1997BASI...25..461B

Bull. Ast r. Soc. India (1997) **25**, 461-484

Ground-based γ-ray astronomy : Present status and future prospects

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Received 30 December 1996 ; accepted 4 July 1997

Abstract. In this article, we review the observational scene in ground based γ-ray astronomy as it has changed from a rather ambiguous exploratory-phase in the eighties to a more unequivocal consolidation-phase in the recent times. We suggest that the detection-claims, made in the eighties in the TeV-PeV photon regime with regard to Cyg X-3 and Her X-1, may be genuine and reconcile these results to the present non-detections by presenting two plausible time-variability scenarios. Finally, we refer to the upsurge that is being witnessed in the field currently on the experimental front and comment on the progress that is likely to result, particularly in the tens of GeV - tens of TeV energy regime. An epoch-making result presented here, is the first-ever detection of a TeV γ-ray signal from a cosmic γ-ray source (BL-Lac object Mkn-501), concurrently by a global network of 4 imaging γ-ray telescopes, viz., Whipple (USA), CAT Imager (France), C-HEGRA (Germany) and TACTIC (India).

1. Introduction

The unusually wide span of the gamma-ray spectral window, covering at least ten decades of photon energies (~ 10^5 - 10^{15} *eV*), can be organized into two broad segments from the viewpoint of the basic detection strategies, presently in vogue for accessing this window, viz., direct or space-borne and indirect or ground-based (Ramana Murthy and Wolfendale 1986). As of today, the dividing line between the direct and indirect detection methods lies around a photon energy (E_γ) value of a few tens of GeV, with cosmic γ-ray signals at higher E_γ being too weak to be amenable to a direct detection on a satellite platform because of practical restrictions on the payload size, weight and active lifetime. Instead, ground-based detection is more promising at higher photon energies on account of the helpful transducing role of the terrestrial atmosphere, wherein the incident γ-ray photon initiates an extensive airshower (EAS), the secondary electrons and the tertiary Cerenkov photons from which reach the surface of the earth dispersed over a significantly large area. This helps to effectively offset the problem of extremely low photon flux, typically encountered at these energies (< 0.1 *photon* m^{-2} day $^{-1}$ at > 1 TeV). The two principal ground-based detection methods, that follow from this benign atmospheric intervention, are the **Atmospheric Cerenkov Technique** (ACT) and **Extensive Air-Shower Technique** (EAST), with the former being deployed principally in the very high energy (VHE) or TeV region (1 TeV = $10^{12}eV$) and the latter addressing the ultra-high energy (UHE) or PeV photon range (1PeV = $10^{15}eV$), usually from a high-altitude station (Weekes, 1988). In case of the ACT, the effective observation time is restricted to dark clear nights only, leading to an operational duty-cycle of < 10% at a good observatory site (some recent innovative detection schemes, aimed at extending the operational schedule into the semi-dark or moonlit part of the night, have now started bearing fruit; see Catanese *et al.* 1995). However, this rather restricted duty-cycle is getting largely compensated by the fact that the technique allows to access lower E_γ and, in the bargain, also secure a higher degree of accuracy in determining the arrival direction of the incident photon – an essential pre-requisite for several γ-ray astronomy applications.

For both, the ACT and the EAST, the incredibly weak and, as a rule, non-steady γ-ray signal has to be retrieved from an excessively large background of cosmic-ray-generated events. Historically, grappling with the attendant poor-sensitivity problems has turned out to be a major bottleneck in achieving progress in the field of ground-based γ-ray astronomy at the same quantitative level as that achieved at lower E_γ (~MeV-GeV) through satellite-based instrumentation, particularly the successful launch of the Compton γ-ray observatory by the NASA, USA, in April 1991 (Fichtel 1995). A discussion of the notable achievements of the Compton Observatory is beyond the scope of the present paper and we refer the reader to the recent reviews by Dingus (1995) and Kanbach (1995). We shall, instead, trace here the rather zig-zag course along which the ground-based γ-ray astronomy has progressed since its inception in the seventies. We shall then discuss briefly the contemporary observational scene and go on to draw some important inferences from it. Towards the end, we shall refer to the major experimental installations which are in the implementation or planning phase presently and will discuss the prospects that they will have in realizing the promise that has been associated, for long, with this astronomical window (e.g., Aharonian, 1995).

2. Observational scene

The observational scene in the field of ground-based γ-ray astronomy can be divided into two periods from a historical perspective : pre-1990, when simpler experimental systems (first-generation atmospheric Cerenkov telescopes and moderate-sized EAS arrays) were used for carrying out searches for point γ-ray source candidates (Weekes, 1988); and post-1990, when these searches and associated spectral and temporal studies are being undertaken with dedicated, higher-sensitivity experimental systems (Weekes, 1992). In the TeV energy range, the new generation atmospheric Cerenkov telescopes deploy imaging cameras, which yield a 2-dimensional distribution of the recorded atmospheric Cerenkov photons, leading, in turn, to useful information on the energy and the nature of the shower-initiating particle (Hillas, 1996). For the first time, this important technical innovation has made it possible to detect, not only TeV γ-ray signals from a number of cosmic sources at hitherto unmatched statistical confidence levels, but also carry out good-quality spectral and long-term time-behaviour studies of some of these objects. Other methodologies invoked for rejecting the ubiquitous cosmic-ray background, though with a comparatively limited effectiveness, are based on securing precise arrival-direction information of the progenitor particle and exploiting the differences, expected in the lateral distribution of Cerenkov radiation produced by a γ-ray photon vis-a-vis a cosmic-ray primary (Fegan, 1992; Patterson, *et al.* 1995)

At higher (~PeV)energies, where experimental systems generally utilize the air-shower detection technique, the desired sensitivity augmentation is sought by using bigger and higher-density particle-detector arrays. These arrays are supplemented with a high-resolution timing capability for a more precise event arrival-direction reconstruction and a large-area muon-detector assembly (also a hadron-calorimeter, sometimes) for discrimination against EAS events induced by background cosmic-rays (e.g. Weekes,1988)

2.1 Pre-1990 phase

During this largely exploratory period, a host of claims have been made for detection of TeV γ-ray signals from a wide range of cosmic bodies, located mainly within the galaxy. The more prominent detection claims involve sources such as the supernova remnant Crab Nebula, the galactic radio-pulsars PSR 0531+21 (Crab) and PSR 0833-45 (Vela), the enigmatic X-ray source, Cygnus X-3, the low-mass X-ray binary system Her X-1, as well as the cataclysmic variables AM-Herculis and AE-Aquarius (Weekes, 1988; Bhat, 1993 and references therein). In general, the case for the association of the detected 'signal' with a putative source was made on the basis of a periodic time-modulation which was noted in the corresponding data-base and was found to bear a cognitive relationship with the orbital, spin or precessional period of the compact member of this astrophysical system. It was also noted during these early investigations that the detected 'signals' are invariably of an episodic nature, with the on-time varying on a time-scale of minutes to months. As for extragalactic systems, no VHE γ-ray signals were reported with the sole exception of the Centaurus A (distance ~ 5Mpc), for which only a one-time evidence was presented for this emission at a rather moderate statistical significance (4.5σ), based on observations made with a dual-beam Cerenkov system, operating from Narabarri, South Australia (Weekes, 1988 and references therein).

No dedicated experiments were set up during the early part of this phase to search for γ-ray signals at PeV energies. The implied reluctance on the part of the observational astronomer may be attributed to the caution sounded by his theoretical counterpart against the plausibility of such a signal on the grounds that the progenitor electron-beam cannot be (normally) accelerated to adequately high energies (~tens of PeV) because of attendant synchrotron losses due to the magnetic fields expected to be present in and around the acceleration site. It was the serendipitious detection of a counts-excess from the direction of the Cyg X-3 binary system in the archival data-base of the Kiel air-shower array (Samorski and Stamm, 1983) and the firming up of the source association through the apparent discovery of the 4.8h-modulation period in this signal (believed to be the orbital period of the Cyg X-3 system), which charged up the whole scene literally overnight and made both the theorist and the experimentalist to 'do their sums' all over again! In what may be described as a classic 'wiser-after-the-event' example, the theorist immediately drew attention to the crucial role an UHE proton progenitor (or a higher-Z parent nucleus) can play in producing PeV γ-rays in a Cyg X-3 like binary system through the neutral-pion decay chain $\pi^0 \rightarrow 2\gamma$. According to this picture, the intermediate neutral-pion itself is produced through the progenitor particle undergoing a (p,p) or (p,γ)

interaction in the vicinity of the Cyg X-3 system (e.g. Vestrand and Eichler, 1982; Mitra, 1994).

Apart from being a path-breaking result in its own right in the field of γ-ray astronomy, the reported signal from Cyg X-3 is particularly significant in that, observationally, it underscores the presence of UHE particle accelerators in the galaxy and, in that sense, brings us closer to a satisfactory resolution of the long-outstanding, cosmic-ray origin problem (Ramana Murthy and Wolfendale, 1986). The Kiel result on Cyg X-3, which was subsequently confirmed by the Haverah Park group (Lloyd-Evans *et al.* 1983), quite understandably, set the stage for a phase of intense experimental activity all over the world, leading to evidence for UHE γ-ray emission from some additional X-ray binary systems, notably, Her X-1 and Vela X-1 (Weekes, 1988 and references therein). As in the TeV energy region, the association of the claimed signal with a source was sought to be buttressed by the apparent source-related periodic time-modulation, found to be present in these signals.

