Silver Jubilee article

Gamma-ray astronomy activities in BARC – Past contributions and present challenges

H. Razdan and C.L. Bhat

Bhabha Atomic Research Centre, Nuclear Research Laboratory, Mumbai 400 085, India

Abstract. It was in the early seventies that we made a modest start in the Nuclear Research Laboratory (NRL) of the Bhabha Atomic Research Centre (BARC) in the then-budding field of observational gamma-ray astronomy by setting up an atmospheric scintillation experiment to search for prompt γ-ray emissions from supernovae explosions and primordial black-hole outbursts. This Gulmarg (Kashmir)-based experiment also permitted us to deploy, in a supplementary mode of operations, the atmospheric Cerenkov detection technique to investigate the cosmic-ray energy spectrum around the 'knee' position and, more significantly, to obtain corroborative evidence for the reported ultra high energy γ-ray emission from the enigmatic galactic X-ray source Cyg X-3. This early, exploratory stage (1974-1984) was followed by the first consolidation phase (1984-1992), when we commissioned a multi-mirror atmospheric Cerenkov telescope in Gulmarg and obtained evidence for possible TeV γ-ray emission from several γ-ray source candidates. With over 20 years of experience behind us in the related experimental techniques and theoretical concepts, we have recently embarked on a more ambitious second phase of consolidation (post-1992), with the principal aim of establishing a new, international class astronomy facility, GRACE, in Mt. Abu, Rajasthan. Four high-sensitivity experiments are being set up under this project in order to comprehensively investigate nearly 10 decades of the γ-ray spectral window (10's of keV - 100's of TeV) from one location to operate in time-correlation with one another and with other major experiments in India and overseas, addressing other related spectral bands. In this, largely 'flash-back' narrative, we retrace the path along which we have journeyed over the past 2 decades, referring on the way to some 'bench-mark' investigations successfully carried out over the years on various topical themes, by us and our colleagues in NRL unit of BARC.

1. Introduction

The seventies represent a water-shed decade in the evolutionary history of experimental γ-ray astronomy, in as much as that it was during this period that 4 observational milestones were attained in the field, viz., (i) the serendipitious discovery of cosmic gamma-ray bursts by the

Vela-class of satellites (Klebesdal *et al.* 1973); (ii) the first ever map of the galaxy in the γ-ray light by the SAS-2 satellite (Fitchel 1977); (iii) the unambiguous detection of the 0.511 MeV positron-annihilation line from the direction of the galactic centre in a balloon experiment, marking the birth of the γ-ray line-astronomy (Leventhal *et al.* 1978); and (iv) the first evidence by the Crimean Astrophysical Observatory for the TeV γ-ray signal (1 TeV ~10^{12} eV), from the enigmatic X-ray binary source Cygnus X-3, displaying the tell-tale signature of its well-known 4.8 hour-period modulation feature (Neshpor *et al.* 1979). These 'corner-stone' observational-leads have been vigorously pursued over the intervening-period, leading to an impressive progress in this comparatively younger astronomical field. It was during these exciting, early times, that a potentially important development was also taking place on the theoretical front : it was Stirling Colgate's extensive work on the hydro-magnetic shocks in type II supernovae explosions, with possible far-reaching implications on the long-outstanding problem of cosmic-ray acceleration and origin (Colgate 1968; Colgate 1974). As an important corollary, it followed from this work that such an explosion would be accompanied by the release of an intense, short time-scale burst of ~MeV-GeV γ-rays, with an estimated total energy release of ~5 x 10^{47} ergs. Calculations showed that such an energetic γ-ray burst would excite optical fluorescence emission in the terrestrial atmosphere, which, because of the expected impulsive character of the incident burst, could be detected with a fairly simple experimental set-up. This rather rare combination − strong academic motivation coupled with the need for only a relatively modest resource allocation for accomplishing it − encouraged us to build the necessary detection system and become a part of an international network of 'supernova-explosion watchers', albeit via the unconventional route of γ-ray induced atmospheric fluorescence emission (Fitchel *et al.* 1968).

A similar supernova-induced gamma-ray burst experiment was set up those days by the Tata Institute of Fundamental Research (TIFR) under the leadership of Prof. B.V. Sreekantan. It was conducted for only a short period in Naini Tal and could not generate any conclusive results. On the other hand, the TIFR group, instead, concentrated on ground based searches for very high energy (TeV) and ultra high energy (PeV) photons from cosmic sources, a frontline area where they have carried out pioneering work, both, in the national and international contexts. They have been making these investigations regularly for well over 25 years with atmospheric Cerenkov telescopes and medium-size particle-detector arrays at Ooty and Kolar in South India. During the last several years, the TIFR group has shifted the atmospheric Cerenkov work to Pachmarhi, where the sky-conditions are better and the anthropological noise level is significantly lower than that at Ooty. While a discussion on the TIFR activities in the field of gamma-ray astronomy is beyond the scope of the present paper, it would be in order to underline that a string of important results, some of them world-firsts, have been obtained by them through their Ooty, Kolar (KGF) and Pachmarhi experiments. We refer the reader to the excellent reviews by Rao and Sreekantan (1992) and Vishwanath (1982) for getting a feel of the early work by the TIFR (see also Ramana Murthy and Wolfendale 1986) in the field of ground-based γ-ray astronomy. While on the subject, it also needs to be pointed out that the TIFR scientists have also been quite active in the generically-related field of lower energy γ-ray and X-ray astronomies and have successfully flown a number of γ-ray and X-ray payloads on balloon-and satellite platforms (Agarwal 1991).

Returning now to the subject of detection of the postulated prompt γ-ray emission from supernovae explosions, it eventually turned out that the original suggestion of Colgate was too optimistic (Colgate and Petschek 1979) and the Gulmarg atmospheric fluorescence experiment (or any of its international peers) could not unequivocally establish a generic relationship of the Gulmarg-detected candidate events with a known supernova explosion or any other cosmic phenomenon (Bhat 1985). On the other hand, the omnibus nature of this exploratory experiment allowed it to detect single cosmic ray particles and γ-ray photons in the ultra-high energy region (> 5 X 10^{14} eV) through the atmospheric Cerenkov detection technique (Jelley 1958). The resulting data-bases helped to independently establish the presence of a knee-feature in the primary cosmic-ray energy spectrum (Bhat *et al.* 1977) and, quite remarkably, when considered alongwith the related evidence presented by other groups, also suggested that the ultra-high energy (UHE) γ-ray source in the Cyg X-3 was in its brightest-known phase in 1976-77 and has, there onwards, undergone a drastic secular variation in its luminosity (Bhat *et al.* 1986).

Two other noteworthy explorations, carried out during this nascent phase, involved setting up multi-station, time-coordinated experiments. One of them employed wide-angle photomultiplier detectors simultaneously at Gulmarg and Srinagar, constituting a 30km baseline, to search for simultaneous arrival of short time-scale optical and γ-ray emissions from the explosive evaporation of mini-or primordial black-holes (Hawking 1971; Bhat *et al.* 1980). The other experiment was based on small particle-detector arrays which were operated at Gulmarg and Ooty to search for relativistic dust-grains of the pulsar origin (Bhat et al. 1984 and references therein). Both these 2-station experiments required accurate absolute time-information for event-tagging and an important technical development, successfully accomplished during this phase, was that of developing precision time-synchronizing systems, using high-frequency and TV vertical-synchronization pulses as reference time-markers (Bhat *et al.* 1979; Bhat *et al.* 1982).

The first consolidation phase of our γ-ray astronomy activities started in 1980's, leading to the indigenous development and deployment of the multi-mirror atmospheric Cerenkov telescope at Gulmarg (Koul *et al.* 1989). During the 5-years period that this telescope was used (1985-1990), several genres of cosmic objects were looked at and evidence obtained for possible TeV γ-ray emission from some of these candidate-sources (Razdan 1989; Bhat 1993). Recognising the urgency for working, now, with higher-sensitivity detection systems at an observatory site with substantially better observation conditions than those obtained at Gulmarg, we have recently embarked on a second consolidation phase and are presently setting up a new γ-ray astronomy facility at Mt. Abu, Rajasthan (Bhat *et al.* 1994). Four world-class experiments are being set up there in a phased manner with a view to address the γ-ray spectral window over nearly 10 decades of photon energies (10's keV to 100's TeV) and investigate a variety of interesting γ-ray phenomena in a detailed manner.

In what follows, we shall present various important milestones of each of these phases of our γ-ray astronomy programme.

2. Exploratory phase

2.1 Detection techniques

The atmospheric mantle around the earth does not permit primary cosmic-ray and γ-ray radiations to reach the terrestrial surface. On the other hand, if the primary particle energy is sufficiently high ($\geq$ tens of GeV), this particle, alongwith its progeny, undergoes nuclear and/or electromagnetic interactions with various nuclei in the lower atmosphere (Fig. la). Eventually, this culminates in the development of an extensive air-shower (EAS), comprising a core of hadrons and muons (in the case a of hadron-induced cascade) and an outer, laterally extended disc, populated by secondary electrons, γ-rays and muons (the latter, in a negligible number, in the case of a photon-induced primary). Of main concern to us, here, is the electron component of the EAS (Weekes, 1988), which, being numerically dominant and well spread-out laterally, can be efficiently detected as such at primary energies $> 10^{14}eV$ at a high altitude station, like Gulmarg, with the help of a spaced-array of conventional particle detectors (scintillator-based or water-Cerenkov type), as sketched in Fig. la.

On the hand, while hurtling down the atmosphere with relativistic velocities, the electron- and the muon-secondaries in an EAS polarize the ambient atmospheric molecules and shock them into producing a fairly collimated beam of optical Cerenkov photons (typical emission-cone semi-angle ~1°). Unlike the electron secondaries themselves, the tertiary Cerenkov photons largely escape atmospheric attenuation in the visible spectral band (λ ~300-600nm) and can be detected from a clear, dark site with the help of a fast photomuliplier tube (PMT)-based light detector, which is generally supplemented with an appropriate light-focussing optics (spherical-or parabolic mirrors) to push down the value of the minimum detectable primary energy. This constitutes the basis of the atmospheric Cerenkov detection technique (Jelley 1958), which was used at Gulmarg for γ-ray source studies in the ultra-high energy (UHE) bracket (Fig. la).

Yet one more detection method makes itself available for effective exploitation when it is realized that the electron-secondaries, down to a few eV energy, can interact with the atmospheric molecular nitrogen and ionize and /or excite it, eventually resulting in the release of isotropic atmospheric scintillation light (Fazio 1967). The most prominent emission band is the one at (391.4 $\pm$ 2) nm, produced by molecular–nitrogen ions(N_2^+), which, as is shown in Fig.la, may be detectable from a far-off distance from the ground ($>$ 100m) on a clear, dark night with the help of a PMT-based detection system. In addition to a single, ultra-high energy primary producing the scintillation light at lower atmospheric altitudes through the intermediary role of EAS electron-secondaries, as outlined above, this light can also be generated at a higher atmospheric altitude ($\geq$ 50km) by a burst of lower energy γ-ray photons (E_γ ~ 10's keV to 100's MeV). It is this detection mode (see Fig. lb) which was deployed at Gulmarg in search for prompt γ-ray emission from supernova explosions.

