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VHE gamma-ray astronomy experiments in India – Imaging Cerenkov Technique

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Abstract : The recent advances in the field of very high energy (VHE) or TeV gamma-ray astronomy, culminating in the unambiguous detection of several galactic and extragalactic sources, owes itself largely to the successful exploitation of the Cerenkov imaging technique in the mono-and stereo operation modes. In this method, substantially improved detection sensitivities are achieved by recording the two – dimensional Cerenkov light distribution patterns in the focal plane of one or more light collectors and rejecting ≥ 99 % background cosmic ray – initiated events on the basis of their distinct image shape and orientation characteristics. In the present communication, we describe the basic methodology of the Cerenkov imaging technique, particularly in the context of the TACTIC and MACE imaging systems, which are being set up by our group at Mt. Abu, India. The special design features of these two systems and the astrophysical problems likely to be addressed by them will be highlighted in this review.

1. Introduction

Ground-based gamma-ray astronomy, involving the detection of cosmic photons in the 100's of GeV – 10's of TeV energy range through the atmospheric Cerenkov technique, has over the last decade or so graduated into a regular astrophysical window with the potential to provide a new insight into the non-thermal universe (Cronin et al, 1993). Definitive detections have been made of at least 8 gamma-ray sources in the TeV (1TeV = 10^{12} eV) energy range, 3 of which are the closest BL Lac objects of the X-ray loud type (Mkn 421, Mkn 501 and 1ES2344 +514) while the rest are all galactic sources associated with supernova remnants (Ong, 1998 and references therein). The three northern hemisphere sources, namely, the Crab Nebula, Mkn 421 and Mkn 501, have been studied relatively more extensively, leading to some interesting strands of information of significant astrophysical importance. The Crab Nebula, a supernova remnant of the Plerionic (centre-filled) variety has been detected repeatedly by several groups and is justifiably recognised today as the TeV gamma-ray 'standard candle' source owing to its constant TeV gamma-ray flux over a period of several years (Weekes et al, 1989; Weekes, 1992 and references therein). Its differential energy spectrum in the TeV range has been measured with a high level of precision and explained through the synchrotron self-compton (SSC) model where ultra relativistic electrons (≥ 10 TeV), accelerated in the nebula, generate TeV photons by interacting with the background synchrotron photons produced by the same electrons in the nebular magnetic field (de Jager, 1995). The highest photon energy detected from the Crab Nebula (or any other TeV source) is ~ 20 TeV (Amenomori et al, 1997), which is not high enough to be uniquely attributed to a hadron (as against a lepton) progenitor and thus makes it difficult to make a convincing case for cosmic ray origin/acceleration in these sources. The high resolution spectra derived for the extragalactic sources Mkn 421 and Mkn 501, when they are detected in their occasional states of flare activity, also extend upto ~ 20 TeV but deviate from a pure power law and exhibit an exponential cut off in the tens of TeV range, indicating the important role of absorption effects (due to $\gamma - \gamma$ interactions) in the intergalactic space (Stecker, 2000). In fact, there are rather persuasive reasons to believe that observations of extragalactic sources would provide strong constraints on the extragalactic background IR density (Biller et al, 1999) and lead to a model-independent determination of the Hubble constant (Salamon et al, 1994).

A notable disappointment in high energy gamma-ray astronomy has been the non-detection of TeV gamma-ray signals from classical sources like Cyg X-3 and Her X-1 and supernova remnants like IC 443, W44 etc. which happen to be associated with molecular hydrogen clouds and provide the necessary accelerated particle beam plus target combination for gamma-ray production (Weekes,1992 ; Ong, 1998). Similarly, no pulsed emission at TeV energies has been reported from the 6 EGRET – detected gamma-ray pulsars (including the Crab pulsar) or any other radio pulsar despite the higher sensitivity of the Cerenkov imaging technique (Lang et al, 1991 ; Ong, 1998 and references therein). While these new results are in complete disagreement with the positive detections of TeV signals from a number of these sources by the first generation (non-imaging) atmospheric Cerenkov telescopes, (Weekes, 1988), they are in apparent agreement with the recent revised theoretical estimates of high energy gamma-ray signals from these sources (Aharonian et al, 2000). Attempts to detect VHE spectral tails in cosmic gamma-ray bursts have also failed, except for a single possible detection reported from the MILAGRO water Cerenkov detector system (Leonor, 1999).