2.2 Post-1990 phase

In the VHE region, thanks to the advent of the Cerenkov Imaging Technique, 4 firm detections have been made so far (Fegan, 1996). These involve the supernove remnant Crab Nebula and the pulsar PSR 1706-44 in the galaxy and the nearby active galaxies, Markarian-421 and Markarian-501, (red-shift factor $z \sim 0.03$). The HEGRA collaboration (Aharonian, 1996), while confirming the Whipple detections of the Mkn-421 and Mkn-501, have independently come forth with the evidence suggesting an episodic release of TeV γ-rays from the transient X-ray source GRS 1915+105. This galactic system is usually referred to as a 'micro-quasar' on account of the presence of jet-like morphological features in it. It is noteworthy that, while both Mkn-421 and Mkn-501 have been detected only as weak sources by the EGRET detector on-board the Compton Observatory (the latter as recently as April-May, 1997; Sreekumar : private communication), they seem to be relatively more prolific emitters of TeV γ-rays, displaying a dramatic time-variability on time-scale down to hours and days. It may also be noted in the case of Mkn-501 that, although it was visible to the BATSE detector as a more or less steady source with an estimated flux of 1.5×10^{-12} $erg\ cm^{-2}\ s^{-1}$ in the lower energy γ-ray photon energy bracket, $E_\gamma \sim$ 20-100 keV (Malizia, A. 1997), its discovery as a high energy γ-ray source has come via the Cerenkov route – a vindication of the fact that the ground-based γ-ray astronomy has graduated today into an independent diagnostic probe of important astrophysical phenomena.

At least 6 groups, most of them using the Cerenkov Imaging Technique, have detected TeV γ-ray signals from the Crab Nebula, making it the most extensively studied galactic object to date in this energy regime (Stepanian, 1995 and references therein). The signal is of a d.c. nature and does not exhibit any significant time-variability on a time-scale of days to months. Although there is a significant incompatibility in the flux values quoted by different groups, the overall measured spectrum is found to be broadly consistent with a Compton self-synchrotron mechanism (see Fig.1), proposed recently in an updated form by de Jager (1995) : Here, TeV γ-rays are generated due to Compton-boosting of lower energy photons (X-rays, γ-rays), which themselves are produced within the Nebular region by VHE electrons via the synchroton process. The γ-ray signal detected from the PSR 1706-44 by the CANGAROO imaging telescope

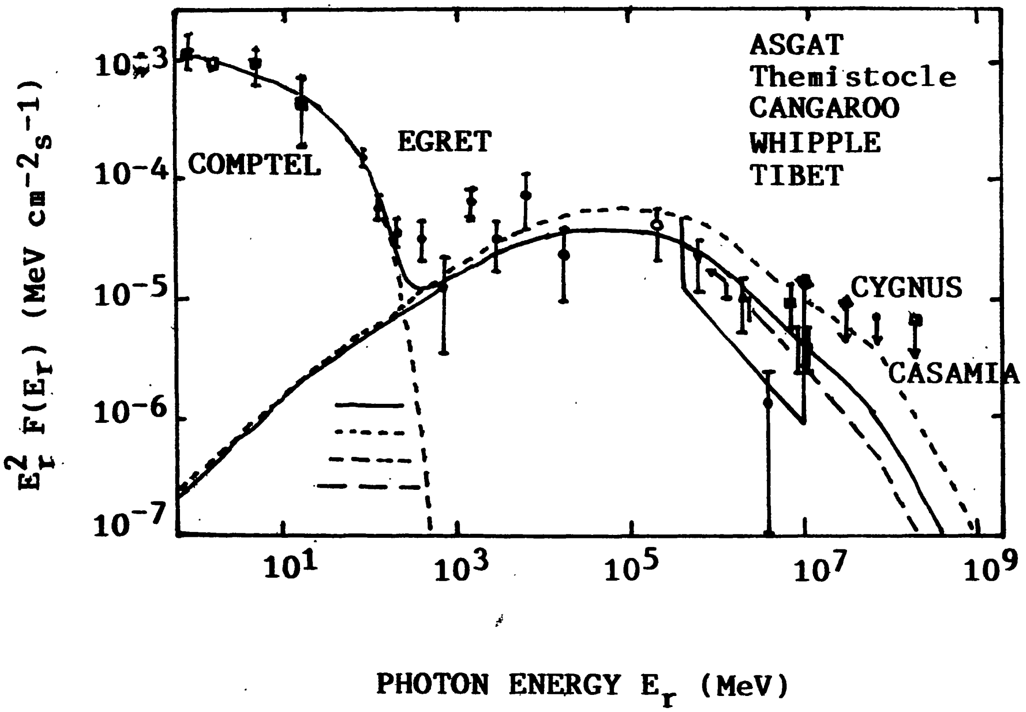

Figure 1. Energy spectrum of the Crab Nebula as measured in the γ-ray energy interval 1MeV - 10 TeV alongwith model-fits, based on the synchroton (<1GeV) and Compton-boosted self-synchrotron (> 1 GeV) mechanisms.

(Kifune *et al.* 1995) at Adelaide, Australia, is again of a d.c. type and does not exhibit any significant periodic modulation at the pulsar spin period of ~102ms. This suggests that, as in the case of the Crab Nebula, theTeV γ-ray signal from this source too emanates presumably from a site far removed from the pulsar surface.

As for γ-ray signals from the BL-Lac objects Mkn-421 and Mkn-501, both have been successfully recovered by the Whipple group from their Cerenkov-image database (Fig.2), using the optimized supercuts image-processing procedure (Punch et al. 1992; Catanese et al. 1995). In what can be a potentialy significant astrophysical spin-off from the field of ground based γ-ray astronomy, Stecker and de Jager (1996) have used the apparent steepening in the spectrum of Mkn-412 at E_γ > ~5-10 TeV for deriving an upper limit on the average density of infra-red photons from the direction of this source. A recently-completed analysis of the augmented Whipple Observatory data-base from this source, on the other hand, yields no evidence for this steepening (Fegan, 1996), with obvious implications on the above-referred inference on the density of metagalactic infra-red photons. A typical feature of γ-ray emission from the Mkn-421(and presumably other BL-Lac objects) is that the signal is seen to display a significant time variability on a time-scale of hours-days (Fig.3). An important landmark in this connection is the 'capturing' of a 2-day flaring episode from the Mkn-421 by the Whipple imaging telescope during the period when this source was also being viewed by the EGRET γ-ray detector in.the MeV-GeV energy bracket, the ASCA satellite at X-ray photon energies

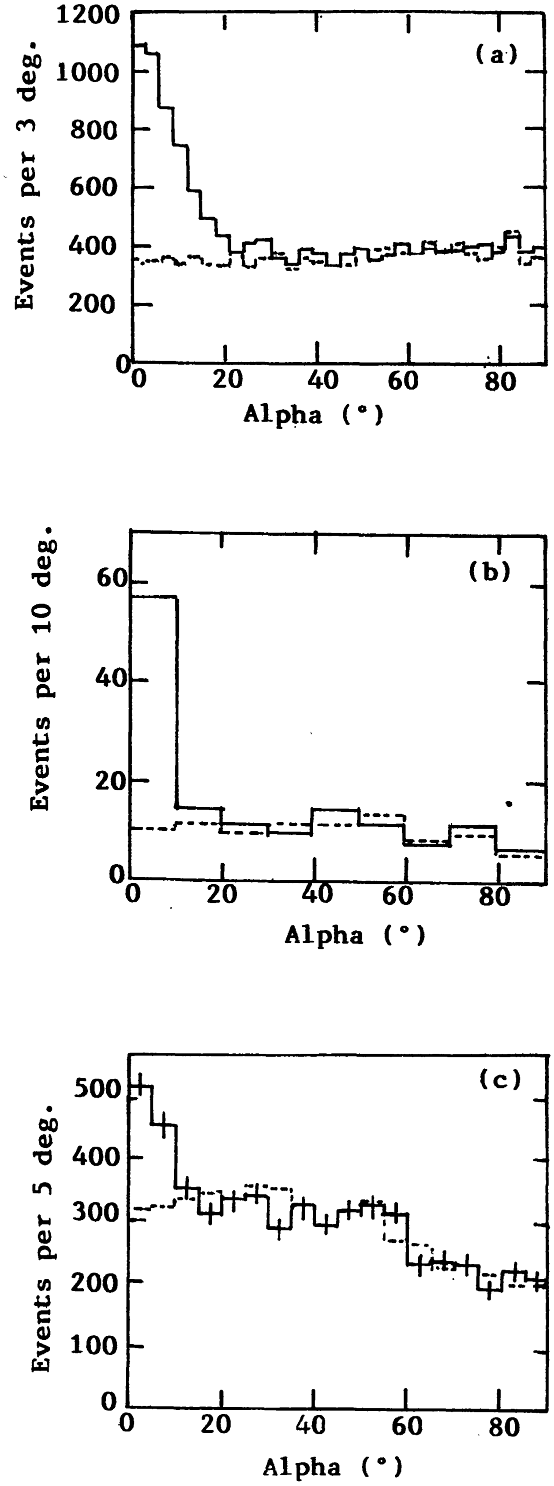

Figure 2. TeV γ-ray signals (histograms) from the galactic plerion Crab Nebula (a) and the two neighbouring active galactic nuclei Mkn-421 (b) and Mkn-501 (c), as revealed unequivocaly by the Cerenkov image-orientation parameter 'alpha'. The experimental background level is shown by dotted lines. The γ-ray signal domain is alpha < 15° - 20°.

and an optical telescope in the visible band (Kerrick et al. 1995; Buckley and McEnery et al. 1997) : A near time-correlated enhancement was noted at, both TeV and X-ray photon energies. The reader is referred to Buckley et al. (1996) for recent results on another highly successful multi-spectral band observation campaign carried out on this source in 1995 April 20-May 5. Yet another extremely important recent development, involving this source, is the detection of an unprecedented flux shoot-up (> 60σ excess in the 'alpha' image-parameter plot) and the subsequent turn-down, all in a matter of few hours (Fegan, 1996). This observation has important astrophysical implications on, both, the size and the nature of the VHE γ-ray source in AGN's, as also on the circumstellar photon fields present around these sources (e.g., Kerrick et al. 1995).