2.2 Gulamrg wide-angle photomultiplier experiment

In its main configuration (Fig.2), this experiment deployed 3 closely-placed, vertically-oriented, large-area photomultiplier tubes (30cm-dia, EMI 9545 B) which were provided with cone-
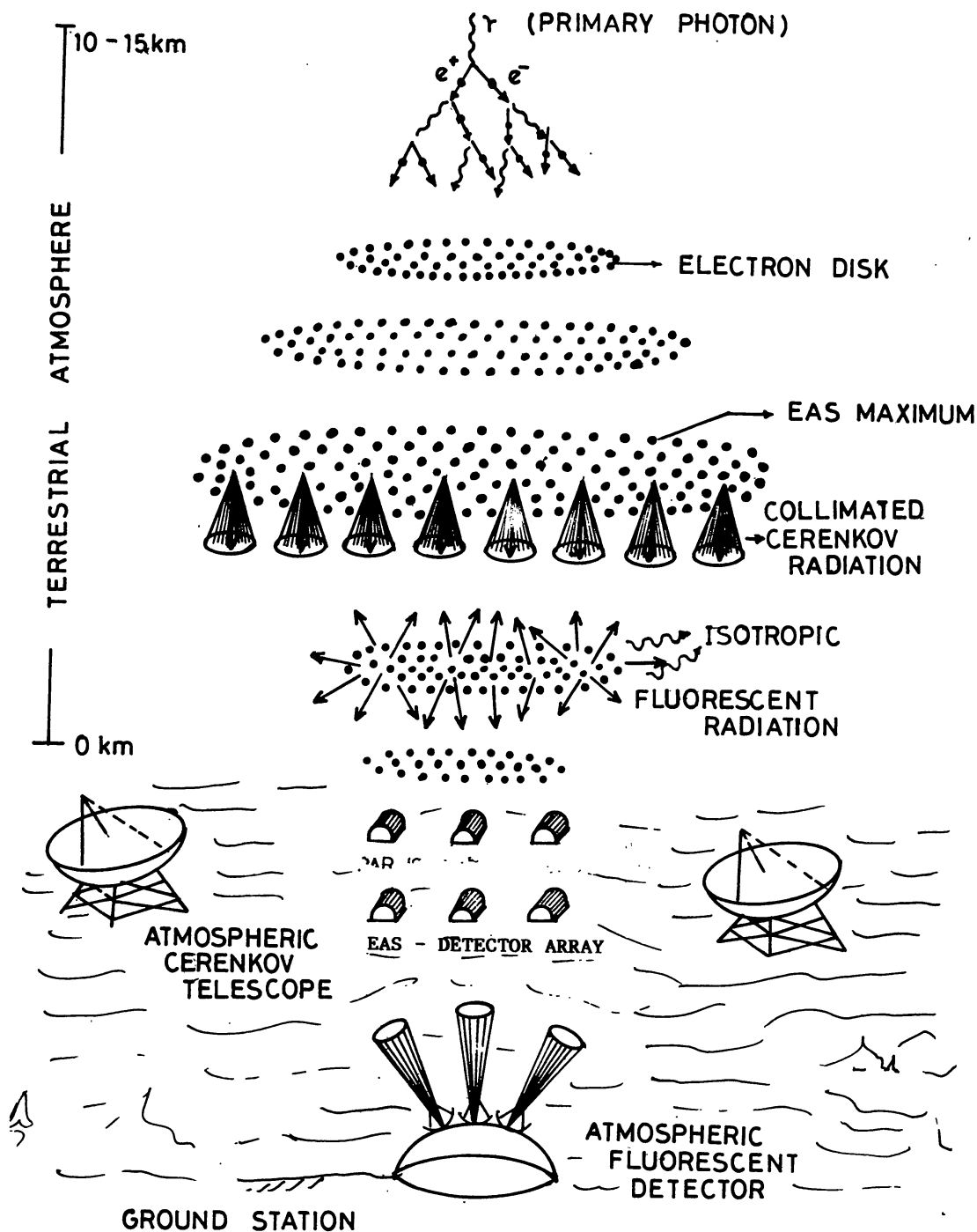
Figure 1(a). A schematic representation of 3 detection techniques, viz., those of extensive air-shower, atmospheric Cerenkov and atmospheric fluorescence, employed to detect ultra-high energy cosmic-ray particles and γ-ray photons through the beneficial transducing-role of the terrestrial atmosphere.
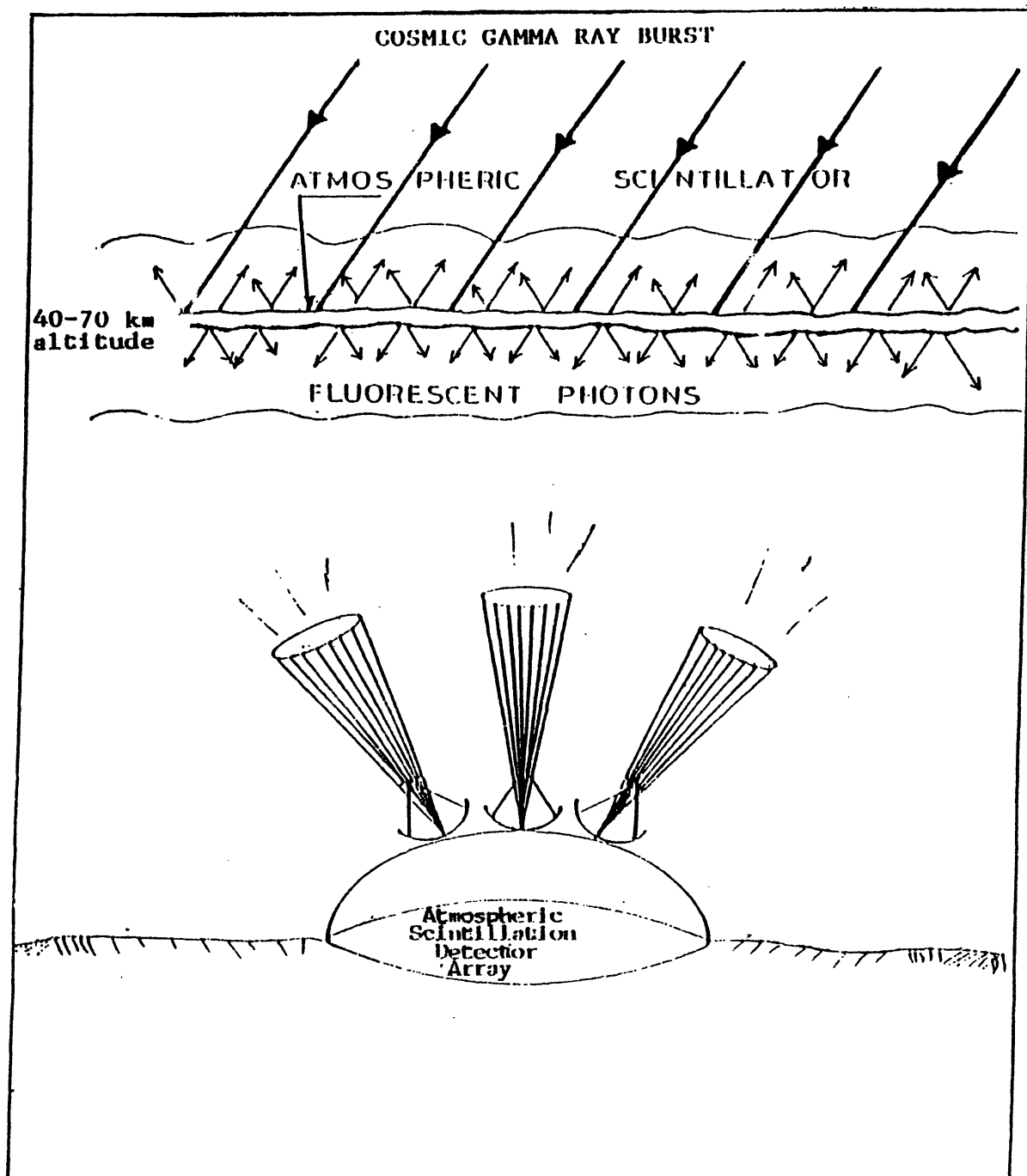
Figure 1(b). The principle behind the atmospheric fluorescence technique proposed in early seventies, for detection of short-duration γ-ray bursts of supernova or primordial black-hole origin.
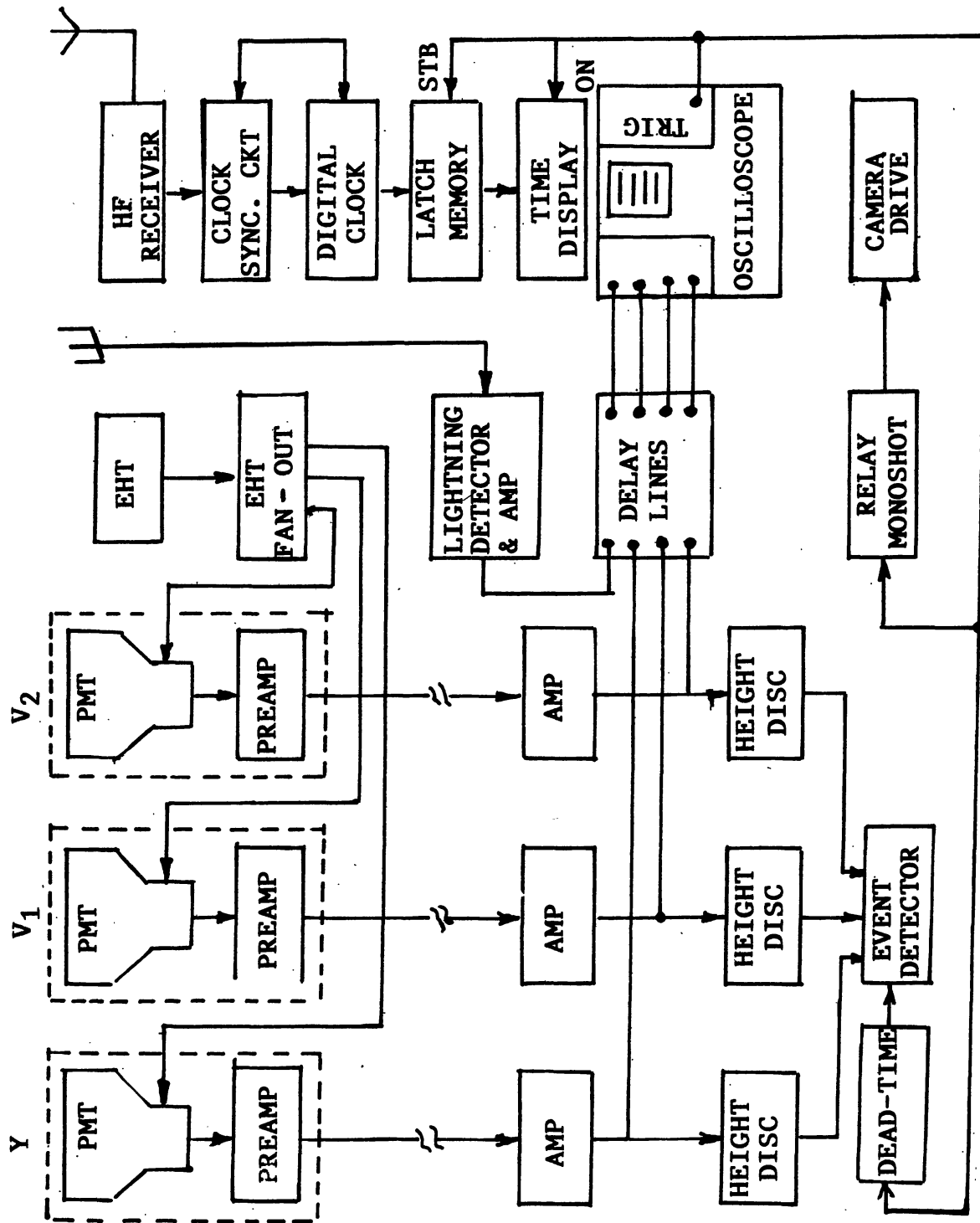
Figure 2. A block-diagram representation of the wide-angle photomultiplier system used in Gulmarg, Kashmir, during 1973-1983, for a variety of exploratory investigations, including those for prompt γ-ray emissions from supernova and primordial black-hole explosions, using atmospheric fluorescence technique, and for ultra-high energy cosmic-rays and γ-ray photons via the atmospheric Cerenkov detection mode.