Most of the reported successful detections in the TeV energy band have come about through the Cerenkov imaging technique, (Fegan, 1996 and references therein) pioneered by the Whipple group in the USA, in which the overwhelming cosmic ray background is sought to be rejected on the basis of subtle differences in the shape and orientation of 2-dimensional Cerenkov images recorded by a matrix of photomultiplier tubes in the focal plane of the light collector (Hillas, 1985). The promise of the imaging technique has been recognised universally and has provided the basic motivation for the design and development of the TACTIC – a 4- element array of TeV atmospheric Cerenkov telescopes with a central imaging element (Bhat et al, 1993). This array is already operational at Mt. Abu and the BARC group is presently engaged in designing and setting up the stereo-MACE system – a 2-element stereoscopic array of high resolution Cerenkov imaging telescopes with 17 m diameter light collectors. An alternative approach, called the wavefront sampling technique, has been followed by the TIFR group at Pachmarhi (Bhat, 2002) with remarkable success. In the present review, we first introduce the Cerenkov imaging technique and then describe the design considerations and present status of the TACTIC and MACE systems. We also briefly describe the important results obtained from the several observational campaigns carried out with the TACTIC imaging element, including the first-ever multi-station detection of Mkn 501 during a flaring state.

2. Cerenkov imaging technique

Imaging Cerenkov telescopes use a matrix of photomultiplier tubes in the focal plane of a large light collector to record the 2-dimensional distribution of Cerenkov photons generated following the initiation of an extensive air shower by a primary gamma-ray or cosmic ray hadron with energy exceeding tens of GeV. The so-called Cerenkov image of the shower is related to both the longitudinal and lateral development of the shower and has a shape which depends on both the impact parameter of the shower (distance of shower core from the telescope) and the nature of the primary progenitor particle (gamma-ray/cosmic ray hadron). The concept of discriminating gamma-rays and cosmic ray protons on the basis of their shower images was first proposed about 20 years back (Weekes and Turver, 1977) and implemented first of all by the Whipple group in 1990 (Cawley et al, 1990). Detailed Monte Carlo simulations have shown that the Cerenkov image resulting from a typical gamma-ray induced shower is compact and roughly elliptical in shape and has an orientation (major axis) which always points towards the centre of the field of view (Hillas, 1985). On the contrary, Cerenkov images resulting from showers initiated by primary cosmic ray hadrons (protons etc.) are bigger in size and irregular in their shape and are randomly oriented in the focal plane due to the isotropic nature of the primary cosmic ray beam. Fig. 1 shows typical gamma-ray and cosmic ray proton-initiated Cerenkov images that would be seen by the TACTIC imaging camera with its pixel

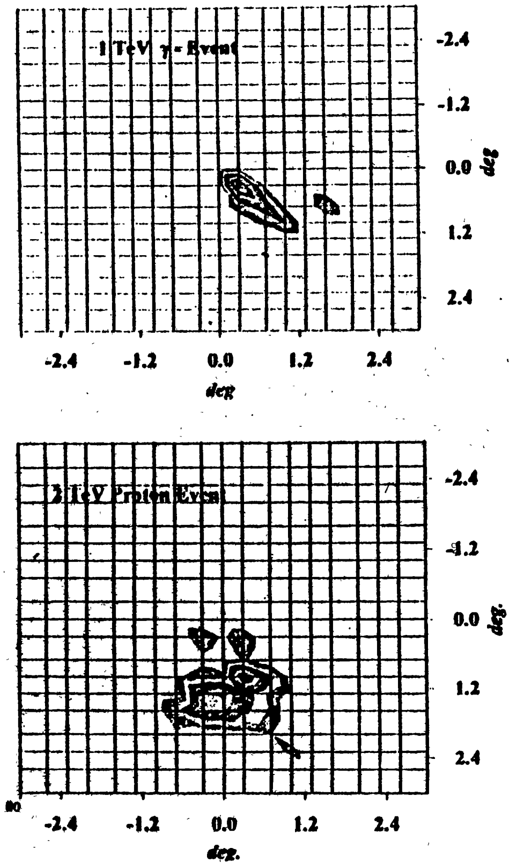

Fig. 1: Typical γ-ray and proton images recorded in TACTIC camera.

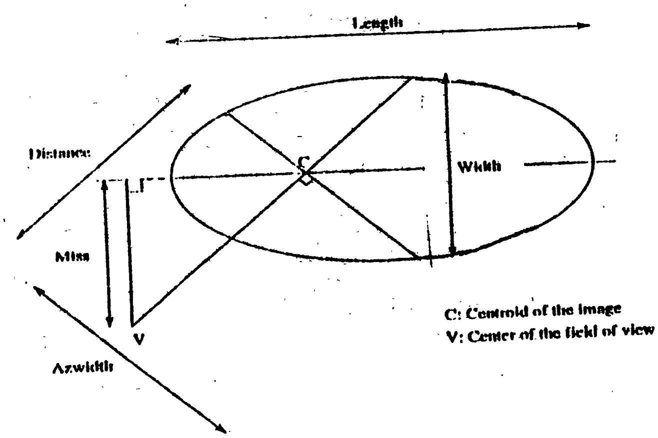

Fig. 2 : Definition of Cerenkov image parameters.