In recent years, the Whipple group have carried out systematic observations of some representative members of various types of galactic and extragalactic objects (e.g., Lessard et al. 1995). They include pulsars, supernova remnants, X-ray binary systems within the galaxy and different sub-classes of active galaxies and quasars from without the galaxy. The supercuts background-rejection methodology, which has worked excellently when applied to the Crab Nebula, Mkn-421 and Mkn-501, has thrown up no evidence for significant TeV γ-ray signals from any of these sources (Weekes, 1992). Nor have other imaging analysis methods, like the 2-dimensional grid technique specially designed to retrieve possible γ-ray signals from extended sources, like the shell-type supernova remnants (Lessard et al. 1997), or the analogous method developed for non-centred source detections (Connaughton et al. 1997). Notably, the fairly-long list of null-detection includes several 'classical' candidate-sources, viz., Crab pulsar, Cyg

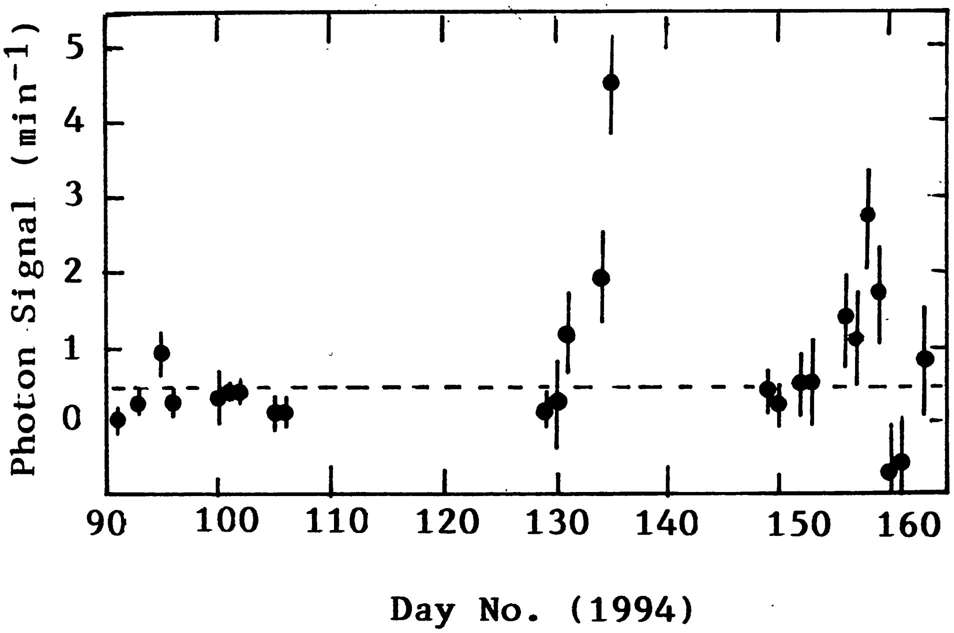

Figure 3. Time variation observed in the TeV γ-ray emission from Mkn-421 by the Whipple group between April 01 - June 12, 1994. A far more spectacular time-variation has been recorded by this group recently, with the observed flux changing by an unusally large amount in a matter of a few hours.

X-3, Her X-1, AM-Her, AE-Aqr, etc., from which TeV γ-ray signals have been claimed during the pre-1990 phase (Bhat 1993 and references therein), based on observations with generation-I, non-imaging Cerenkov telescopes (section 2.1). This disconcerting disparity calls for a proper explanation, particularly so in the light of persistent claims being made by some well-experienced groups about possible detection of pulsed signals from the Crab and Geminga pulsars (see Nel and de Jager, 1994 and references therein). Whileas the statistical significance of the claimed signals is admittedly only moderate – these groups are using non-imaging, background-rejection criteria – what is particularly difficult to ignore is the fact that the associated γ-ray light curves for the two pulsars exhibit a bimodal pulsed-emission, reminiscent of a similar behaviour by these sources at EGRET γ-ray energies.

Other detection claims made in the post-1990 phase, on the basis of observations made with non-imaging Cerenkov systems, concern the cataclysmic variable systems AE-Aqr (Chadwick et al. 1995), the pulsar PSR 0355+54 and the region intermediate around it (Senecha et al. 1995 and references therein). As regards the intermediate-polar AE-Aqr, short-duration (~ minutes) episodes of TeV γ-ray emission were first reported from the source by the Potschefstroom group in South Africa (Kifune 1996 and references therein). The Durham group (Chadwick et al. 1995), operating a high-sensitivity non-imaging Cerenkov system in Narrabari, Australia, have recently picked up another such episode of TeV γ-rays from this source (Fig. 4). While this independent observation gives further credence to the viewpoint that cataclysmic variables, involving a white dwarf compact object (instead of the more usual neutron star), may represent a hitherto unknown class of γ-ray sources, what is again baffling is that the Whipple imaging system has not revealed any analogous episodic activity during its fairly-long observation-spells on the AE-Aqr (Lang et al. 1995).

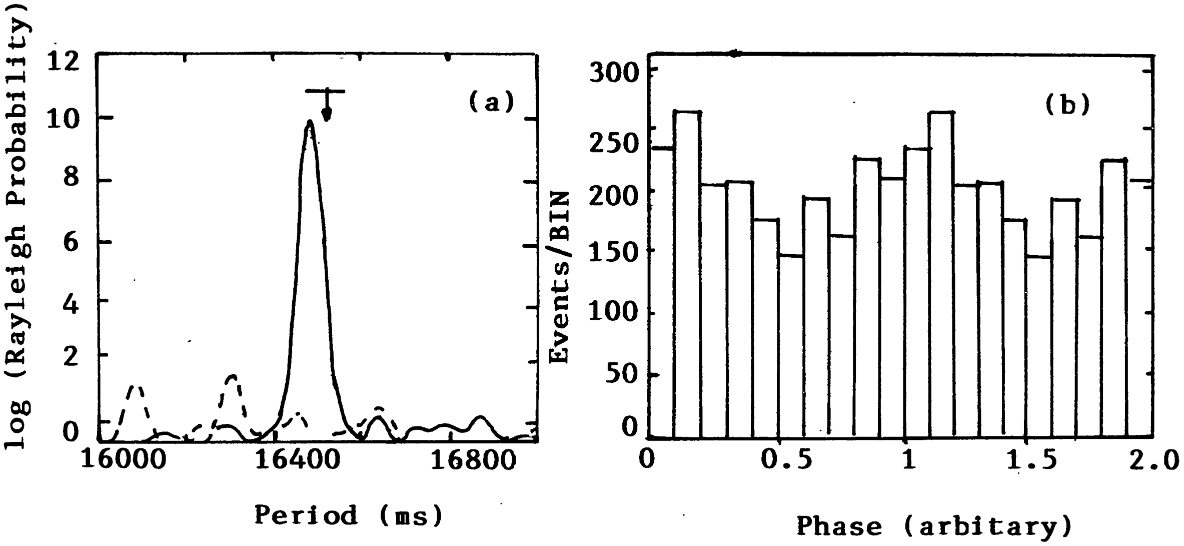

Figure 4. Evidence suggesting the emission of a 70 minute-burst of pulsed TeV γ-rays from the intermediate polar AE-Aquarii. It is based on the observations made by the Durham group with a low-resolution imaging telescope operating from Narrabri, South Australia. (a) summarizes the results of Rayleigh-power analysis of on-source (full-line) and off-source (dashed-line) events and (b) gives the corresponding γ-ray light curve obtained by epoch-folding the on source events with the white-dwarf spin period of 16.4838s.

Turning now to the radio-pulsar PSR 0355+54, a significant pulsar period of ~156ms has been reported from it by the Pachmarhi group (see Senecha et al. 1995 for references), during maiden observations made by them on this source in December 1987. Again, the Whipple group have reported a null detection from this source during the follow-up observations in September-December, 1989. On the other hand, based on observations made at Gulmarg in November-December 1989, Senecha et al. (1995) have recently reported the detection of a moderately significant (~4.1σ) flux of γ-rays from the overall pulsar region (but no pulsed emission), which is perhaps associated with the supernova remnant that may be surrounding this 5 X 10^5 year-old pulsar. The absence of the implied d.c. excess in the related Whipple data-base is not necessarily in conflict with the Gulmarg result because the putative source is not at the centre of the Whipple field of view and may be extended in size, two factors not compatible with the imaging data-cut philosophy, applied by the Whipple group while searching for the PSR 0355+54 signal (Goret 1993). A new detection, result, obtained using the CT-48 telescope at the Crimean Astrophysical Observatory, concerns a hitherto-unknown source, which is apparently lying close to the X-ray binary Cyg X-3; but is not this object (Neshpor et al. 1995). The image processing technique, deployed during thi detection, was first tried successfuly by the Durham group to detect the AE-Aqr episodic signal (Chadwick et al. 1995).