collimaters to restrict their overlapping field of view to a semi-angle of 50° relative to the zenith. 2 PMT detectors, referred to as the Violet or V-channels, were provided with wide-band optical filters to restrict their response to wavelengths $\lambda \sim 300 - 450 nm$. Similarly, the third PMT detector, called the Yellow or Y-channel, was 'capped' on the photocathode side with a wide-band filter which permitted photons with $\lambda \sim 450 - 600 nm$ to preferentially reach the detector. By demanding a time-correlated signal in the V-channels only, this broad-band spectral cut, implemented on-line, provided a simple albeit effective method for identifying atmospheric fluorescent events. A unique feature was the incorporation of a lightning detector (L-channel) in the Gulmarg experiment. This supplementary channel detected short-term variations in the atmospheric electric field, induced by lightning discharges. It proved quite beneficial in tracking down optical transients of lightning origin, which otherwise were 'look-alikes' of atmospheric fluorescence pulses in their gross spectral and temporal signatures (Bhat *et al.* 1987).

The time constant of the system electronics was chosen to be in the microsecond range. While, on one hand, this small integration time allowed an efficient monitoring of atmospheric fluorescence pulses of supernova origin, it also permitted the Gulmarg experiment to be triggered by atmospheric Cerenkov radiation events produced by ultra-high energy cosmic rays and γ-rays (Jelley 1958). The triggering rate of the system due to these events averaged around $\sim 1 \ minute^{-1}$, corresponding to a primary γ-ray threshold energy of $\sim 5 \times 10^{14} \ eV$.

All the events, triggering the Gulmarg system, were displayed by a 4-beam Cathode Ray Oscilloscope and were recorded on a 35mm-photographic film alongwith the event-epoch. The time-information was provided by a local clock with a precision of $1 \mu s$ and an absolute time-accuracy of a fraction of a second. Fig.3 shows some representative examples of events recorded by the Gulmarg experiment.

2.3 Important results

The most important result from the Gulmarg wide-angle photomultiplier experiment is based on a time-series analysis of the atmospheric Cerenkov pulses, recorded by it from the general direction of the enigmatic X-ray source Cygnus X-3 (R.A. $\sim 20 \pm 03h$). When the data were folded modulo 4.8 h-orbital period of the source, a 4.5σ significant excess of events appeared in the orbital-phase region ~ 0.6 (Fig. 4a). If attributed to Cygnus X-3 generated γ-rays, this excess translates to a detected source flux of $\sim (1.6 \pm 0.4) \times 10^{-12} \ photons \ cm^{-2} s^{-1}$ at γ-ray energies $> 0.5 \ PeV$ for the observation-epoch 1976-77 (Bhat et al. 1986). This flux value turns out to be a factor of $\sim 1.5 - 2$ more than the flux quoted by the Kiel group in their discovery paper for the following 4-year period 1977-80 (Weekes 1988), when account is taken of the differences in their respective threshold energies and due allowance is made for attenuation of the UHE photon-beam from the source through γ–γ interactions with the universal microwave background.

Following its publication, the Gulmarg result (Bhat *et al.,* 1986) attracted a lot of international attention (e.g., Weekes 1988; Chardin and Gerbeier 1989), which was quite understandably tempered with some skepticism also, for the question bothering everybody

(including us) was how could such a simple system detect this signal against an admittedly-large cosmic-ray background and difficult-to-quantify possible systematic effects induced, for example, by night-sky light variations, etc. A collation of the Gulmarg-derived flux-value with the results, obtained over the succeeding years by other groups with more sophisticated systems, may provide the answer : As is evident from Fig. 4b, the γ-ray source in Cyg X-3 may have apparently undergone a dramatic secular variation in its luminosity over the last 20 years or so and the Gulmarg experiment was probably fortunate to catch this enigmatic source 1-2 years even before the Kiel group, when it was presumably in a comparatively brighter state and sufficiently luminous for the Gulmarg experiment to pick it up. This proposal for a long-term cooling of the Cyg X-3 γ-ray source, put forth by us as early as 1985, has gained a wide acceptance in recent years (Weekes, 1992), though there continue to be some adherents for the alternative view point also, viz., all the Cyg X-3 detection-claims made so far are not sufficiently convincing and need to be viewed with caution (Chardin and Gerbeier 1989).

Another interesting, early result from the Gulmarg wide-angle photomultiplier experiment (Bhat *et al.* 1977) was the establishment of the knee-feature in the cosmic-ray spectrum at primary energies $\sim 10^{15}$ eV through the independent route of the atmospheric Cerenkov technique (Fig.5) and thereby vindicating the viewpoint that this feature is not an artifact of the air shower detection technique but of a genuine astrophysical significance. It is noteworthy that, even today, the exact delineation of this feature on the primary energy-scale, as also seeking an answer to the underlying physics, is engaging the attention of cosmic ray physicists, on both, theoretical and experimental fronts.

Yet another elegant result from the Gulmarg exploratory phase is summarized in Fig.6 : it confirms the expectation that the average relative amplitude of an atmospheric fluorescence pulse is significantly more in the V-band ($\lambda = 300\text{-}450nm$) than in the Y-band ($\lambda = 450\text{-}600nm$), compared with the corresponding amplitude-ratio for an atmospheric Cerenkov pulse (Bhat *et al.* 1985). As a corollary, it follows that these two event-classes can be distinguished from each other and, more significantly from a practical point of view, from the virtual deluge of shot-noise fluctuations induced by night-sky background-light, by exploiting the inherent spectral differences amongst the 3 populations and using the resulting V/Y amplitude-ratio parameter. This early lead from the Gulmarg exploratory phase has provided today a novel approach for significantly decreasing the operating threshold energy-level of the TACTIC γ-ray telescope system, which is being built presently for installation at Mt. Abu, Rajasthan (see section 4 below; also Bhat *et al.* 1994).

Several candidate fluorescent pulses, with a time-signature similar to that predicted for the impulsive γ-ray bursts of supernovae origin, were identified from the Gulmarg data-bases. In general, it did not become possible to collate them with the data recorded by similar systems at Naini Tal and Ankara (Turkey), mainly due to limited overlap in the respective observation periods at the three experimental sites (See Bhat *et al.* 1985 and references therein). This turned out to be the main handicap in examining candidate events for a possible cosmic association, particularly so with the several supernovae explosions which were optically detected during the corresponding period and had positions consistent with the field of view and the observation schedules of the Gulmarg experiment. Accordingly, only upper limits could be

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(a)

(b)