size of 0.3^0. The size and shape of the images is characterised by a set of geometrical parameters, derived from a simple moment-fitting technique. Fig 2 illustrates how the various image parameters are defined. Monte Carlo simulations predict that a clear distinction between gamma-ray and proton – initiated events can be achieved by choosing appropriate domains for all the parameters which preferentially select gamma-ray events while rejecting cosmic ray events at a level of ≥ 99%. Figure 3 shows the distributions for various parameter which are obtained from simulations for the TACTIC system, showing a clear distinction between gamma-ray and proton-initiated events. The improvement in system sensitivity through imaging cuts is quantified in terms of 'quality factor' which is defined as

$$\text{Quality Factor } Q = N\gamma / \sqrt{Np}$$

where Nγ and Np are the fraction of γ-ray and background cosmic ray events respectively retained after imaging cuts. A γ-ray retention factor of 50% and a cosmic ray rejection factor of 99.9% (achievable with first level imaging cuts) leads to a quality factor of Q~ 16, which translates to a factor of ~10 improvement in the γ-ray detection sensitivity of the system. Further optimisation of the detection sensitivity has been sought through the exploitation of the stereoscopic imaging technique (Konopelko, 1995) in which two imaging Cerenkov telescopes separated by distances of the order of 100m record stereoscopic images of the same shower which leads to a resolution of ~ 0.1^0 in the primary arrival direction and provides a factor of ~3 improvement in the detection sensitivity as compared to that obtainable with a single system (Kohnle,1999). The HEGRA stereoscopic system (Ulrich et al, 1998) has already provided several high quality detections of TeV gamma-ray spectra of the sources with an energy resolution of better than 20% (Aharonian et al, 1999). Several new, multi-telescope imaging systems, like the VERITAS (Vassiliev et al, 1999) and HESS (Hoffmann, 1999), are presently in the development stage and are expected to provide interesting new results in the GeV – TeV energy range.

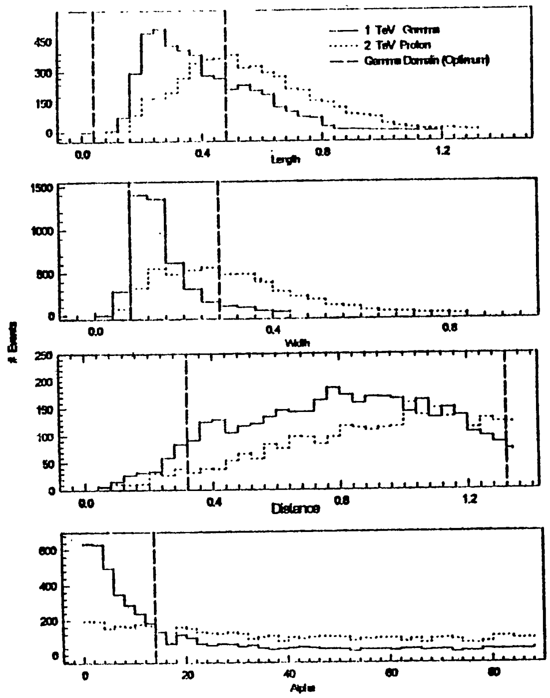

Fig. 3: Image parameter distribution for γ - ray and proton-initiated events

3. The TACTIC array

TACTIC (TeV Atmospheric Cerenkov Telescope with Imaging Camera) is a compact array of 4 gamma - ray telescopes, set up at Mt. Abu (24.65^0 N ; 72.7^0 E ; 1300 masl) India , both to maximize

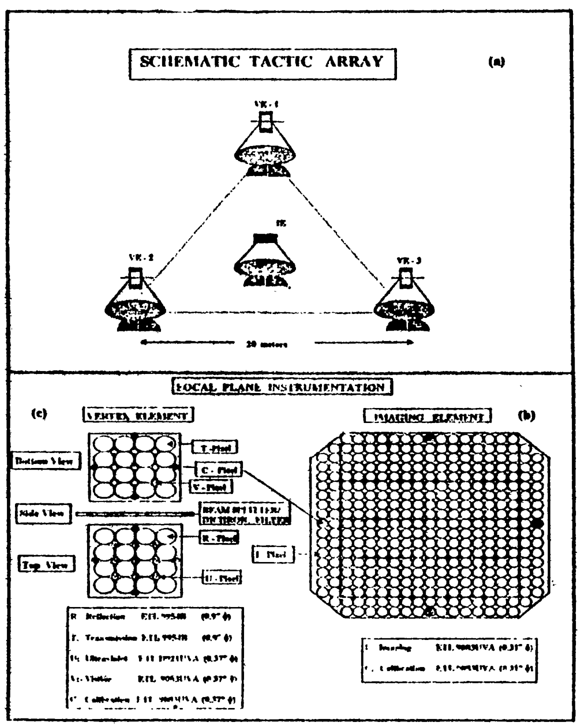

Fig.4 : Schmatic diagram of TACTIC array and IE and VE cameras.