Turning now to the post-1990 observational status in the PeV energy regime, an important development, which followed the detection of UHE photon signals from Cyg X-3 and Her X-1 galactic X-ray systems, was the building of more sensitive EAS arrays for dedicated searches for γ-ray emission from galactic candidate-sources. These systems can more efficiently discriminate against background cosmic-rays on account of their better angular resolution and deployment of large-area muon detectors. The most outstanding example among the new-generation EAS arrays is the CASA-MIA experiment, set up in Utah, U.S.A., and involving the universities of Michigan and Chicago; other notable examples are GRAPES-II (India), EAS-Top (Italy) and the HEGRA (Germany) particle-detector systems (Gupta et al. 1995; Ghia et al. 1995; Prahl et al. 1995). The HEGRA experiment is operating alongside the AIROBICC array of wide-angle Cerenkov detectors at La Palma, Canary Islands(Lorenz 1996). Several all-sky surveys have been made and an extensive list of candidate sources, of both galactic and extragalctic origins, have been monitored for the presence of episodic and persistent signals. Intriguingly, no detection has been made at an adequately higher statistical confidence level by any of the new experimental installations, despite their significantly higher detection sensitivities and fairly long operational time-schedules, lasting for at least a few years. As has been referred to already, the sole deviation from this general trend is a rather weak hint of the 237ms-period pulsed signal from the X-ray pulsar Geminga at $E_\gamma > 100$ TeV, registered by the EAS-Top experiment (see Fig. 5; also Nel and de Jager, 1994 for details). What appears particularly baffling is that these searches have also drawn a blank in case of sources like Cyg X-3 and Her X-1, where the pre-1990 investigations had indicated emission of UHE photon beams (section 2.1).

In another development, several concerted attempts have been made in the recent past to secure observational evidence for the presence of VHE/UHE spectral tails in cosmic γ-ray bursts (Hurley 1996). As is quite well-known, these bursts, which were serendipitously discovered in early seventies by the Vela-group of satellites (Fishman 1993), manifest themselves as

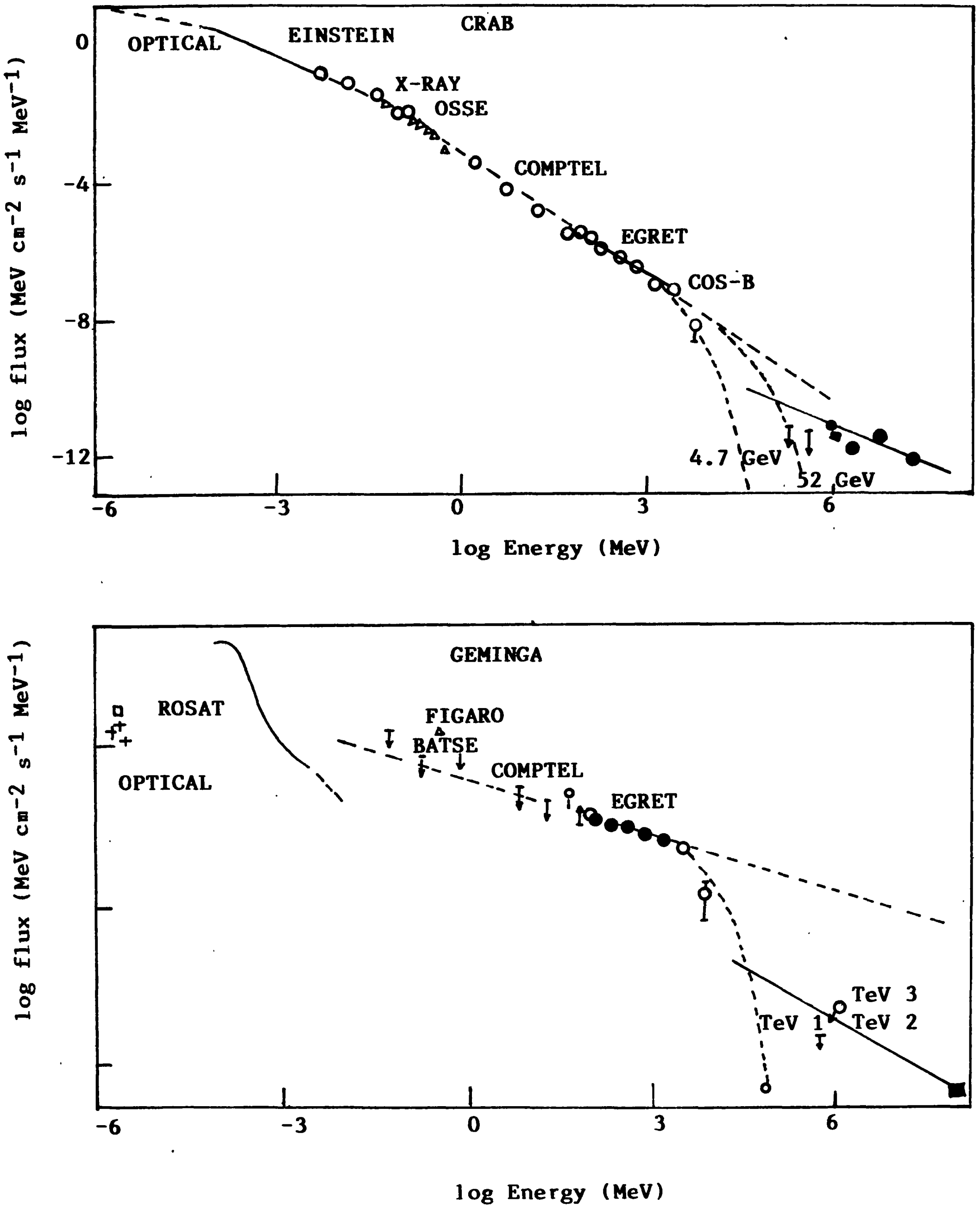

Figure 5. Measured differential energy spectra of the Crab and the Geminga pulsars, extending to ~100 TeV photon energy range. The quoted VHE flux-points lie significantly above the upper limits obtained by the Whipple Cerenkov imaging telescope and have resulted from observations made at Pachmarhi and the EAS-Top with non-imaging systems. Taken at their face value, the TeV flux values suggest a break in the source spectra in the photon energy interval ~1-10 GeV. The text gives an explanation for the apparent disparity between the Whipple upper limits and the quoted flux values in the TeV energy range.

sudden count-rate surges in a satellite-based γ-ray payload, like the BATSE on the Compton Observatory, generally lasting from a fraction of a second upto several minutes. Two hallmarks of the bursts are their spatial non-homogeneity (deviation from the expected -3/2 power -law peak flux distribution) and the isotropicity of their arrival directions (Fishman amd Meegan 1995). Although some authors would like to favour an extended galactic-halo model, the majority view today is that these bursts are of a cosmological origin. (The latter hypothesis has recently received a strong measure of corroboration from the detection of optical, radio and X-ray counterparts of two bursts in relatively distant galaxies, in one case corresponding to a red-shift factor $z \sim 0.8$; see Schilling (1997) and references therein). Time-coordinated TeV observations may give tell-tale clue to the underlying γ-ray production mechanism(s) and, in addition, may help to resolve the burst-origin problem in the following two ways : (i) A firm, correlated detection at TeV energies can result in upper limits on the distance range of the burst-source because of excessive quenching of these photons at longer distances on account of their interactions with the intervening infrared/optical photon-fields; (ii) better source-localization is possible through the atmospheric Cerenkov technique than what is achievable presently via conventional triangulation route, involving a network of satellite platforms.

Finally, in so far γ-ray emission of non-compact or diffuse nature is concerned, the problem has not been addressed yet seriously on the observational front in the VHE/UHE region (e.g., Borione et al. 1995). This includes looking at relatively nearby supernova remnants and molecular clouds, apart from attempting to pick up the truly diffuse components from the galactic-plane and high galactic-latitudes (extragalactic). The main reason for this state of affairs, despite a fairly strong underlying theoretical motivation, is that the existing experimental systems have inadequate detection sensitivities to match the expected diffuse flux, either in absolute terms or in relation to the cosmic-ray background. While on this topic, it would be in order to draw the reader's attention to the recent work by Lessard et al. (1995) and Buckely et al. (1997) which gives the latest (negative) result from the Whipple group on TeV γ-ray emission from the shell-type SNR's and discuss the resulting constraints on cosmic-ray acceleration in these systems through various shock-acceleration scenarios.

2.3 Comments on observational scene

In the TeV energy region, today, we have 4 cases of firm detections, viz, the Crab Nebula and the radio pulsar PSR 1706-44 in the galaxy and two nearby active galactic nuclei, Mkn-421 and Mkn-501. In comparison, the Compton Observatory-borne EGRET experiment, covering the neighbouring energy bracket $E_\gamma \sim$ 20MeV-30GeV, has detected γ-ray emission from 6 pulsars (including the pulsar PSR 1706-44) and nearly 60 AGN, which include the BL-Lac object, Mkn-421 (but not Mkn-501), also detected at TeV energies. The wide disparity between the numbers of AGN, visible in the two energy brackets, is being explained away in terms of spectral steepening which may be intrinsic to the source itself (production mechanism, in-situ absorption by circumstellar radiation fields or, for relatively distant AGN's ($z \geq 0.1$), may occur due to $\gamma + \gamma \rightarrow e^+ + e^-$ interactions of AGN produced TeV photons with the foreground optical/infra-red background radiation fields (e.g., Aharonian, 1995).