(c)
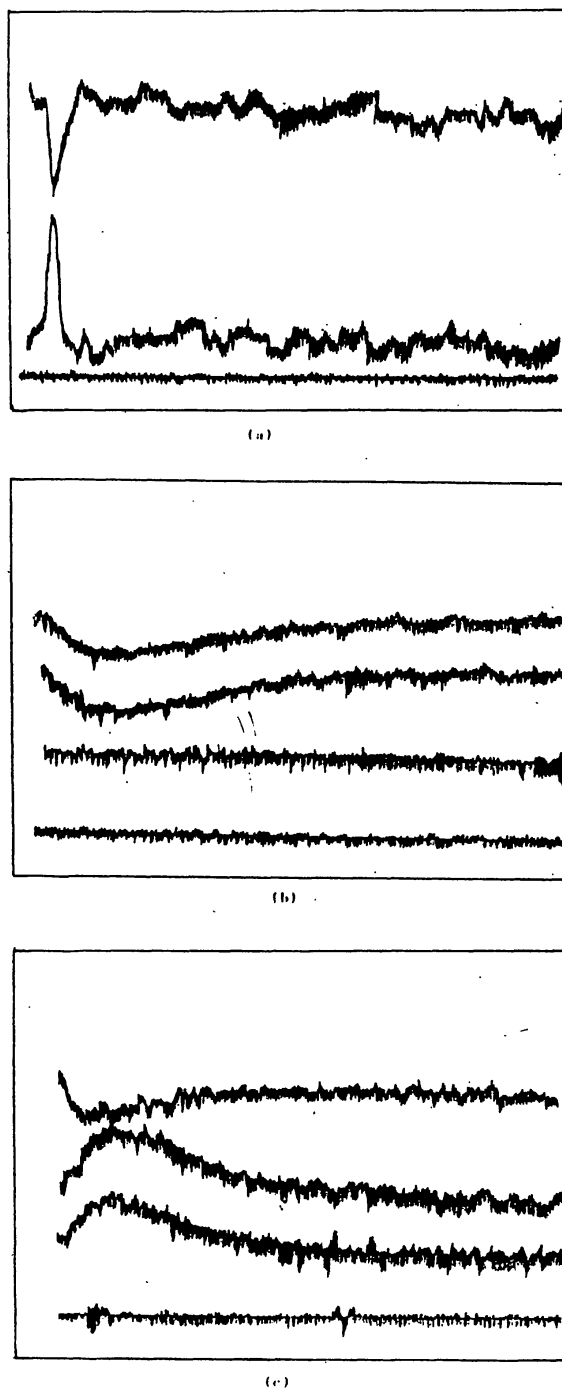
Figure 3. A sample of representative events recorded at Gulmarg during the exploratory phase of 1973-1983, using the wide-angle photomultiplier system sketched in Fig.2: (a) an atmospheric Cerenkov pulse generated by an ultra-high energy (> 5 x 10^{14} eV) cosmic-ray or γ-ray photon primary; (b) a candidate atmospheric fluorescence event of possible cosmic origin; (c) an optical pulse of lighting origin, as revealed by significant activity in the 4th (bottom) trace of oscillograph. Top trace is displayed in an inverted mode in all the 3 oscillograms.
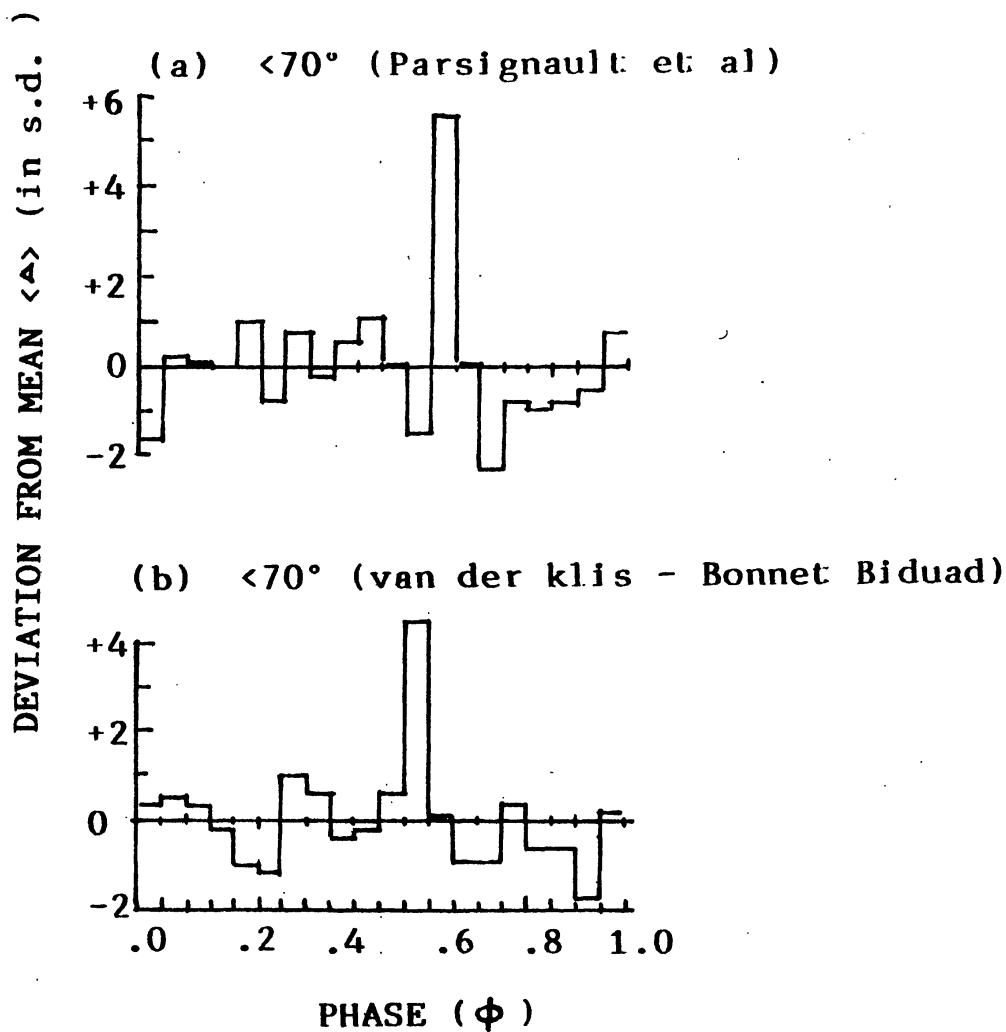
Figure 4a. The light curve of the ultra-high energy γ-ray source in the Cyg X-3 binary system as suggested by the Gulmarg wide-angle photomultiplier system for the epoch 1975-76–an excess of events is evident in the on-source data recorded within the zenith angle of $\psi < 70°$ by this system at the Cyg X-3 4.8h-period phase of $\phi_{4.8h} \sim 0.6$. The epoch-folding has been done using Cyg X-3 ephemerides due to Parsignault et al. (old) and Van der Klis and Bonnet-Bidand (new).
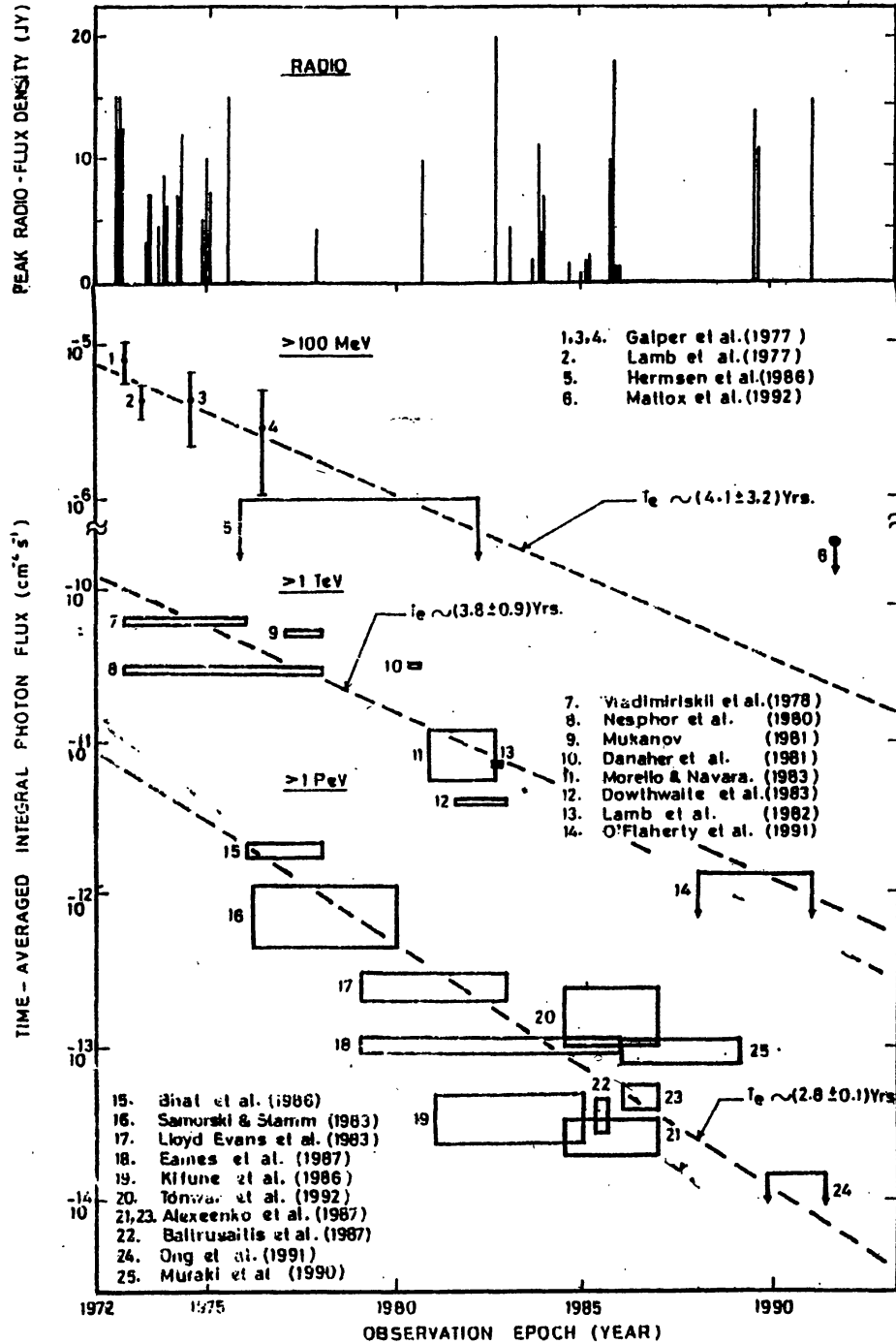
Figure 4b. An inter-comparison of the flux values and upper limits as suggested for the Cyg X-3 γ-ray source at > 1 PeV by various experiments carried out from 1976-77 (Gulmarg) to the present epoch (1995-96; CASA-MIA). There is a strong suggestion that the source may have undergone a rather dramatic secular variation – an observation made first by Bhat et al. (1986) and one, which appears to be holding on even in the face of more recent observations carried out in MeV-GeV, TeV and PeV energy regions with more sensitive experiments. The top panel gives the time-history of the giant radio-outbursts detected from this source over the last 2 decades or so.
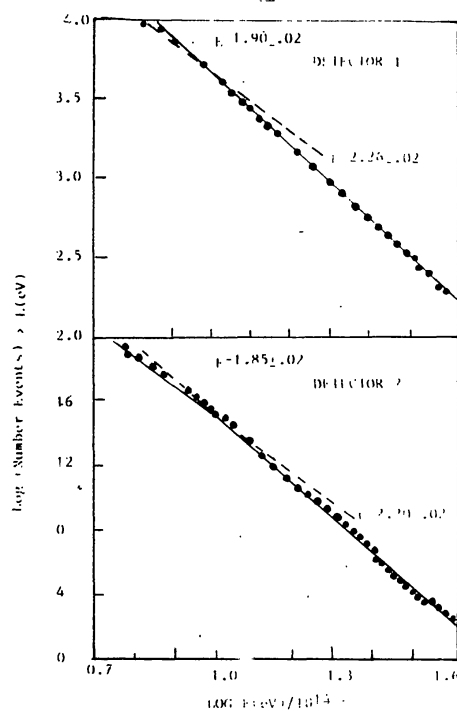
Figure 5. Evidence supporting presence of a knee-feature in the cosmic-ray energy spectrum at primary energies $\geq 10^{15}$ eV, obtained for the first time, using the independent atmospheric Cerenkov date technique at Gulmarg (adapted from Bhat et al., 1977).
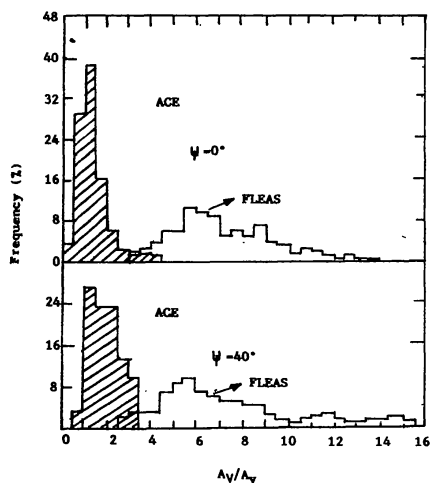
Figure 6. Effective segregation of ultra-high energy cosmic-ray-generated atmospheric fluorescence (FLEAS) and Cerenkov pulses (ACP) based on the use of the V/Y spectral parameter. Here V represents the signal amplitude in the Violet (V) spectral band ($\lambda\sim$300–450nm), while Y stands for the corresponding amplitude in the Yellow (Y) band ($\lambda\sim$450–600nm). The elegant concept underlying this early Gulmarg result is finding use today in improving the sensitivity of the new-generation TACTIC telescope. ψ refers to the zenith angle towards which the fluorescent detector axis was oriented during observations.

derived for the overall energy associated with the postulated γ-ray burst of a supernovae origin (Bhat 1985).