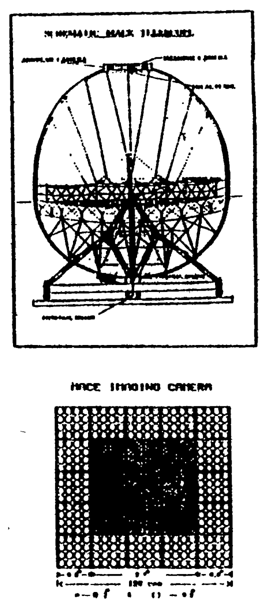

Fig.5 : Schematic diagram of MACE and the high resolution imaging camera.

effective observation time (~ 2000 h year $^{-1}$) in the stand-alone mode as also to provide an opportunity to pursue multi-spectral band observations with the existing optical /IR and radio telescopes in this region (Bhat, 1996). Each telescope element deploys a tessalated light collector (~ 9.5 m^2 area) comprising 34x0.6m dia., front-aluminized glass mirrors (f/1, focal length ~4m) arranged in an overall Davies – Cotton configuration (spot size ~ 0.20^0). Each telescope element uses a computer – controlled, 2-axes drive system designed for a pointing/tracking accuracy of ~ 3 arc min (Tickoo et al, 1999). While 3 telescope elements, referred to as the Vertex Elements (VE), are positioned at the 3 vertices of an equilateral triangle of 20m side, the fourth element, called the Imaging Element (IE) is located at the centroid. Fig.4 shows a schematic diagram of the TACTIC array and the focal plane instrumentation of the IE and the 3 VEs. The TACTIC focal plane instrumentation has a hybrid design so that the system can exploit the diagnostic potential of both the image and non-image parameters of Cerenkov events produced by γ-ray and cosmic ray hadron primaries and thus achieve a higher flux sensitivity than that obtained with image parameterization alone. With this objective in mind, the focal plane instrumentation of the IE is designed to consist of a large field of – view (~6^0 dia) Cerenkov light imaging camera with a uniform pixel resolution of ~ 0.31^0 and comprising a total of 349 photomultiplier tubes. Similarly, the focal plane instrumentation of each VE is specially designed to allow measurement of several non-image parameters of the Cerenkov pulse including the degree and angle of linear polarization, the pulse time profile and the 'hardness ratio', i.e, the ratio of light intensity in the near UV region (λ = 270 –310nm) to that in the visible region (λ = 310-550nm). The details of this rather unique and unconventional focal plane instrumentation of the VEs are given in Sapru et al (2002)

An interesting feature of the 4 TACTIC elements is their low trigger threshold mode of operation. It is achieved in the case of the IE by operating the camera pixels at an unusually high discriminator trigger rate of ~50kHz and demanding a topological trigger involving coincident (~20ns) firing of 4 nearest neighbour, non - collinear pixels (3NCQ trigger mode). Similarly , in the case of the 3 VE's, a low trigger threshold energy is achieved by demanding a coincident firing of two nearest neighbour pixel pairs sitting across the beam splitter and followed by a pre-programmed delayed coincidence between the matching pairs of the three VE's . This approach helps to effectively overcome the problem of after-pulsing recently recognised to be afflicting the operation of photomultiplier tubes exposed to the light of night sky background and resulting in significantly broader, non-Poissonian photoelectron noise profiles (Mirzoyan and Lorenz, 1995).) Another important provision made in TACTIC is for on-line absolute calibration of all the pixels in the IE and VE cameras. For this purpose, 4 pixels of each one of these cameras are provided with an Am^{241} isotope – based scintillation light pulser. The details of this calibration facility are available in Tickoo et al (2002).