Turning now to the pulsed γ-ray flux from the galactic pulsars at TeV energies, there is no suggestion of its detection by the recent Cerenkov imaging experiments, although at EGRET energies (10's MeV - 100's MeV), as referred to above, 6 pulsars have been detected with the corresponding light curves displaying time-modulations characteristic of these sources. These sources include the Crab and the Geminga pulsars for which there are tantalizing indications of pulsed emission at TeV energies, albeit with low statistical significances, both from archival data searches as also from contemporary work carried out by the Pachmarhi and EAS-Top groups, using non-imaging techniques (see section 2.2). Fig.5 compares the observational situation for the two pulsars from optical wavelengths to ~ 100 TeV energy range. In both the cases, taking the plotted fluxes at their face value, there is a clear suggestion of a sudden spectral break at E_γ ~1-10 GeV, perhaps implying operation of two γ-ray production mechanisms (e.g., inner-versus outer-gap models) on either side of the break region. What is of particular interest in the present context is that the spectrum in the TeV energy domain is quite flat and, as has been argued by Bhat et al. (1994a), the sensitivity of the Cerenkov image parameters like Length, Width, Alpha, etc., gets significantly undermined in this situation because these parameters have a marked dependence on the primary photon energy. This, in turn, leads to an attendant loss of effective detection area and hence of signal events (γ-ray-like) through software-filtering procedures used during the analysis of data-bases from the imaging systems, like the Whipple telescope in case of γ-ray sources with a relatively flatter spectrum in the TeV energy region (differential exponent < 2 compared with ≥ 2.5 for sources detected with the imaging systems). While the statistical significance of the detection claims made on the basis of non-imaging systems needs to be improved before the results can be taken seriously, it would be also desirable to keep in mind that the negative results obtained by Whipple-like systems on the Crab and Geminga pulsars (and possibly binary sources like Her X-1 and AM-Her) may be a reflection of the presents day limitations of the imaging technique, including the one referred to above.

As for the rather surprising null results of the new-generation, higher-sensitivity experiments on Cyg X-3 and Her X-1, two candidate sources which have held the centre-stage in 1980's as classical examples of TeV and PeV γ-ray emitters (Weekes 1988; Weekes 1992), one serious school of opinion would like to dismiss away all the previous detection claims as 'red-herrings' on grounds of inadequate statistical confidence levels or non-reproducibility of results, etc. (Chardin and Gerbeier 1989). There is an alternative viewpoint which seeks a reconciliation between the previous detection-claims and recent non-detections by invoking, among other things, source time-variability, and this author subscribes to the second school of thought. Thus, an examination of the overall Cyg X-3 γ-ray data-base, spanning nearly 10 decades of photon energies (~ MeV-PeV) and 25 years of observation period (~1972-1996), supports this viewpoint and suggests that the γ-ray source in Cygnus X-3 may have been witnessing a dramatic secular variation characterized by an e-folding time ~2-3 years (Fig.6). What is remarkable is that the quite strongly-constraining, contemporary upper limits from the CASA-MIA (~PeV), the Whipple Imaging telescope (~TeV) and the EGRET (~MeV) are all compatible with this trend (Bhat et al. 1994b). In a recent work, Bhat et al. (1997a) have attemped to trace back the turn-on phase of the γ-ray source in the Cyg X-3 system to September 1972, when 3 time-clustered giant radio-flares were witnessed from this source (Fig.6) - a rather unique event in the closely monitored radio-flare time-history of this enigmatic system.

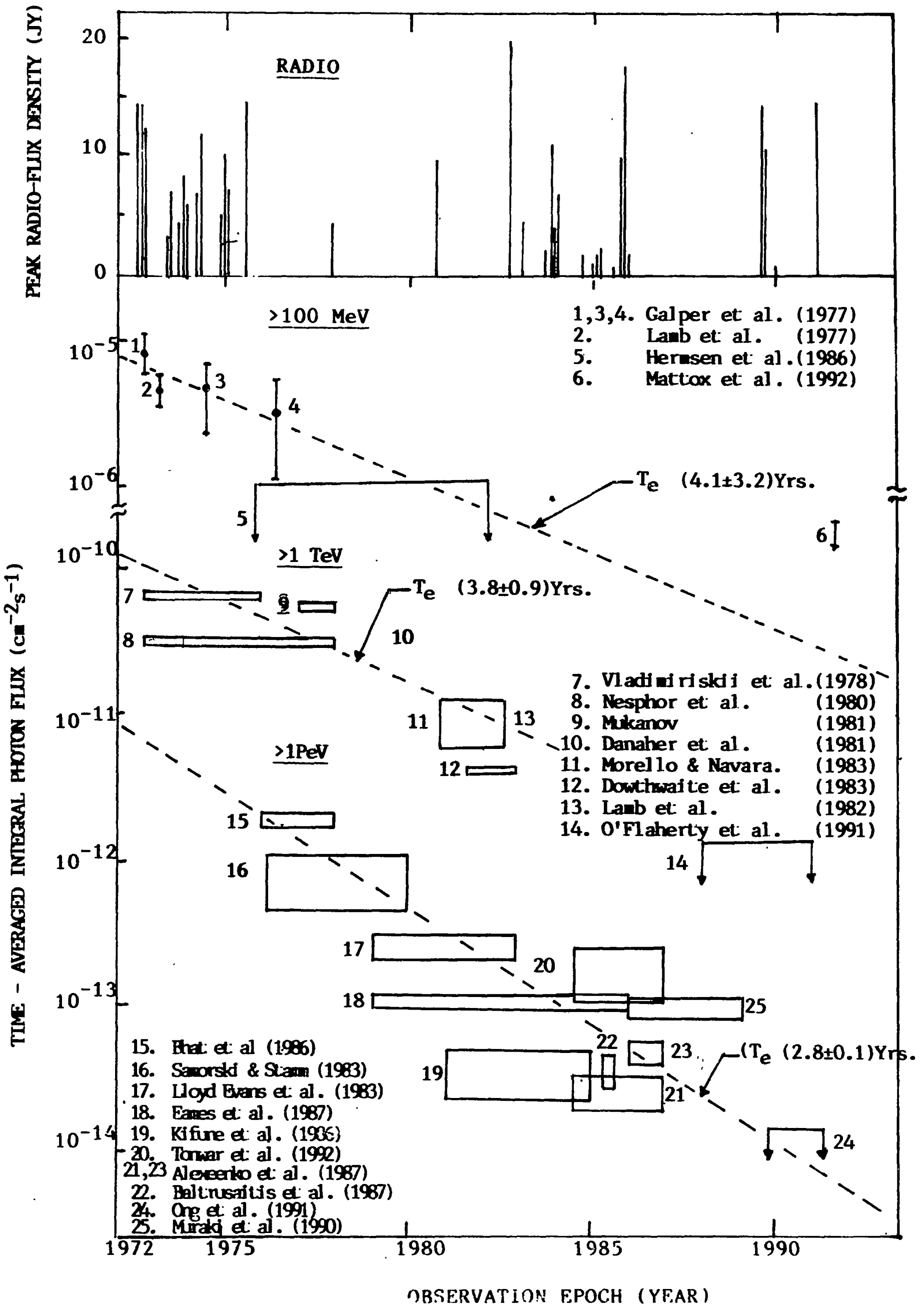

Figure 6. A global picture of the flux measurements carried out on Cyg X-3 over 7 decades of γ-ray photon energies (~100keV - 1 PeV). There is a strong suggestion that the γ-ray source has undergone a dramatic secular variation since it was apparently switched on in 1972, in association with the 3 time–clustered giant radio-flares witnessed from this system that time (see upper panel).

On the other hand, in the case of Her X-1, the weight of cumulative evidence suggests a rather sudden switch-off of the putative TeV/PeV γ-ray source in the post-June 1988 period. Bhat et al. (1997b) have drawn attention towards the systematic trend which is apparent in the derived value of the γ-ray period of the source (Fig.7) : decreasing continously at first with respect to the corresponding X-ray period between ~1983-1986 and then increasing gradually, with effect from ~ June 1986 to revert back to the X-ray period value around ~ June 1988, in apparent time-synchronization with the apparent fading-out of the Her X-1 γ-ray source. In this work, they are investigating the possibility whether such a trend for the time evolution of the γ-ray source period in Her X-1 is consistent with a lump of target matter, which is rotating around the Her X-1 neutron star with a gradually shrinking orbit size, until it has reached the magnetosphere of the neutron star (~post-June 1996) and is ultimately lost there.