Late seventies saw a flurry of theoretical activity, triggered by the pioneering work of Stephen Hawking on the quantum-mechanical treatment of black-holes (Hawking 1971; Hawking 1974; Page and Hawking 1976). An important sequel to this work is that primordial or mini-black-holes (pbh), presumably, formed during density fluctuations in the early universe, should undergo a terminal phase of runaway mass-loss and those with masses $\sim 10^{15} gm$ may explosively evaporate in the present epoch. These explosions would manifest themselves as γ-ray bursts, with the burst time-scale and spectrum depending on the details of the particle-interaction model actually guiding black-hole evolution near its terminal stage. Thus, while composite particle model predicts a burst of $\sim 0.1\text{-}1 GeV$ photons with a duration of $10^{-7} s$ and an overall energy of $10^{35} ergs,$ the burst energy is 10^{30} *ergs* and duration $\sim 100 ms$, according to the competing elementary particle model. An important difference is that photon spectrum in the latter case is expected to be harder, with individual photon energies possibly going as high as $> 5 \times 10^{13} eV$.

A modification of the Hawking scenario, subsequently proposed by Martin Rees (1977), is that the electron - positron ejecta from the mini-black-hole explosion would interact with the interstellar magnetic fields, resulting in the production of an extremely short-duration optical pulse ($\sim 10^{-15} s$) with an estimated energy of 10^{30} ergs. Two groups − one at the Whipple Observatory, U.S.A. and the other ours (Bhat *et al.* 1980 and references therein) - set out for testing these exciting ideas independently. In our case, a second, dual-channel, wide angle photomultiplier system was installed in the base-laboratory campus in Srinagar, a distance of '$\sim$ 30km from the Gulmarg observatory, as the crow flies and operated for about 2 months a time-coordinated manner with the already-functional photomultiplier experiment at Gulmarg. To check for the ultra-short signature of the optical pulse of the pbh-origin, predicted by Rees, it was decided to look for two Cerenkov-like 'impulsive' pulses recorded at the two stations simultaneously, that is, within the experimental absolute-time resolution of $< \sim 1 ms$. During an effective overlapping observation time of $\sim 100 h$, only one candidate event was recorded as against the corresponding chance expectation value of ~ 0.3. In the absence of a statistically compelling evidence, a moderately constraining upper limit (that time best−value) resulted from the Gulmarg-Srinagar coincidence experiment (Bhat *et al.* 1980).

Another exploratory experiment, carried out in association with the Tata institute of Fundamental Research, involved the simultaneous operation of small plastic-scintillator arrays between Gulmarg and Ooty in time-correlation (Bhat *et al.*, 1984). The aim of this, $\sim 3500 km$-long baseline experiment was to search for correlated air-showers in the form of concurrent counting rate enhancements at the two stations. A potentially interesting source of spatially-correlated showers are relativistic dust-grains of presumably pulsar-origin. They can undergo photo-disintegration events during their passage in the vicinity of the solar system, resulting in the production of correlated air-showers. Having found no significant rate enhancements on a variety of times-scales, an upper bound was placed on the rate of production of relativistic grains in the pulsar environment.

3. Consolidation phase

This phase commenced in 1983, when it was decided to build and operate an atmospheric Cerenkov telescope at Gulmarg for dedicated observations on γ-rays source candidates in TeV energy domain. The atmospheric Cerenkov technique is the only viable detection method available today for accessing this energy range. The main motivation for investigating the TeV spectral window was the realization that, typically, γ-ray signals are expected to be stronger in this photon energy bracket than at higher energies and, in that sense, this spectral band offers better prospects for meaningful γ-ray astronomy investigations (Weekes 1988; Weekes 1992). Based on the leads available from earlier studies, it was decided to make periodic sources, in particular, the prime targets for our investigations so that the anticipated periodic modulation of the associated γ-ray signal could be exploited to discriminate against the otherwise dominating, but randomly-occurring cosmic-ray background. This strategy was aimed at achieving a reasonably high sensitivity for the first-generation gamma-ray telescope at Gulmarg and thereby make these explorations more meaningful. With this end objective in mind, special emphasis was placed on the telescope data-acquisition and timing systems so that the occurrence time of each individual event could be logged in with minimum dead-time losses (Sawhney *et al.* 1989). Equally important, a precision timing-system was developed which, while using the more readily-available high-frequency timing-signals as reference time-markers, was capable of giving absolute event epoch accurate to $\sim \pm 250\mu s$ for the entire duration of an observation-campaign, lasting typically for upto 2 months per source (Sapru *et al.* 1990).

Surprisingly, the search for mirrors for the Gulmarg Cerenkov telescope proved to be quite tortuous, despite their fairly-relaxed technical specifications. The trail finally ended in the Mumbai junk-market where we were able to locate 8 parabolic mirrors - all search-light reflectors of the World War-II vintage, and evidently, not of a particularly great optical quality! The telescope mounts were fabricated, based on a design provided by the Ooty based gamma-ray astronomy group of the Tata Institute of Fundamental Research. A special design feature of the Gulmarg telescope was that it could be reorganized into two identical sections, with a provision to deploy them for viewing either two different candidate-sources concurrently, or, taking observations on the same source, with one section taking an on-source scan and the other, engaged in the simultaneous off-source monitoring. The second operation mode was found to be particularly suitable for picking up episodic emissions from γ-ray sources – an emission-mode, believed to be quite common-place among very high energy γ-ray sources.

The telescope was operated at Gulmarg for the 5-year span 1985-90, during which period several candidate-sources were observed and evidence obtained for TeV photon signals from a number of them. We shall now present the salient design-features of the Gulmarg telescope and review the highlights of the results.

3.1 Gulmarg atmospheric Cerenkov telescope

As is seen in the Fig.7, the Gulmarg telescope comprised seven, 0.9m-diameter parabolic, backcoated glass mirrors (f/0.5-type), which were placed on independent equatorial mounts and operated side by side over an area of $6m \times 7m$ (Koul et al. 1989). One of these mirrors was devoted to sky-patrol duties and it gave a measure of the night-sky background light level

and the atmospheric transparency conditions while the experiment was in progress. The other six mirrors were organized into two independent telescope-banks, each having a synchronized drive-system for its 3 constituent mirrors. The back - end instrumentation consisted of a single, fast PMT (RCA 8575), placed centrally in the focal-plane of each mirror. A circular mask, mounted close to the photocathode of the PMT, restricted its field of view (FOV) to a circle of diameter 4°. This FOV was consistent with the rather moderate optical quality of the mirror and, while helping to maximize the collection of the Cerenkov light for impact distance of ~100m, it also restricted access to the background cosmic-ray events within manageable limits.

An event-trigger consisted of all the 3 PMT detectors of a telescope-bank generating a $\geq$ 4σ output within a coincidence gate resolution of ~20ns.The resulting prompt trigger rate was typically ~ 1Hz, (vertical pointing), with < ~ 10% chance contribution, due to a random line-up of $\geq$ 4σ amplitude shot-noise fluctuations in the 3 detector channels. Each event trigger led to the temporary logging of the event epoch with a 1μs precision in a memory bank, from where it was subsequently transferred into the hard-disk of a PC-XT computer (Sawhney *et al.* 1989). In addition, system health-monitoring parameters, including single-channel rates and the 3 - fold chance-rate were recorded periodically for rejecting anomalous data-spells at the stage of detailed off-line data analysis and interpretation. A special provision was made to stabilize the ambient light level seen by each PMT detector as the telescope element tracked different parts of the night-sky in the course of the observations (Koul *et al.* 1989). For this purpose,
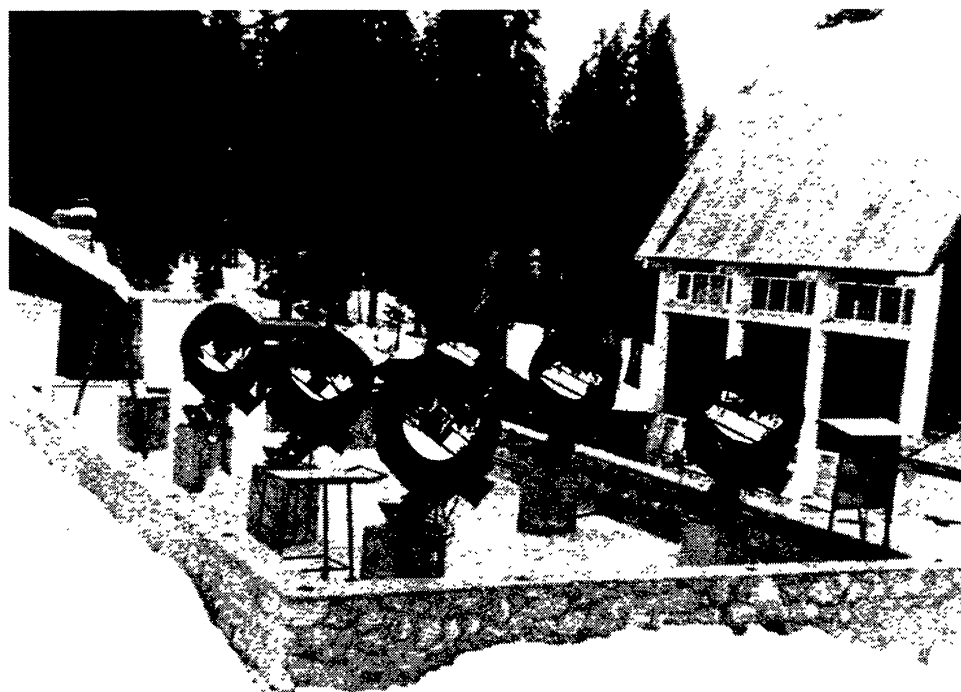
Figure 7. A photograph of the 7 x 0.9m-diameter mirror Gulmarg gamma-ray telescope used, in searches for γ-ray emission from a variety of cosmic objects, including pulsars, supernova remnants, X-ray binaries and cataclysmic variables.

each detector was provided with an LED-lamp whose light level was automatically regulated by a closed-loop circuit so as to keep the total light flux (night sky + LED), incident on a PMT, always near the same level. The tracking accuracy of the telescope was maintained within ~ 0.5° for upto 6 hours of continuous tracking.

3.2 Search for TeV γ-ray signals

The first source viewed by the Gulmarg telescope was Geminga (Kaul *et al.* 1989). This source was discovered by the SAS-II satellite and confirmed by the COS-B satellite as the second brightest Mev-GeV γ-ray source after the Vela pulsar (Bignami, 1984 and references therein). It has recently been revisited by the ROSAT X-ray satellite, as also by the EGRET experiment on the Compton Observatory, and it is today known to be a radio-quiet pulsar with a period of 237ms (Weekes, 1992). Observations were carried out from Gulmarg in the tracking - and on-off modes during two observation spells : December 20, 1984-February 18, 1985 and November 11, 1985-December 13, 1985. At the time of these observations, the nature of the source was uncertain and it was generally believed that the source-related SAS-II and COS-B data-bases were indicative of a pulsed signal with a period of ~59s and a positive period-derivative. The Gulmarg data-acquisition system was quite slow in the beginning and only event rates with a sampling time of $\geq$ 1 second could be recorded at the time of Geminga observations. It was, in fact, the above-referred suggestion of the unusally long-period of 59s which persuaded us to make Geminga the first target-object of the Gulmarg γ-ray telescope. No significant signal was detected at this putative period, resulting in an upper limit of 2.4 x 10^{-12} *photons cm^{-2}s^{-1}* from this source at γ-ray energies E_γ > 6*TeV* (Kaul *et al.* 1989). Though 3 ground-based astronomy groups, employing the conventional detection approach, have since claimed 237ms-pulsed signals from this source over the energy interval ~ 1 - 100TeV (Bhat, 1996 and references therein), a few detection systems, based on the recently-developed, higher-sensitivity Cerenkov Imaging Technique, have consistently reported null results in the TeV energy bracket (Weekes, 1992). To clear the present foggy picture, we plan to revisit Geminga when our new telescope systems become operational at Mt. Abu in the next few years (see section 4 below).