The trigger threshold energy for the IE and the VE is estimated to be ~ 0.3 TeV while the image threshold energy is ~ 1 TeV (Koul et al, 2002). The unusually large field-of-view of the TACTIC IE, alongwith its uniform pixel resolution, allows it to generate high quality images of Cerenkov events produced by ultra high energy (≥ 50 TeV) cosmic ray hadrons upto large impact distances of ~ 500 m. When operated in the large zenith angle mode, the IE can detect these events with a reasonably high rate, indicating the possibility of using this system for cosmic ray mass composition measurements in the ≥ 50 TeV energy range if an appropriate image parameter-based algorithm can be devised to segregate the events in terms of the primary mass. Preliminary simulation studies (Bhat et al, 2001) have shown encouraging results and are being pursued further. Another advantage of the large field-of view and uniform pixellation is the possibility of carrying out concurrent on-source/off- source observation scans – an important consideration in searches for transient TeV emissions in addition to providing an effective doubling of the available observation time (Tickoo et al, 2001)

4. The stereoscopic MACE system

The stereoscopic MACE (Major Atmospheric Cerenkov Experiment) system is planned to be a system of 2 high- definition imaging Cerenkov telescopes, operated in a stereo mode for gamma-ray astronomy investigations in the sub-TeV (projected gamma-ray threshold energy ~ 20 GeV) energy range. Fig. 5 shows a schematic diagram of one of the two MACE telescope systems and the high-definition Cerenkov imaging camera to be mounted in its focal plane. Each altitude azimuth mounted MACE element will use a 17m diameter, high optical quality metallic mirror made up of diamond-turned aluminium facets, similar to that used in the MAGIC telescope (Barrio et al, 1998). The overall profile of the light collector approximates a paraboloid surface comprising concentric rings of mirror facets with a graded focal length. Such a profile is isochronous and also produces a sharp focus. The imaging camera, mounted in the mirror focal plane, comprises a cluster of 832 photomultiplier tubes of two sizes, providing an overall field- of view of 4^0 x 4^0. The innermost pixels (2.4^0 x 2.4^0),used for generating the event trigger, will have a resolution of 0.1^0 while the remaining pixels will have a resolution of 0.2^0. The signal processing electronics and instrumentation is mounted at the back of the mirror of the corresponding telescope in order to retain the relative sharpness of the Cerenkov pulse (duration ~10ns) and thus avoid accepting excessive light of the night sky noise which would otherwise lead to a higher threshold detection energy for the MACE.

The proposed stereoscopic mode of operation for the MACE leads to the following important advantages : It effectively suppresses the local muon background, an important constraint on sensitivity in the sub-TeV energy regime. It also helps to preferentially pick-up gamma-ray events of a point source origin and significantly reject isotropic backgrounds of cosmic ray hadron and electron origins. Furthermore, this mode of operation may lead to a lower effective gamma-ray threshold detection energy and a more accurate estimation of the primary energy. Given these design specifications, the stereo-MACE system promises to be a powerful instrument for gamma-ray source studies in the sub-Te energy range, including EGRET-detected sources like pulsars, SNR's, active galactic nuclei and the so-far unidentified objects. Monitoring of high energy tails in cosmic gamma-ray bursts is another important experimental objective for the MACE system. Figure 6 compares the estimated sensitivity of a single MACE telescope with the Crab pulsar spectrum modulated by an exponential tail characterised by an energy cut-off value of E_0 ~ 60 GeV. Two values of the on-source observation time (50h and 100 h) and the pulsar light curve duty cycle (10% and 100%) have been considered. Experimental upper limits derived by the Whipple group for PSRB1957+20 and PSRB0656+14 are also shown in the diagram. It is seen that even for a mono MACE, the flux sensitivity is sufficient to detect possible crab pulsar emission upto ~ 100 GeV.