Whereas the above-stated line of argument may explain non-detection of γ-ray signals (in the UHE region) from the two galactic sources Cyg X-3 and Her X-1 in the recent epochs, what about the higher-sensitivity experiments like CASA-MIA, HEGRA and EAS –Top drawing a blank in the general source-surveys that they have systematically carried out for UHE γ-ray emissions? Evidently, it would not be plausible to take recourse to the time-variability argument in all cases. The inevitable conclusion that follows is that there are not many UHE γ-ray sources present today, at least ones having brightness levels which are compatible with the (significantly enhanced) detection sensitivies of the present-day arrays. On a closer examination, such a conclusion is not surprising, although it can have momentous implications for the future development of the PeV γ-ray astronomy field : As UHE γ-ray photon beams from extragalactic

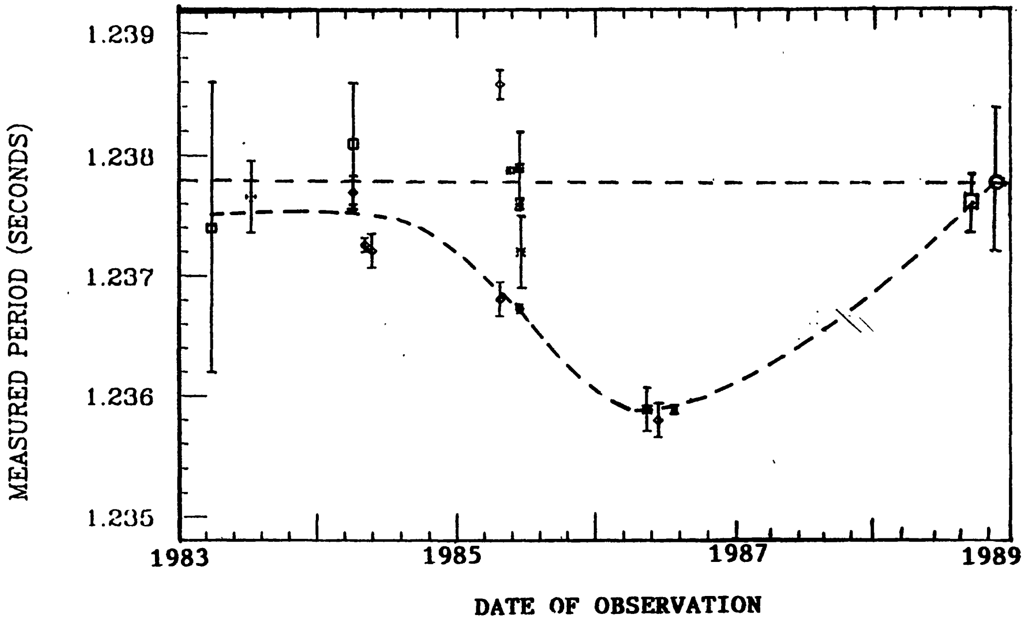

Fig. 7. Apparent systematic variation in the pulsation period of the γ-ray signal detected from the X-ray binary system Her X-1 relative to its X-ray period (horizontal dashed line) over the 10 years period. See Bhat (1993) for references.

distances suffer significant quenching due to their interactions with 2.7°K microwave background in the intervening space, inevitably, PeV γ-ray astronomy has to have essentially a galactic range only.

On the other hand, it is reassuring that the bulk of cosmic rays, with energies going up all the way to the PeV range, are believed to be of a galactic origin, implying that there exist in the galaxy viable accelerators which can boost progenitor particle energies to the UHE region (Drury 1995). What can be the likely sources here and what is the basic recipe via which they can generate UHE γ – rays ? The most promising candidate sources in this context are pulsars, supernova remnants and X-ray binaries in the galaxy for they also meet the desired energy-budget requirements. But the important question to ask, from the view point of the γ-ray astronomy, is whether conducive conditions are obtained in and around these energy-reservoirs for efficiently converting the progenitor particle energies into γ-rays. A mandatory requirement for this is the availability of a proper beam-dump against which the progenitor particle beam would strike, leading to the generation of UHE γ-rays. Two types of beam-dumps, generally considered in the present context, are matter and photonic targets, where γ-rays can be produced largely through (p,p) or (p,γ) interactions via the intermediate π^o-decay process. It is in the case of X-ray binaries that one can readily observe a plausible matter target being offered by the envelope of the secondary star or by the associated accretion column or disk. In the case of the pulsars and supernova remnants, on the contrary it seems comparatively difficult to 'engineer' a viable matter target which can sustain the optimum column density of 50-100gcm^{-2} long enough for these sources to shine as a γ-ray emitter. Instead, photon fields (X-rays to radio), surrounding a pulsar or present around an SNR, in principle, offers a more sustainable photon target against which UHE particle beams, accelerated by the pulsar or the SNR shock-waves, may undergo photomeson interactions to yield γ-rays.

Whereas the $(p+p)$ interaction scenario has been considered fairly extensively in literature in the context of all the 3 potential γ-ray source types, surprisingly, the photomeson process has received comparatively lesser attention so far (see Mitra 1994), despite the suggestion made here that it offers a more viable γ-ray generation-route in the case of SNR and pulsars. It will be desirable therefore that all the related aspects are properly studied and the expected luminosity of the underlying γ-ray source worked out. Admittedly, this is going to be significantly lower than what are the current theoretical predictions for the competing (p,p) process. This may then explain why the recently conducted searches for UHE γ-ray emitters have not met with success : Apparently, the detection sensitivity requirements have been grossly underestimated, presumably because, in designing the new EAS arrays, the main guidance in this respect has been drawn from the flux values quoted for (Cyg X-3 by the Kiel and Haverah Park groups which, in all probability, represent two atypical γ-ray sources (Weekes 1988 and references therein).

3. Future directions

After taking cognizance of the contemporary observational scene and drawing guidance from related theoretical considerations, it would appear to be a prudent strategy that one should primarily concentrate on fully exploring the lower γ-ray energy domain in the coming few years, viz., between ~ tens of GeV to tens of TeV. Two detection methods, presently available for accessing this energy domain, are air-and water-Cerenkov techniques (Ramana Murthy and Wolfendale 1986; Yodh 1996). The former method is relatively more economical and gives excellent direction information, but suffers from the disadvantage of a comparatively lower operational duty-cycle. As for the competing water Cerenkov detector, although a wider slice of the γ-ray window can be spanned by such an experiment with a higher operational duty-cycle, it has a comparatively poorer angular resolution. The latter limitation results in an impairment of the detection sensitivity of water Cerenkov detectors, particularly so in the more promising, lower primary energy regime.

3.1 Major new developments

An extremely useful development for ground-based gamma-ray astronomy and the cosmic ray physics has been the release of the EAS simulation code, CORSIKA, in the public domain by the Karlsruhe group (Capdevielle et al. 1992). The recent versions of this code employ the EGS routines for simulating electromagnetic interactions and the VENUS and the GEISHA routines, for the nuclear interactions that a high-energy γ-ray or a cosmic-ray nucleus and its progeny particles may undergo in the terrestrial atmosphere. Cerenkov routines have also been incorporated in the CORSIKA to account for the atmospheric Cerenkov radiation that the EAS secondaries (electrons, muons and hadrons) produce in the atmosphere. In its present form, the CORSIKA can be reliably employed over the primary energy range of ~10'sGeV-10's PeV and several γ-ray astronomy and cosmic-ray physics groups, all over the world, (including ours), have adapted the CORSIKA code for predicting and optimizing the performance of their respective experiments and, later on, in inter-comparing their results in a more convenient way.

Referring now to developments on the experimental front, it has been decided to close down in the near future the CASA-MIA array of particle-detectors, primarily designed to carry out high-sensitivity investigations in the PeV γ-ray spectral window. On the contrary, the moderate-sized EAS arrays, HEGRA and EAS-Top, set up more or less contemporaneously with the CASA-MIA, are going to continue their operations and will go on providing useful data on possible γ-ray emission from compact sources and source-regions in the PeV energy bracket. On the other hand, big, new experiments, being built presently to cover the PeV energy range, like the KASCADE at Karlsruhe (Rebel, 1995) and the GRAPES-II at Ooty (Gupta et al. 1995), will mainly focus on ultra-high energy cosmic-ray particle, though UHE γ-ray astronomy explorations will also be carried out in a supplementary mode of investigations. The Auger-Pierre project (Watson, 1996), currently in the planning phase, will involve setting up of two $5000 km^2$ giant EAS arrays, one in the Northern hemisphere (USA) and the other in the Southern hemisphere (Argentina), to address the extremely high energy cosmic-ray domain and generate good statistics on events with primary energy values beyond the GZK energy cut-off value ($\sim 3 \times 10^{19} eV$). These arrays are proposed to be equipped with appropriate detector hardware and back-up software to differentiate amongst various primary-particle species, including γ-rays. It may thus be possible to do γ-ray astronomy at the highest-known particle energies ($\geq 10^{20}$ eV) with the help of the AUGER experiment in years to come. Likewise, the Telescope Array project (Teshima, 1992), which is currently undergoing phototype testing in

Utah (USA), will use the twin detection techniques of atmospheric Cerenkov and fluorescence radiations to perform γ-ray astronomy investigations over the unusually wide energy range of 10^{10}-$10^{20} eV$ (apart from cosmic-ray studies at extremely high particle energies).

Two experiments, which are presently operating in the photon energy range of tens to hundreds of TeV, are the Tibet EAS array (Amenomori et al. 1995) and the AIROBICC wide-angle air-Cerenkov detector array (Lorenz 1996). These experiments have been generating data for the last couple of years now, but no source-detections have been possible to date, underlying the need for a further upgradation of the detections sensitivity in this otherwise promising energy window. In response, the Tibet array is undergoing a major augmentation these days. Likewise the MYSTIQUE array of large-area wide-angle atmospheric Cerenkov detectors (Bhat et al. 1994a), which parallels the AIROBICC in its basic detection philosophy, but has a factor of 10 larger effective detection area and a lower threshold energy of ~5TeV, is being planned by us for operation from Mt. Abu as a part of the on-going project GRACE (for **G**amma-**R**ay **A**strophysics **C**oordinated **E**xperiments). For a reasonable background rejection factor of ~99%, the projected sensitivity of this experiment is such that the Compton self-synchrotron model spectrum of the Crab Nebula can be realistically followed upto ~50 TeV energy (de Jager 1995). Another attractive design-feature of the MYSTIQUE array is the real-time reconstruction of the event arrival direction through the innovative artificial neural network approach (Bhat et al. 1995); among other things, this would lead to a substantial data-compaction, an important consideration on account of the high data-throughput anticipated for the full-blown MYSTIQUE experiment.