The next two sources to be looked at by the Gulmarg telescope were the X-ray binary systems, Cyg X-3 and Her X-1, both of which have attracted a lot of attention from ground-based γ-ray astronomers all over the world (Weekes 1988; Weekes 1992; Bhat 1996). Cyg X-3 was observed for ~11 hours during October 10-16, 1995 and for 29 hours during October 13-16, 1988 and August 29-October 4, 1989. An immediate success was the detection of two short-duration bursts of TeV γ-rays from the source (Fig. 8), just around the time it produced a giant radio-flare, reaching a peak flux density of ~18 Jansky on 1985, October 09 (Rawat *et al.* 1989 and references therein) The Baksan carpet-array also reported an apparent PeV γ-ray flux from the source, ~ 2 days after the radio-flare peak-epoch. Berezinsky has provided a plausible theoretical frame-work for enhanced Cyg X-3 TeV and PeV luminosity in association with the radio-flare and has explained how the PeV flux would be suppressed in the beginning by γ-γ interactions that these UHE photons may undergo with the emitted radio-flux, leading to the appearent delay between the Gulmarg (TeV) and Baksan (PeV) signals.

The binary nature of the intriguing X-ray system, Cyg X-3, is still controversial, and situated as it is close to the galactic plane, it is generally believed that the best option for identifying the neutron-star compact object, assumed to be present in this system, is through the TeV γ-ray astronomy route. Two TeV γ-ray astronomy groups, one from Crimea (Zyskin *et al.*, 1987) and the other from Durham (Chadwick *et al.* 1985), were first to take up this challenge. They produced evidence from their respective Cyg X-3 data-bases, indicating significant pulsations at periods of ~9.22*ms* (Crimea) and ~12.6*ms* (Durham), which were presumed to be related to the spin-period of the compact primary. In particular, the Durham group's claim of 12.6 ms period is based on a series independent measurements (see Weekes, 1988 and references therein), carried out by them with different telescopes at Dugway (USA), La Palma (Canary Islands) and Narrabri (Australia). Recognizing the astrophysical significance of these early leads, we designed our second observation campaign on Cyg X-3 to particularly suit this mission but, like several other groups who had also set out on the same trail, did not succeed in picking up any significant signal at either the Crimean period of ~9.22ms or the Durham period of ~12.6ms (Rannot *et al.* 1994). The cumulative evidence of negative results places a question-mark on the reported γ-ray-emitting neutron star in the Cyg X-3 system.

On the other hand, our observation-campaign on the X-ray binary source Her X-1, was quite successful in this respect (Rawat *et al.* 1991). We looked at this source during June 11-16, 1988 in the on/off mode, with each on-scan lasting for 30 mins. and the following off-scan, covering the same region of the sky as the preceding on-scan, for an equal length of time. The resulting data-bases were corrected for the clock time-drift and were transferred to the barycentre
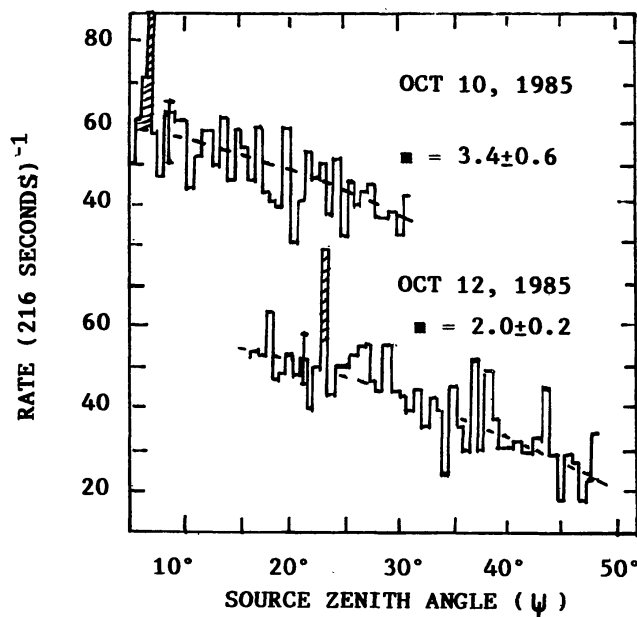
Figure 8. Observation of 2 short- duration TeV γ-ray bursts (hatched area) from Cyg X-3 binary system around the time (~October, 1985) it produced a major flare. An apparently-correlated source signal was also claimed at PeV γ-ray energies within a few days of the peak-epoch of the radio flare (October09, 1985, at 23:76 UT) by the carpet air-shower array at Basken.

of the Her X-1 binary system before being subjected to a period search through the standard Rayleigh power analysis technique. A 15 minute on-source episode, recorded on June 12, 1988, showed significant pulsations close to the X-ray spin-period of the Her X-1 neutron star (Fig. 9a). Quite significantly, essentially the same γ-ray period was also reported by the Durham group for Her X-1 for nearly the same observation epoch (Fig. 9b; see also Weekes 1992). No experiment has since reported any γ-ray emission from Her X-1, despite the fact that significantly more sensitive systems have been pressed into service in recent years for making these observations at, both, TeV and PeV energies. The question that follows naturally is whether the source has gone into a state of hibernation since the Gulmarg and Durham groups last detected it in 1988? A close examination of Fig. 9b provides a tantalizing possible answer : here we find the Her X-1 γ-ray period increasing systematically at first and then decreasing gradually again to become equal to the X-ray period around the time of Gulmarg and Durham observation epochs. As discussed in a recent work by Bhat *et al.,* (1997) this trend is consistent with a lump of target matter which, while rotating around the neutron star with a gradually decreasing orbital radius (longer period), is lost forever when it reaches the magnetosphere of the neutron star (co-rotation), leading to the apparent abrupt extinction of the Her X-1 γ-ray source.

A possible discovery result from the Gulmarg telescope is the detection of a TeV signal from AM-Herculis, the prototype cataclysmic variable (CV) (Bhat *et al.* 1991). The signal is found to be modulated with the characteristic 3.4h orbital period of the system and an outstanding feature of the light curve is its striking morphological resemblance with the circular polarization
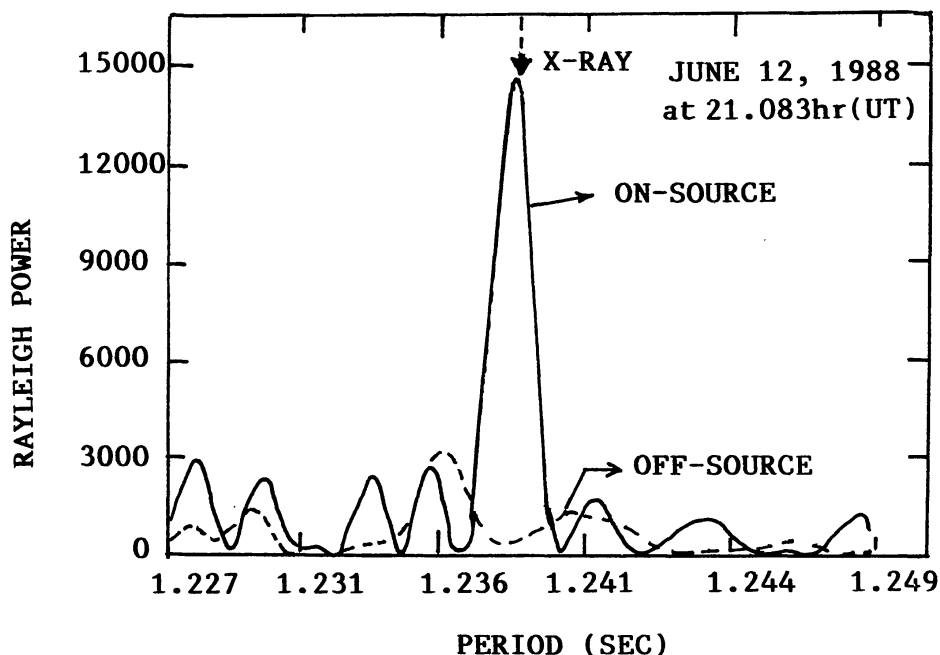

Figure 9a. Evidence for a 15-minute-long episode of pulsed TeV γ-ray emission from the X-ray binary system, Her X-1. The detected pulsation period of 1.2376s, also reported by the Durham group for a neighbouring observation period, happens to be indistinguishable from the corresponding spin-period of the Her X-1 X-ray pulsar.