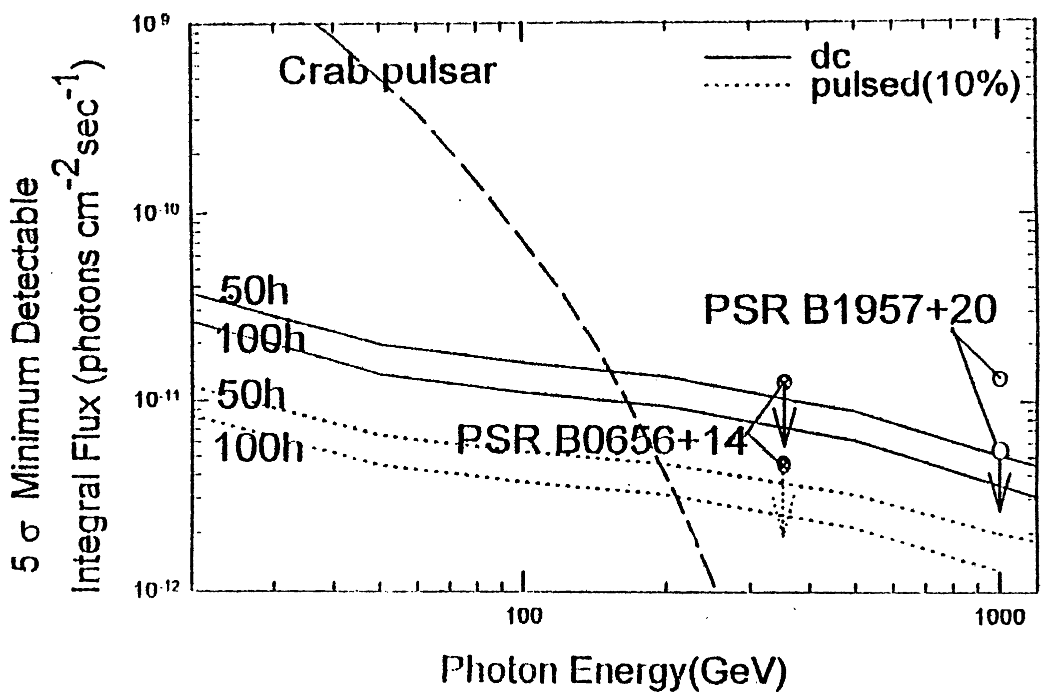

Fig. 6 : Sensitivity estimates of MACE in terms of signal recovery time for 5 σ detection in 50/100 h of source observations

The design and development activity related to the MACE system is at a fairly advanced stage. With the aim of ensuring a fast time response, high channel density and low power dissipation, special signal processing electronics modules based on ASIC's (Application Specific Integrated Circuits) and hybrid circuits are being developed for the MACE system. The first MACE telescope is scheduled to become operational by 2007 end while the complete stereo-MACE system is likely to see first light in 2008.

5. Observations with TACTIC IE and first results

5.1 **First detection of Mkn 501** : The TACTIC IE, equipped with a prototype 81 pixel camera, saw first light in April 1997, and fortuitously caught the extragalactic blazar Mkn501 in a high activity (flaring) state. Fig. 7 summarizes the results obtained by various atmospheric Cerenkov systems, including TACTIC, which were operational during this epoch of enhanced high-energy gamma-ray activity from Mkn 501 (Protheroe et al, 1997). This particular detection, representing the first ever multi-station detection of a TeV gamma-ray source during its flare state, has important implications regarding the acceleration of progenitor particles in the blazar jet and the propogation of the gamma-ray signal through the intergalactic medium.

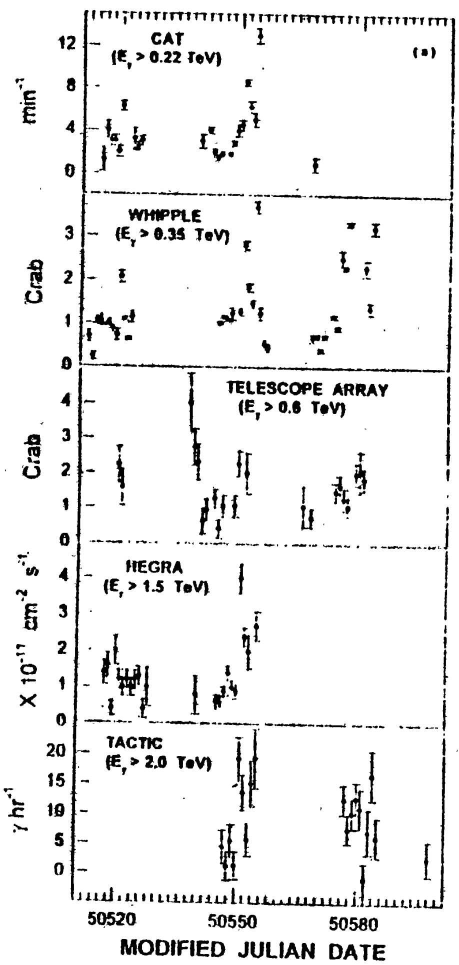

Fig. 7: Mkn 501 light curves recorded during March – May, 1997 by TACTIC and other imaging systems.