Figure 8. The Imaging Element of the 4-element γ-ray telescope array, TACTIC, installed recently at Mt. Abu. A 349-pixel Cerenkov light Imaging Camera is mounted in its focal-plane, covering a field of 6° x 6° and with a uniform pixel resolution of 0.31° x 0.31°, for better event calorimetry and image charaterization. Presenlty, innermost 9 x 9 pixels have been made active for image registration and 9 x 4 pixels for trigger-generation.

In years to come, the main attention of various ground-based γ-ray astronomy groups will undoubtedly be centered on the E_γ range lying between tens of GeV and tens of TeV photon energies. This is partly in recogntion of the fact that the detection technology (e.g., Cerenkov Imaging Technique), available here, has already led to successful source-detections and partly because the lower portion of this energy domain represents a totally unexplored ground with excellent prospects for spectral and temporal studies of γ-ray-loud AGN class, recently discovered by the EGRET experiment (Dingus 1995). In the TeV energy interval (~0.1-10 TeV), major new experiments based on the imaging technique, which have started their operations recently, are the CAT Imager at Themis (Degrange 1993) and the 4-element TACTIC array at Mt. Abu (Bhat et al. 1994a). Fig.8 presents a photograph of the Imaging Element of the TACTIC experiment, recently installed at Mt. Abu for carrying out high-sensitivity investigations in the TeV γ-ray spectral window (~ 0.2-20 TeV) as well as cosmic-ray spectral and mass-composition studies in the sub-PeV (~ 10-100 TeV) energy bracket. The highlight design features of the TACTIC are its excellent capability for event calorimetry and primary characterization, based on multi-parameter measurements, including atmospheric Cerenkov pulse time-profile, image, polarization state and spectral content. An updated description of this instrument, expected to be fully operational by December 1997, is given in Bhat (1996). Fig.9a presents evidence for detection of a robust signal (statistical confidence level ~11σ) from the BL-Lac object Mkn-501 by the TACTIC Imaging Element within a few days of this instrument seeing the 'first light' As shown in Fig. 9b, this unprecedented flaring episode from this source has also been picked up concurrently by the CAT-Imager and the Whipple and C-HEGRA telescopes. While the details of this important multi-station observation campaign will be published elsewhere, it would be in order to underline that it is for the first time that a TeV γ-ray signal has been detected simultaneously over essentially a global baseline, marking the start of a scientifically-rewarding phase of coordinated observations in this promising spectral window.

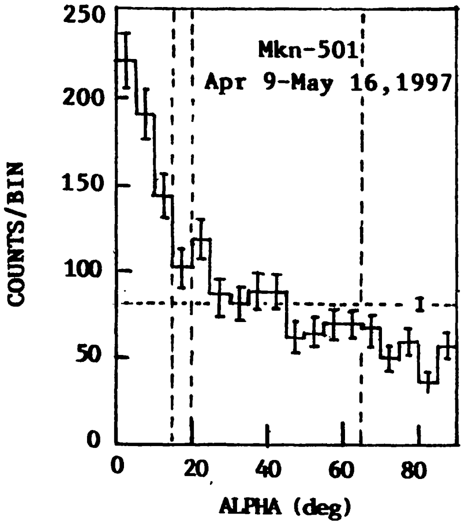

Fig.9. (a) Evidence for a γ-ray signal from the active galactic nucleus Mkn-501, obtained by the TACTIC during its maiden observation campaign on the source from April 9-May 31, 1997. The estimated time-averaged flux for this flaring episode (the first major one detected from Mkn-501) is (7.6 ± 0.7) 10^{-11} *photons* $cm^{-2}\,s^{-1}$ at > 0.7 TeV (~ 4.5 Crab units).

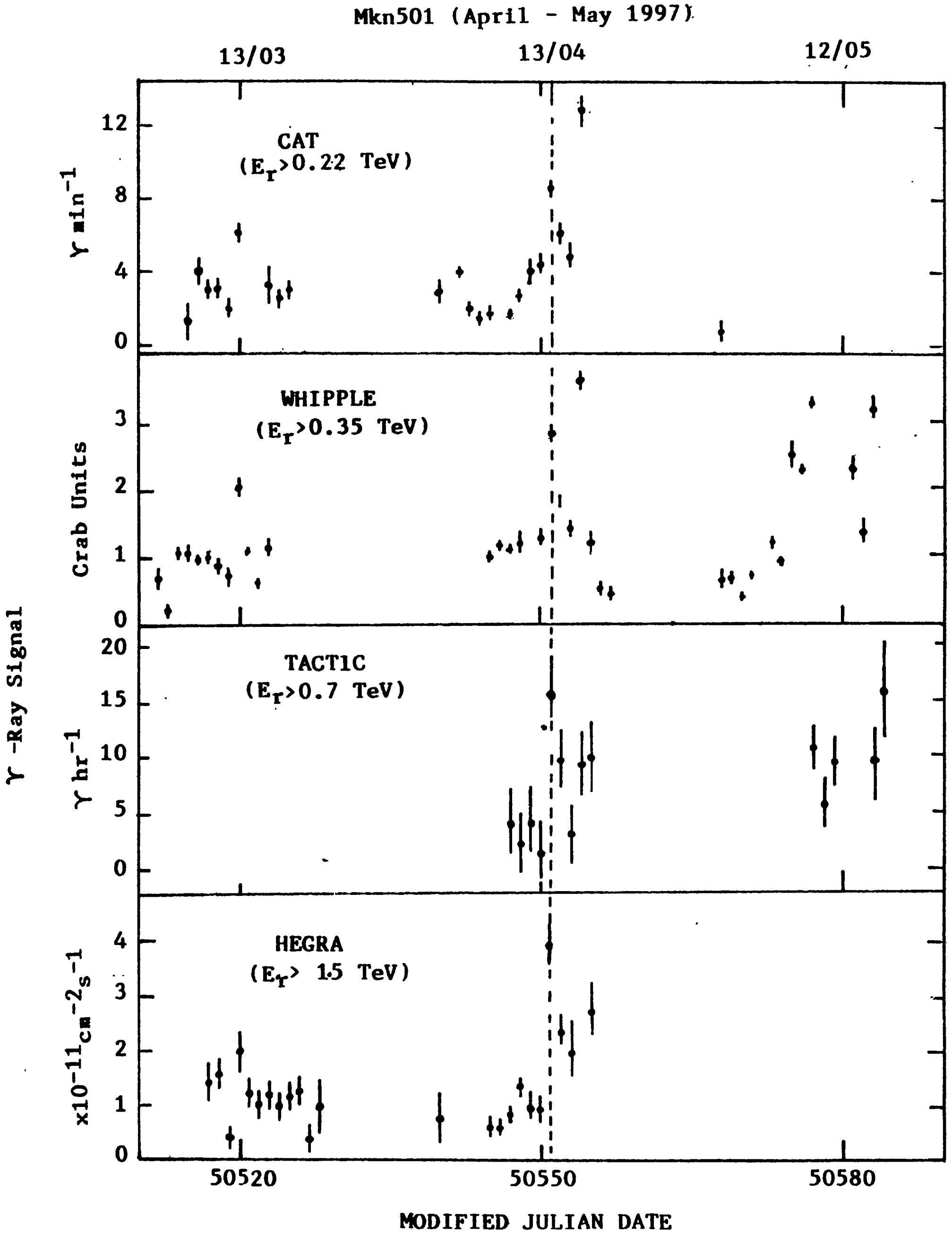

Figure 9. **(b)** Time history of the Mkn-501 flare as seen by the CAT-Imager (> 0.23 TeV), Whipple (> 0.35 TeV), TACTIC (> 0.7 TeV) and HEGRA (> 1.5 TeV). The flare peak of April 13, 1997 is seen in time-synchronization by all the four observatories. This is the first - ever concurrent detection of a γ-ray signal by a global network of Cerenkov detectors.

Several on-going TeV Cerenkov experiments are undergoing a significant upgradation, including the 'old war-horse', Whipple Imaging Telescope (Lamb et al. 1995), where the present camera is being replaced by a bigger one, resulting (as for the TACTIC), in quantitative improvements in its event characterization and calorimetry capabilities. Similarly, the existing C-HEGRA Cerenkov detector array at La Palma is being augmented to a 5-telescope array with a provision for stereoscopic imaging between 2 or more array elements (Hermann, 1995). The MILAGRO water-Cerenkov detector (Yodh, 1996) presently under development near Los Alamos, U.S.A., represents an efficient alternative technique (non-imaging) for accessing the sub-TeV to tens of TeV photon energy range. Although having a significantly poorer angular resolution than air-Cerenkov systems operating in the same energy window, a unique feature of this wide-beam instrument will be its ability to carry out concurrent multi-source observations with additional advantage of a relatively larger operational duty-cycle. This would be a great practical advantage in explorations for VHE tails in cosmic gamma-ray bursts.