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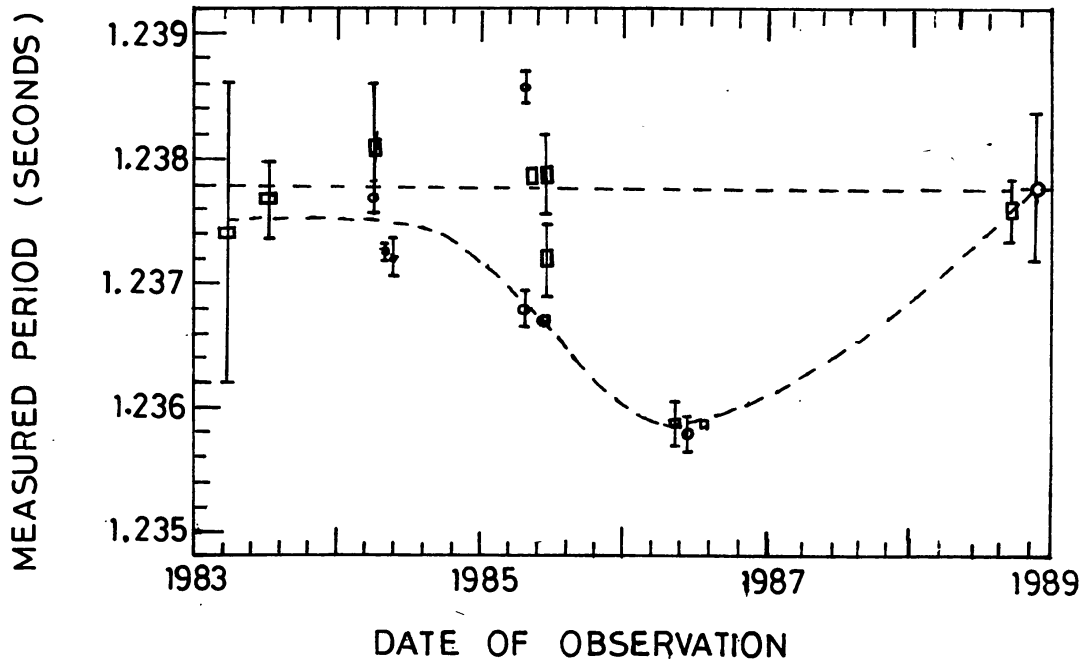
Figure 9b. A time-history of the apparent evolution of the pulsation period of the γ-ray signal from Her X-1 reported by various experimental teams. The neutron-star spin period, as derived from X-ray observations is also shown in the figure.
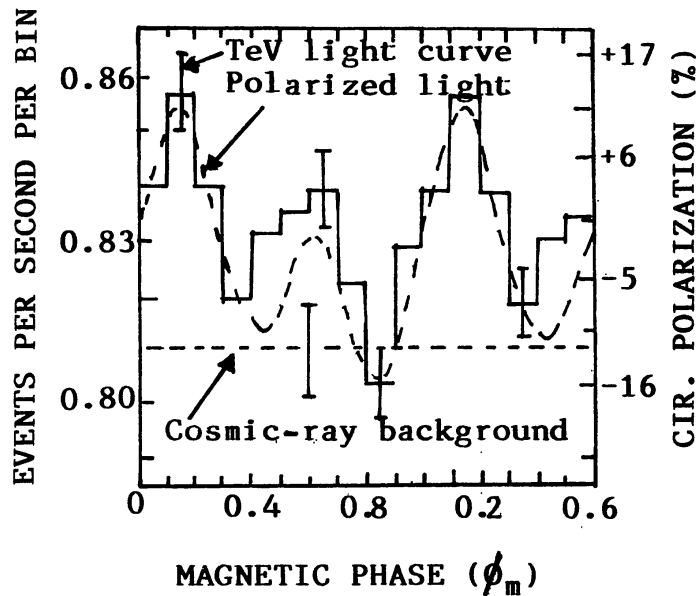
Figure 10. TeV γ-ray light curve of the prototype CV system AM-Herculis, obtained for the first time on the basis of Gulmarg observations. A bimodal emission at magnetic phase value ~0.2 and 0.6 is indicated. Note the remarkable morphological similarity of the plotted phasogram with the circular polarization curve of the system (dashed-line).

curve of the source (Fig.10). Quite analogous trends were noted by us subsequently in case of two other AM-Her systems, VV-Puppius and E1405-451, when the COS-B satellite data-bases related to these sources and involving photons of energy > 100 *MeV*, were subjected to a similar time-series analysis-treatment (Bhat 1990 and references therein). Equally reassuring, two other groups (Kifune 1996 and references therein), operating in the Southern hemisphere, have also reported detection of bursts of TeV γ-ray photons from the DQ-type CV-system, AE-Aqr. On the other hand, the Whipple Cerenkov Imaging Telescope has looked in the AM-Her direction in the recent past, but has not detected a significant TeV photon excess from this direction (Weekes, 1992). A plausible explanation for this disparity may be the relative inefficiency of the Cerenkov imaging technique in retrieving signals from sources with spectra flatter than that of the Crab Nebula in the TeV energy range (Bhat *et al.,* 1994). There are indications from Gulmarg observations that the source spectrum may be fairly hard in the TeV region.

CV binaries of the polar type involve a white-dwarf compact primary which spins synchronously with the orbital period of the companion secondary (unlike in the case of intermediate polars or DQ-Her systems). The magnetic field of the white dwarf is typically $\sim 10^9$ Gauss, which, when combined with its slow spin-period, rules out the possibility of particle acceleration by the conventional $\vec{\Omega} \times \vec{B}$ pulsar-mechanisms. On the other hand, as shown by Kaul *et al.* (1993), particle acceleration is possible by diffusive shock acceleration at a distance of ~ 20 white-dwarf radii away from the primary and the γ-ray production is due to the accelerated particles beam-dumping against the accretion column channeling the matter flow from the CV secondary companion to the primary white-dwarf.

Another interesting result from the Gulmarg telescope concerns the observations made in the general direction of the pulsar PSR 0355+54 (Senecha *et al.,* 1995). Earlier, the Pachmarhi group (Bhat *et al.* 1990), using their non-imaging Cerenkove telescope to track the source in December, 1987, had reported a moderately significant signal, (4.3σ), modulated with the pulsar spin-period of $\sim 156.38ms$. When we looked at the source from Gulmarg in November 20–December 3, 1989, for a total of 34 hours of observations, no pulsed signal was found, nor was it detected by the Pachmarhi group when they revisited the source during 1989-1992 around the same time when we were observing it (see Senecha *et al.* 1995 for references). An intriguing observation made by us during this period, however, is that of a significant d.c. excess from the overall source direction. This result is shown in Fig. 11. It stands to reason to ask if we are witnessing here a manifestation of particle acceleration and interaction in the outer parts of the supernova remnant which may be still lurking around the pulsar. Our scanning of the supernova remnant catalogues, based on both, radio and X-ray (ROSAT) observations, have not given any indication of a plausible candidate.

Other observations carried out with the Gulmarg telescope were of the Crab nebula / pulsar region (Sapru *et al.* 1996) and the X-ray binary source, Cas γ-1 (Rannot *et al.* 1992; Rannot *et al.* 1994). Data were collected on these sources in the on-off and tracking modes for 81h (Crab) and 87h (Cas γ-1). No significant phase-modulation of a periodic nature, which could be attributed to the Crab pulsar (period : 33ms), could be detected from the related data-base. Although a Rayleigh power peak is seen in case of Cas γ-1 at a trial-period of 3.6407s

(Fig.12),it has only moderate statistical significance. Moreover, it is significantly deviated ($\sim 0.7\%$) from the corresponding X-ray period and there is an apparent absence of a significant on/off d.c. excess in the Cas γ-1 Gulmarg data-base. In view of this, it would be prudent to await observations with more sensitive systems in future before attributing the peak in the periodgram of Fig.1 as suggestive of γ-ray emission from this source.

4. New vistas with project GRACE

Seeking guidance from our past experience and the contemporary global trends in the field of gamma-ray astrophysics, the outlook for making major advances in this, still-largely unexplored area in coming years is indeed quite bright, thanks mainly to the recent advent of superior detection techniques, both on ground and in space. In order that Indian astronomers can partake of the excitement that has started unfolding on the world scene and can make worthwhile contributions in near future in this up and coming field, it is imperative that the level of experimental activities is significantly scaled up, both in quality and magnitude. Important stipulations for satisfactorily serving this important mandate are : (i) time-bound setting-up of new, high-sensitivity experiments in the γ-ray window at a proper observatory site, preferably operating in coordination with ground-based and satellite-borne experiments, addressing other spectral windows (Bhat *et al.* 1995); and (ii) a quantitative upgradation in the time-and spectral-resolutions of these experiments compared with what has been possible in the past, so that the underlying physics can be better understood. These experiments should preferably be based on the well-established atmospheric Cerenkov and scintillation techniques, which apart from being cost-effective, offer the advantages of a fast time-response and a linear energy-scaling over a wide range of incident energies, and hence provide an excellent calorimetric capability. Moreover, the fine differences imprinted in the atmospheric transducer, in response to hadronic and electromagnetic interactions, also enable this technique to be used for the characterization of the primary particle − an important requirement for sensitivity improvement.

Keeping all these requirements in mind, a couple of years ago, we set out on a new phase of consolidation by starting the execution of the project GRACE (for **G**amma **R**ay **A**strophysics **C**oordinated **E**xperiments). Under the project (Bhat *et al.* 1994), a new astronomy facility is being established in Mt. Abu, Rajasthan, at Gurushikhar, by the side of the already-existing Infra-red observatory of the Physical Research Laboratory, Ahmedabad. This place has turned out to be the best-known Indian location for the air-Cerenkov work (Kaul *et al.* 1994), offering the advantages of significantly higher observing time (a hefty 250% increase with respect to that at Gulmarg, which is more or less evenly spaced throughout the year, (except for the monsoon months of July and August), a reasonably high-altitude (1700m asl) and a provision for low-elevation viewing over a large azimuthal-angle slice (of particular interest for detecting neutrino-induced extensive air-showers), ready accessibility from major Indian towns (only $\sim$ 600km from Mumbai and Delhi) and ease of operation on account of fairly moderate climatatic conditions throughout the year. Moreover, Mt. Abu is located in nearly the same longitude zone as Tien Shan, Tibet, Hanle, Pachmarhi, Pune and Ooty. This fortuitous longitude clustering
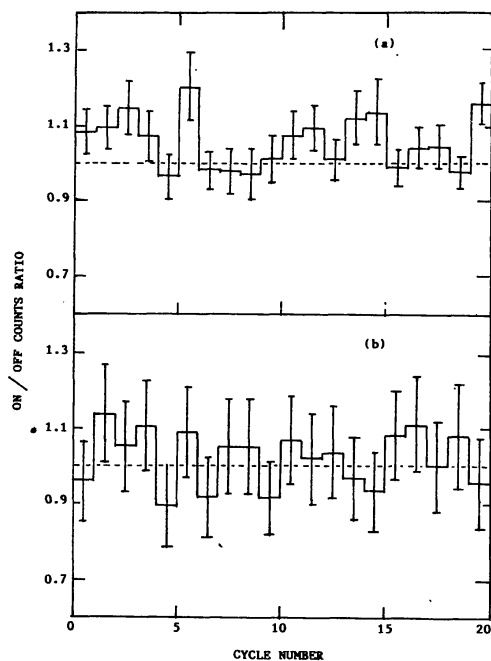
Figure 11. Suggestion for a non-pulsed (d.c.) γ-ray signal at TeV energies from the overall region associated with the pulsar PSR 0355+54. The events-ratio for a majority of on-off cycles (a) are found to lie above the no-signal expectation value of 1, leading to an overall on-source counts-excess of $(5.68 \pm 1.35)\%$ and a corresponding signal flux of $4.5 \pm 0.8) \times 10^{-11}$ *photons* cm^{-2} s^{-1} at photon energies $> 4TeV$. (b) gives the corresponding on-off counts ratio distribution of 3-fold chance rates as recorded by the 3-element telescope-bank.
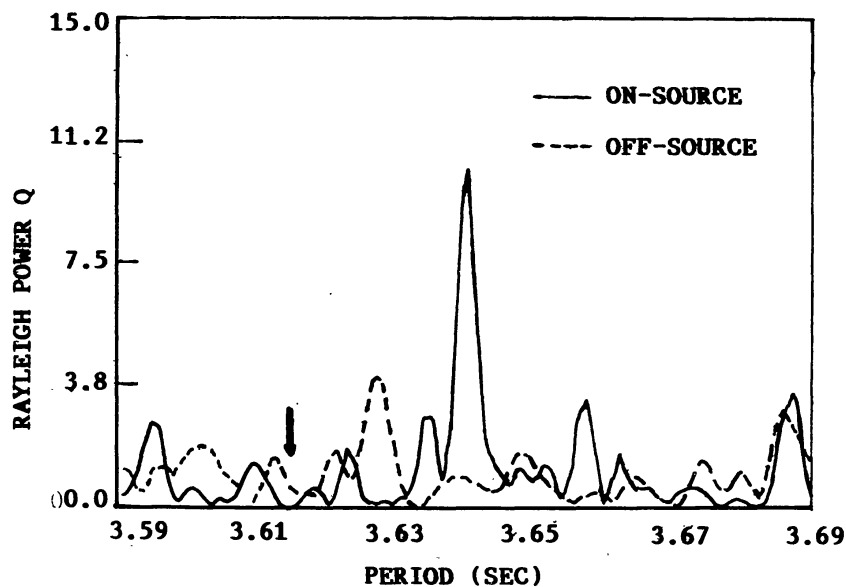
Figure 12. Periodgram of the on-source data (full-line) for the 1h long episode recorded on 1987 November 14, when the Gulmarg telescope was tracking Cas γ-1. The corresponding off-source periodgram (dot-dash line) is also shown for comparison. Period range covered is 3.5916-3.6897s. The arrow shows the position of the expected X-ray period of Cas γ-1.

of major experimental facilities in the region greatly enhances the prospects for undertaking time-coordinated, multi-spectral band observations on candidate γ-ray sources, in particular, pulsars and γ-ray-loud active galactic nuclei, and thereby obtaining fresh insights into the nature of these sources.