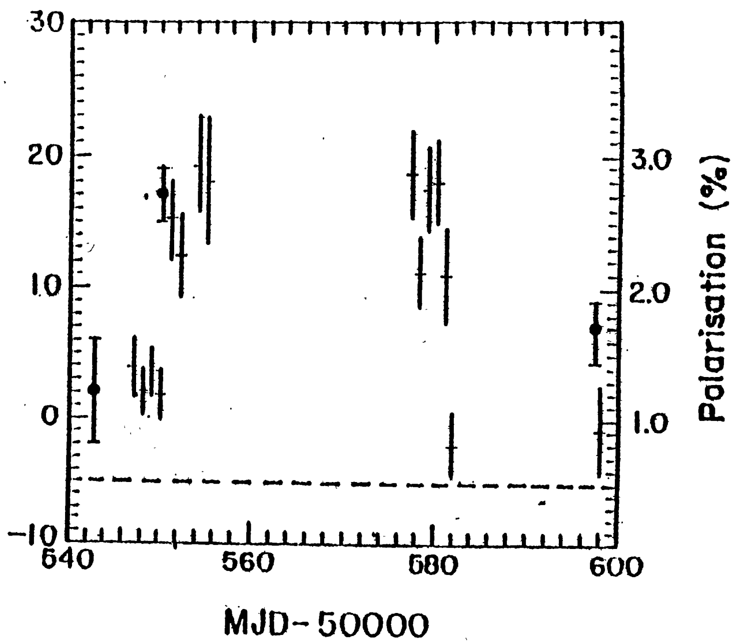

Fig. 8: Mkn 501 light curve during March – May, 1997 from TACTIC and optical polarization measurements from Gurushikhar telescope.

5.2 Correlated polarized optical and TeV gamma-ray emissions from Mkn501 : During its maiden observational run on Mkn 501 in April –May 1997, the TACTIC imaging element recorded a time variable signal from the source (Bhat et al, 1997). During the same period, the source was also monitored with the Gurushikhar 1.2m optical/IR telescope using an optical polarimeter. A significant increase in the degree of polarization of the optical radiation in association with the enhanced TeV gamma ray activity was observed on three nights (Fig.8). The observations have been interpreted in terms of a possible leptonic origin of the TeV gamma - ray

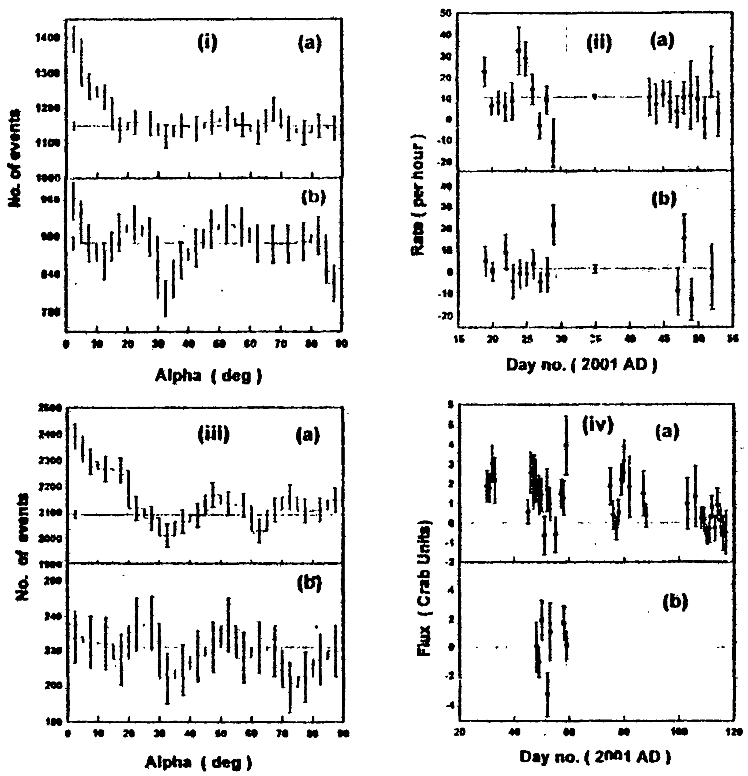

Fig.10 : α - plot of events from Mkn 421

Fig.9: α - plot of events from the Crab. An excess in the $\alpha \leq 20$ region indicates the gamma-ray signal.

signals, the progenitor electrons producing the associated polarized optical radiation through synchrotron process in the jet magnetic field (Joshi et al, 2000).

5.3 Observations of the Crab Nebula : The TACTIC imaging element was used in the on-off mode to observe a possible TeV gamma-ray signal from the galactic plerion, the Crab Nebula, during Dec. 2000 – Feb. 2001. In 40h of on-source observations, a statistically significant signal (~6σ) of ≥ 1 TeV gamma-rays has been derived from image parameter analysis (Fig. 9). The signal is seen to be almost constant on a day to day basis, consistent with the known behaviour of this supernova remnant at TeV energies.

5.4 Observations of extragalactic sources (blazars) : Observations (40h) of the extragalactic active galactic nucleus (AGN) Mkn 421, an X-ray loud blazar, during Jan.- March 2001, have also revealed a significant (~ 4σ) signal at ≥ 1 TeV from this source (Fig. 10) . The signal is found to be variable on a day to day basis, consistent with the gamma-ray emission activity of this source as observed by several other atmospheric Cerenkov telescopes. The successful detection of the Crab Nebula and Mkn 421 signals with the TACTIC IE has validated the expected performance of this telescope and the backend data recording and analysis software.

