triplets (3NCT) topological logic by demanding a signal ~7 *pe* for the 3 pixels which participate in the trigger generation. The telescope has a pointing and tracking accuracy of better than 3'. The details of the various subsystems of the telescope are discussed in [30, 31, 32, 33].

The Crab nebula has been observed with the TACTIC telescope repeatedly since 2001 for the purpose of its calibration. A strong signal of 960 ± 87 gamma-rays at a statistical significance of ~11σ was detected from ~103 h of observation during 2003-04. The measured energy spectrum is in agreement with observations by other groups.

Mrk 421 was observed for 202 h during Dec 05-April 06 [34] . Flaring activity was detected from the object during the first 97h of observation and a flux of > 1 crab unit was seen on several nights. A time averaged differential gamma-ray spectrum in the energy range of 1-11 TeV was determined and is shown in Fig. 11 along with the Crab nebula spectrum observed during the corresponding period. The TeV light curve as recorded by the telescope is shown in

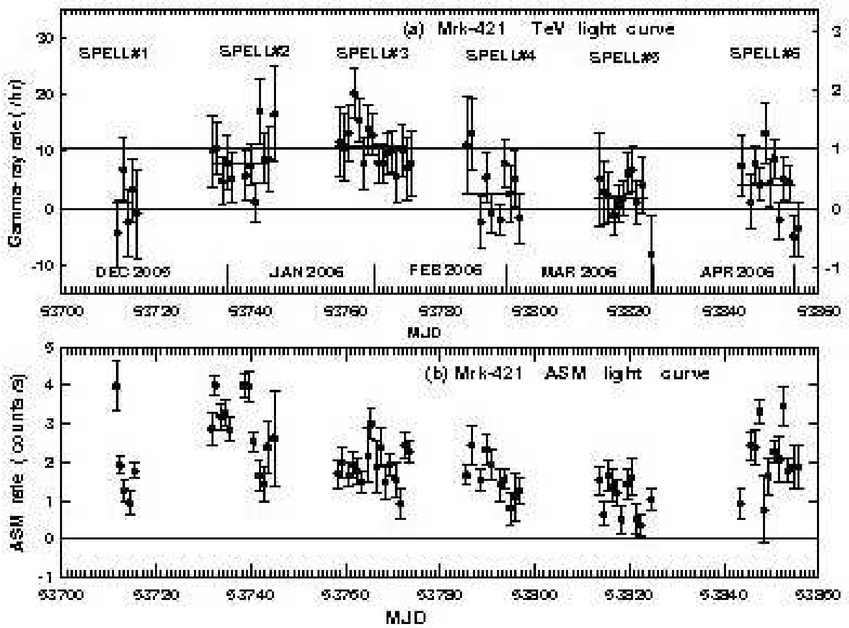


Fig. 12: **(a) Light curve for Mrk 421 as recorded by the TACTIC telescope during Dec. 05-April 06. (b) Daily plot of the average count rate in the 2-10 keV energy range as determined by RXTE/ASM X-ray detector**

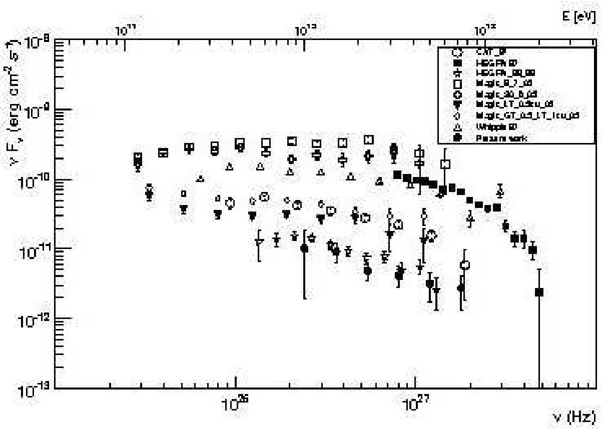


Fig. 13: **Comparison of the TeV energy spectrum of Mrk 501 determined by TACTIC during Feb-May 2006 with those obtained by other telescopes during different epochs**

figure 12 along with the daily plot of the average count rate in the 2-10 keV energy range as determined by the RXTE/ASM detector.

1ES2344+514 was observed for 60h during Oct 04-Dec 05 and an upper limit of < 3.84 x 10^{-12} photons cm^{-1} s^{-1} was determined for the integrated gamma-ray flux at 3σ confidence level [35]. Flaring activity was detected during observation of Mrk501 for 66h during Feb-May 2006. A gamma-ray signal with a statistical significance of 7.5 σ above 1 TeV was detected [36] and the time averaged differential energy spectrum of the object in the 1-10 TeV energy range was determined. This spectrum along with the spectra determined by other telescopes at different epochs are shown in Fig. 13. H1426 +428 was observed for about 244h during 2004-07 and an upper limit of < 1.18 x 10^{-12} photons cm^{-1} s^{-1}on the integrated gamma-ray flux at 3σ significance was determined [37].

The TACTIC telescope has a sensitivity of detecting a gamma-ray signal above 1 TeV at a significance of 5 σ in 25 h of observation. This makes it an ideal instrument for long term monitoring of well established TeV blazers. As discussed above the telescope has been used in this mode for the last few years and has detected flaring activity from Mrk 421 and Mrk 501 on a number of occasions. Attempts are also being made to improve the sensitivity of the telescope by innovative use of the data collected by its 3 vertex elements and use of improved data analysis techniques [38].

Conclusions

Ground based gamma-ray astronomy has been pursued in India for the last four decades. The low sensitivity first generation gamma-ray telescopes were operated in Ooty, Pachmarhi and Gulmarg. After the detection of TeV flux from the Crab nebula by the Whipple telescope the field was pursue vigorously by setting up a larger wave-front sampling array at Pachmarhi and a medium resolution imaging telescope at Mt. Abu. Both these telescope systems have detected flaring activity from extragalactic sources and have led to the acceleration of efforts in the country for setting up of sensitive GeV/TeV telescopes. These efforts have culminated in the recent commissioning of the HAGAR array and the commencement of work for the large area MACE telescope at Hanle. When fully operational in 2015 the observatory at Hanle will have a unique distinction of having a wave-front sampling telescope, an imaging telescope and a 2m optical telescope in one campus.

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