The Adelaide collaboration is presently building a 'super-CANGAROO' which will use a 10m Cerenkov light concentrator of high optical quality, thereby allowing this group to work at a lower γ-ray threshold energy of ~20-30 GeV (Kifune and Tanamori 1993). The Lebedev group (Sinitsyna 1995) are working in the direction of supplementing their presently-operating 144-pixel Cerenkov imaging telescope (SHALON-I) at Tian-Shan (Kazakhistan) with one more similar unit (SHALON-II) and, later on, deploy an array of 8 smaller telescopes for measuring the lateral distribution and relative arrival-time information of the registered events. The TIFR group (Bhat 1995) are currently implementing at Pachmarhi (78°.26′E, 22°.28′N, 1075m asl) an augmentation-plan aimed at operating there, in the next few years, a narrow-beam array of 25 Cerenkov detector-banks, each ~4m^2 in area and spread out over a physical area of $85m \times 100m$. This non-imaging Cerenkov experiment seeks a rejection of cosmic-ray background events on the basis of differences expected in the lateral distribution and arrival directions of Cerenkov events induced by γ-rays from a point source as against those by the general cosmic-ray background.

On the Cerenkov image-processing side, the Whipple group (Fegan 1996) have developed new algorithms for image treatment which will enable to study γ-ray sources even at low elevations. On one hand, this important development will help to increase the effective collection area and, on the other, provide access to larger primary energies, thereby permitting to carry out the spectral measurements over an extended E_γ range. The C-HEGRA group (Mathias 1995) have similarly tested an algorithm which makes it possible to determine the primary photon arrival direction with a high degree of precision, even from a single imaging Cerenkov telescope. An important technical innovation, proposed for Cerenkov Imaging cameras by our group (Bhat et al. 1994b), is that of an intelligent trigger-generation scheme, which, on one hand, helps to operate at a relatively lower threshold-energy level and, on the other, provides an effective discrimination against background events generated by stray muons which may thread the glass envelopes of the camera photomultiplier pixels.

Important new experiments being planned in the tens of GeV energy region, are the CELESTE (France; Quebert 1995), STACEE (USA; Ong 1995) MAGIC (Germany; Bradbury et al. 1995) and MACE (India; Bhat et al. 1994a). The first two experiments plan to deploy the heliostat fields available at two defunct solar power stations in Themis (France) and California or

Sandia (USA) to obtain the necessary light-collector area (hundreds of m^2), required for accessing the tens of GeV γ-ray spectral band. On the other hand, the MAGIC and the MACE plan to use single light-weight metallic reflectors of a large aperture (17m for MAGIC and 25m for MACE). The reflectors would be provided with a 2-axes drive system for a full steerability and will carry imaging cameras in their focal planes covering a field of view ~ 3.5°. The MAGIC (Fig.9) will use a high optical quality reflector (made by milling solid 50*cm* 50*cm* - 0.4*cm* thick plate) and a high-resolution imaging camera, most likely based on AsGasP photocathode with an Avalanche Pin diode back-up (expected quantum efficiency ≥ 0.4 in $\lambda \geq 300$nm). Among other things, this will enable the MAGIC to perform low-elevation γ-ray astronomy in the red region of Cerenkov spectrum at TeV photon energies with a significantly increased light collection area. On the other hand, the light collector to be deployed by the MACE is based on the use of a thin Al foil with a honey-comb back-up. The overall surface quality will be just right for using a conventional photomultiplier-based camera with a pixel resolution of ~0.3°. The duplex-design of the MACE camera may enable to discriminate against single muon-generated events by measuring the polarization properties of the recorded Cerenkov light. An interesting design feature of the MACE is the supplementary focal-plane instrumentation being provided to carry out efficient monitoring for cosmic γ-ray bursts in the energy region ~ 10's keV-100's MeV through the atmospheric fluorescence technique (Bhat et al. 1997c).

For Cerenkov systems operating in the tens of GeV region, the main backgrounds to contend with are Cerenkov pulses produced by cosmic rays muons as well as primary electrons and not the cosmic ray hadron-progenitors encountered in the TeV photon bracket (because of the steeper particle -spectra of the muons and electrons). Unlike in the case of protons, except for the orientation parameter, other image-parameters cannot help to reject these background events. Keeping in mind these practical difficulties, an efficient alternative approach has been proposed by the Whipple collaboration for exploring the tens of GeV energy bracket (Weekes 1996). It envisages using an array of 3-10 medium size Cerenkov telescopes, operating either in tandem, in the stereoscopic imaging mode, or as independent systems for a systematic, long exposure monitoring of γ-ray emitters for a possible significant time-variability. This alternative approach has recently been accepted for implementation by the Whipple collaboration under the project name VERITAS (for **V**ery **E**nergetic **R**adiation **I**maging **T**elescope **A**rray **S**ystem).

3.2 Future scientific goals

What scientific agenda can be expected to be served in the next one decade or so, using the above referred high-sensitivity detection systems? The present author would like to propose it to be along the following (admittedly ambitious) lines, mainly with a view to draw the reader's attention to the full gamut of astrophysical investigations which can, at least in principle, be addressed through the γ-ray window : First and foremost, the ground-based γ-ray astronomy should move out of the present strait-jacket of a few-source astronomy to a stage where a comprehensive catalogue of γ-ray sources has been compiled, encompassing both galactic and extragalactic objects of different genres. Equally important, the spectral and temporal properties of cosmic γ-ray sources should be thoroughly studied to facilitate modelling of the underlying particle-acceleration mechanism(s) and the γ-ray generation process(es). The possibility of exploiting the extragalactic sources as an efficient probe of the foreground radiation fields

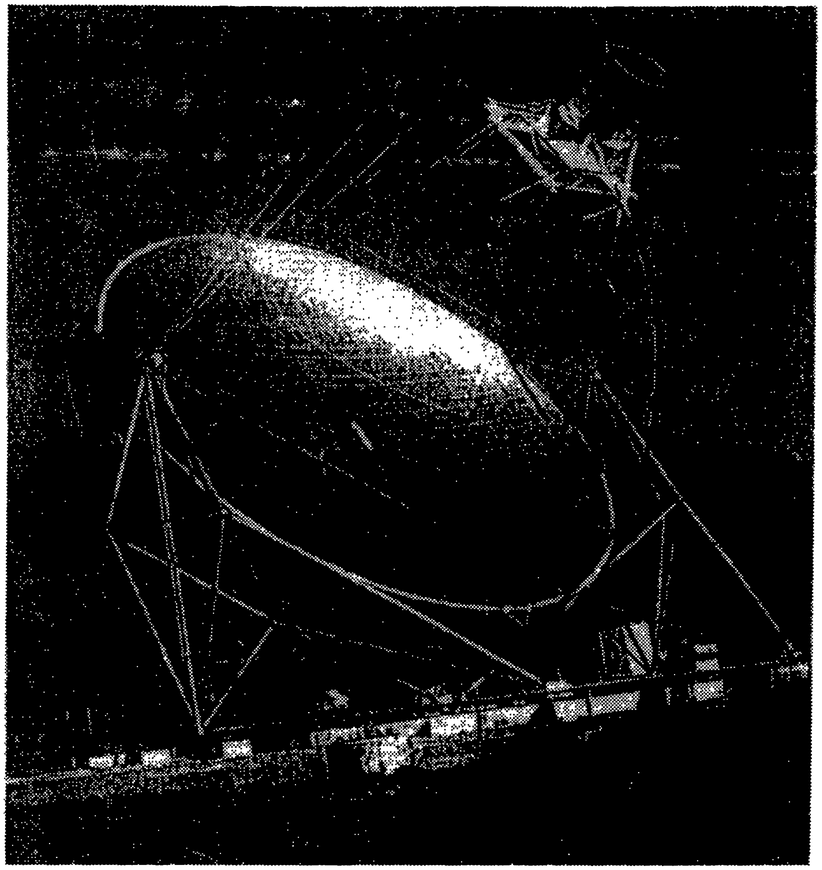

Figure 10. A sketch of the 17m-diameter paraboloid light concentrator of the MAGIC γ-ray telescope proposed for γ-ray investigations in the as-yet inaccessible, albeit promising, tens of GeV energy bracket.

should also be properly explored (Stecker and de Jager 1996). Alternatively, spectral data from γ-ray loud active galaxies may be carefully examined in order to obtain an independent estimate of the Hubble constant and hence the age of the universe (Salamon et al. 1994). As for the galactic γ-ray emitters, their detailed studies may be undertaken in order to obtain clues to the conditions of matter and radiation fields surrounding these objects. More specifically, if γ-ray emitting binary pulsar are discovered in years to come, the resulting data may be used for testing the general theory of relativity, as has been demonstrated so convincingly at radio frequencies, using the Hulse-Taylor binary pulsars. Yet another challenging area can be the detection of gamma-rays from extended source-regions and of a genuine diffuse origin (Borione et al. 1995). A serious attempt should be made to identify the cosmological window in this diffuse background (Protheroe and Stanev 1993), and thereby obtain important leads about the origin of extremely high energy cosmic ray component. The possibility of the γ-ray line emission at $\sim$ 0.1-1 TeV, due to annihilation of neutralions, the SUSY-predicted elementary particles and dark matter candidates (Buckely and Jungman 1995), may also be investigated as should be the generic relationship between production sites for neutrinos and γ-rays at ultra high-energies.

Acknowledgements

This review is a written version of the invited talk given by the author at the 17th meeting of the Astronomical Society of India, organized in Guwahati, Assam in January 1996. CLB would like to thank the Scientific Organizing Committee of this meeting, headed by Prof. H.L. Duorah, Vice-Chancellor, Guahati University, for extending the necessary invitation. I also take this opportunity to thank all my colleagues in BARC-NRL for sparing me time for attending to this work. Finally, I express my gratitude to the anonymous referee for valuable comments, which have helped to make this review-article more topical and, hopefully, more readable.

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