5.5 **Observations of blazar IES2344+514 and pulsar PSRB0355+54 :** The TACTIC IE has recently (Nov. 2001 – Jan., 2002) been used to observe the X-ray blazar IES2344+514 (~40h) and the galactic pulsar, PSRB0355 + 54 (~40h) under good sky conditions. No indication of a steady TeV gamma-ray signal has been obtained from these sources.

5.6 **VHE gamma-ray energy spectrum of the Crab Nebula and Mkn 421 :** Extensive simulations, using the CORSIKA air shower simulation code and a properly trained artificial neural network (ANN) have been carried out to convert the recorded image parameters (size) to the energy of the primary progenitor particle. Using guidance from these simulations, involving the dynamic supercuts procedure, the recorded image sizes have been converted to the primary energy and the differential energy spectrum of the two detected sources (Crab Nebula and Mkn 421) derived in the 1-10 TeV energy band. Fig.11 shows the derived Crab Nebula and Mkn 421 differential spectrum (points with error) which , in the case of the Crab , is seen to closely match the source spectrum derived by the HEGRA Cerenkov telescope in the 1-10 TeV energy range (Aharonian et al, 2000). Further optimisation of the primary energy determination, with an energy resolution of ≤ 20%, is being sought from simulations to accurately determine the source spectra.

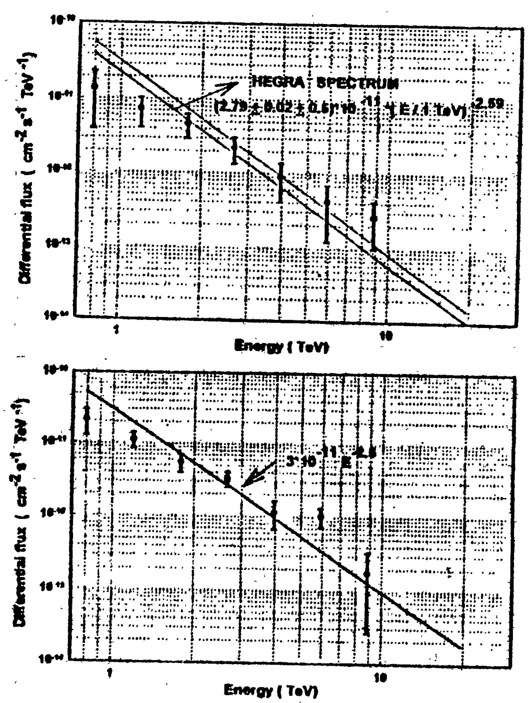

Fig.11 : Differential energy spectra of the Crab Nebula and Mkn 421 inferred from the TACTIC observations.

6. Future plans

The complete 4-element TACTIC array is expected to become operational by the middle of 2002. The initial observations with the TACTIC imaging element have shown that this system presently has the sensitivity to detect a 5 σ signal from the Crab Nebula in ~ 20 h of observations. Attempts are being made to optimise the system performance so that the desired sensitivity of a 5 σ signal from the Crab Nebula in 5h of on-source observations is achieved. Attempts are also being made to assess the possibility of using the Vertex Elements at a reduced threshold energy of ~ 300 GeV (without high resolution imaging) and using the TIPS (time profile, imaging polarization and spectral cuts) strategy to effectively suppress the background cosmic ray – initiated events. (Bhat, 1996)

The first MACE telescope is expected to become operational by the end of 2007 and the complete stereo – MACE system is planned to be completed by the end of 2008 . At present, the mechanical structure for the 17m – dia MACE light collector is being designed at Central Workshop, BARC. Work has also been initiated to design and fabricate special ASIC's –based backend instrumentation for the MACE. The experience gained through the successful implementation of the TACTIC system is likely to prove very useful in ensuring a timely completion of the MACE project.

7. Conclusions

The imaging Cerenkov technique has proved to be a very powerful method for ground-based studies of cosmic gamma-ray sources in the 100's of GeV to 10's of TeV range by providing an efficient method for rejecting ≥ 99.9% of the overwhelming cosmic ray background through image parameter analysis. The successful operation of the TACTIC telescope system, the first imaging Cerenkov telescope system in India, has shown that with further optimisation of the telescope performance. Many more sources (both galactic and extragalactic) may be waiting to be detected by this system and others of its kind. Moreover, the proposed stereo – MACE system, which is expected to operate at a gamma-ray threshold detection energy of ~ 20 GeV, will surely extend the spatial range of our searches for gamma-ray sources in the galaxy and beyond, especially for sources whose spectra tend to steepen beyond 10's of GeV range due to absorption effects or particle acceleration cut offs.

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