The principal objective of the project GRACE is to comprehensively cover, from one location, almost the entire γ-ray spectral window lying between 10's of keV to 100's TeV. Two high-sensitivity experiments, TACTIC and MYSTIQUE, are being set up for this purpose in the first phase to investigate the very high energy γ-ray region between 10's GeV to 100's TeV through the atmospheric Cerenkov technique (Two other experiments MACE and BEST are at the planning stage at present and will not be discussed here). While a prototype MYSTIQUE array has already been set up at Mt. Abu, the TACTIC is at an advanced stage of implementation and should become operational by December 1997. When fully commissioned, the GRACE would enable our scientists to carry out the following important investigations : (1) make detailed spectral and temporal studies of compact and non-compact γ-ray sources of galactic and extragalactic origins; (2) measure the primary electron and diffuse γ-ray background components, and, in particular, make a systematic search for the 'cosmological window'; (3) measure the cosmic-ray energy spectrum and mass-composition around the knee region; (4) use the γ-ray probe to get a measure of the metagalactic radiation field between the ultraviolet and infra-red wavelengths and/or get an independent fix on the Hubble constant upto the red-shift factor, z, value of ~ 1.5; (5) carry out exploratory studies on dark-matter candidates such as the SUSY particles, neutralinos, and the strange matter nuggets, called nuclearites; and (6) investigate the feasibility of using horizontally-viewing Cerenkov telescopes for detection of ultra-high energy neutrinos.

4.1 MYSTIQUE

The acronym MYSTIQUE or MEUSTEQUE stands for a Multi-Element Ultra-Sensitive TElescope for Quanta of Ultra-high Energies and refers to an array of 225 Large-Area Wide-Angle (LAWA) Cerenkov detectors, each $2m \times 2m$ in physical dimensions (Fig. 13a). The array elements are spread out over an area of ~ 4 × 10^5 m² with an average nearest neighbour spacing of ~ $40m$. The experiment aims at spanning the still-largely unexplored energy range of a few TeV to a few hundred TeV with a sensitivity level which is significantly higher than what has been attemped anywhere so far. This is sought to be achieved through : (i) an almost 10-fold increase in the effective array-area, as compared with, for example, the Tibet air-shower array (Amenomori et al. 1995) or the AIROBICC Cerenkov detection system (Lorenz 1996); (ii) lower operating γ-ray threshold energy of ~ $5TeV$; (iii) cosmic ray background separation through better angular resolution ($\Delta\theta \simeq 0.25°$), intrinsic to the Cerenkov technique, as well as the lateral-distribution and temporal-profile analyses of the registered events. The telescope would enable to carry out concurrent, multi-source investigations over a field of view of half-angle 45°.

In order to meet these, somewhat mutually-contradictory specifications, the LAWA Cerenkov detector will need to have an unconventional design, as illustrated in Fig. 13b. It is shown to consist of 4 juxtaposed glass-sheets, each $1m \times 1m$ in area and coated on the top surface with a suitable, scintillating-dye mixture (BBOT + POPOP). This mixture is tailored to have an
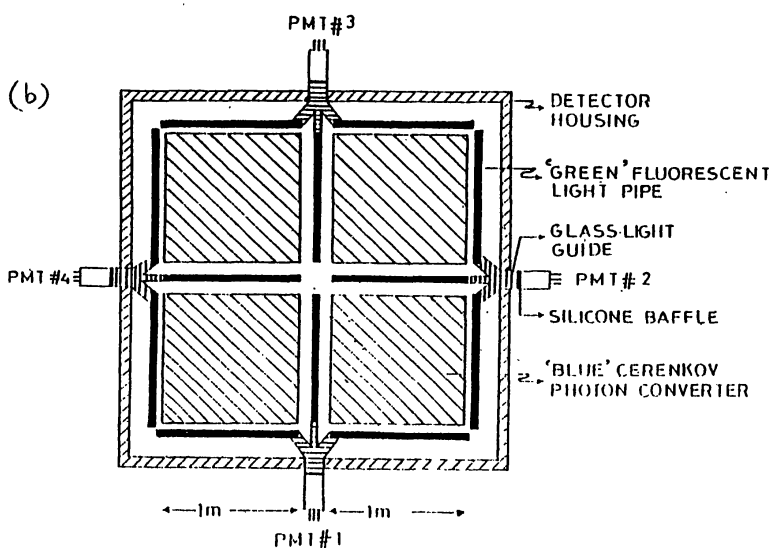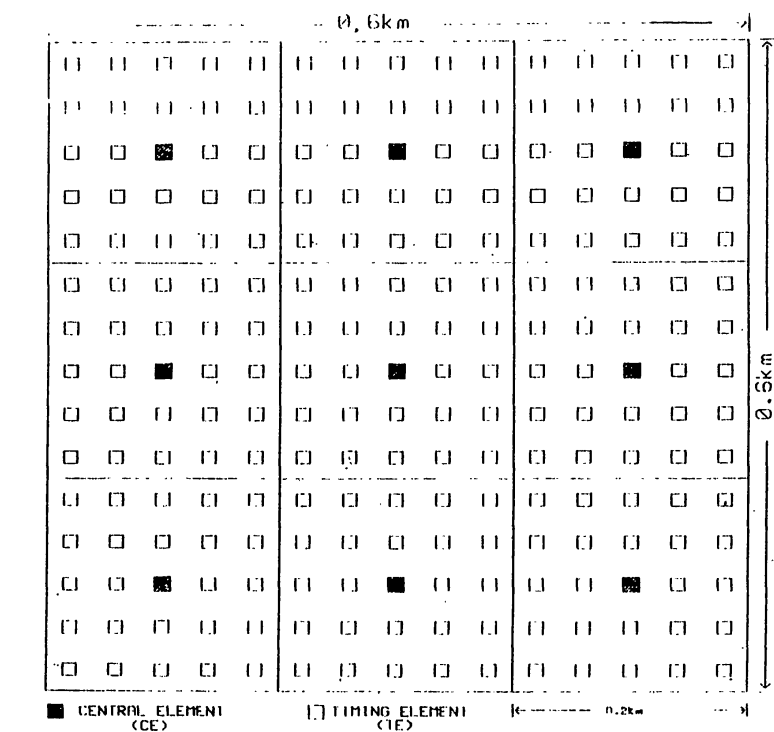
Figure 13. (a) A block-diagram representation of the MYSTIQUE air-Cerenkov detector array planned to be set up at Gurushikhar, Mt. Abu (1700m asl) for concurrent multi-source γ-ray studies in the photon energy range ~ 5-500 TeV. (b) The design-concept of the large-area ($2m \times 2m$), wide-angle (FOV ~ 1.8sr) LAWA Cerenkov detector being used as the basic detector element in the MYSTIQUE array. An overall light-collection efficiency of ~ 20% is expected for the overall detector cell, while the total time-jitter, including that from the PMT detectors and the back-up electronics, is expected to be $\leq 3ns$.

absorption spectrum which significantly overlaps with the detected spectrum of the atmospheric Cerenkov light and thereby absorbs a major part of the light incident on the LAWA sheet (Bhattacharyya *et al.* 1997). A large fraction of the fluorescent 'blue' light, emitted by the scintillating dye, suffers total internal reflection within the body of the glass-sheet and manages to reach the four edges of the glass-sheet. A significant part of this light is eventually ducted unto fast photomultiplier detectors, optically coupled to the ends of 12 'light pipes', placed alongside the edges of the 4 LAWA glass-sheets, as shown in Fig. 13b. Each light pipe consists of a glass-strip which is surface-coated with a 'green' fluor (Coumarin) whose absorption spectrum matches the emission spectrum of the 'blue' dye. The overall light collection efficiency of this arrangement is estimated to be $\sim 20\%$ and the total time - jitter $<\sim 2ns$. Both these values are consistent with the stipulated design specifications of the LAWA Cerenkov detector.

The projected detection sensitivity of MYSTIQUE is compared in Fig. 14 with that of some other major experiments in the related energy domain. The relative superiority of the MYSTIQUE is evident, provided a cosmic-ray background rejection factor of $\sim 99\%$ can be achieved, along the lines outlined above, including the use of event time-profile information. A unique feature of the MYSTIQUE array would be its capability to reconstruct the event arrival direction in real-time using the unconventional artificial neural-network approach (Dhar *et al.* 1996). The experiment will be particularly useful for a detailed general survey of the γ-ray sky as well as for recording episodic events, including γ-ray bursts from primordial black-hole explosions and spectral tails in cosmic γ-ray bursts.

4.2 TACTIC

TACTIC stands for a 'TeV Atmospheric Cerenkov Telescope with Imgaging Camera'. It is a compact array of 4 telescopes, each using a high-quality, light receiver of $\sim 9m^2$ effective area and placed on an alt-azimuth mount, backed up with an accurate computer-controlled drive-system (Fig. 15). The 4 elements of the array are disposed in a triangular configuration and are provided with appropriate focal-plane instrumentation so that, apart from recording lower energy γ-ray events preferentially, information regarding their photon content as well as image, time- and polarization-characteristics are also recorded. The TACTIC will have the unique advantage of using all these parameters in a correlative manner to achieve a high quality factor (Rannot *et al.* 1996). This will enable it, on one hand, to segregate γ-ray-induced events from the general cosmic-ray background events, and, on the other, to differentiate among various nuclear groups from one another and thus carry out cosmic-ray elemental composition studies in addition to γ-ray source investigations.

As is evident from Fig. 16, TACTIC can pick up the Crab Nebula d.c. signal at a 10σ-confidence level in ~ 5 hours of observations, compared to the Gulmarg system which would have needed $\sim 4 \times 10^4$h of real-time to retrieve this signal! A lot of punch has thus been packed into the TACTIC instrument so that it can investigate the TeV γ-ray window in a comprehensive manner and yield good-quality spectral and temporal information about these sources. Source-observations with a 81-pixel imaging camera are planned to be carried out in early 1997, whileas the full-blown 4-element TACTIC is likely to be commissioned by end of the year.
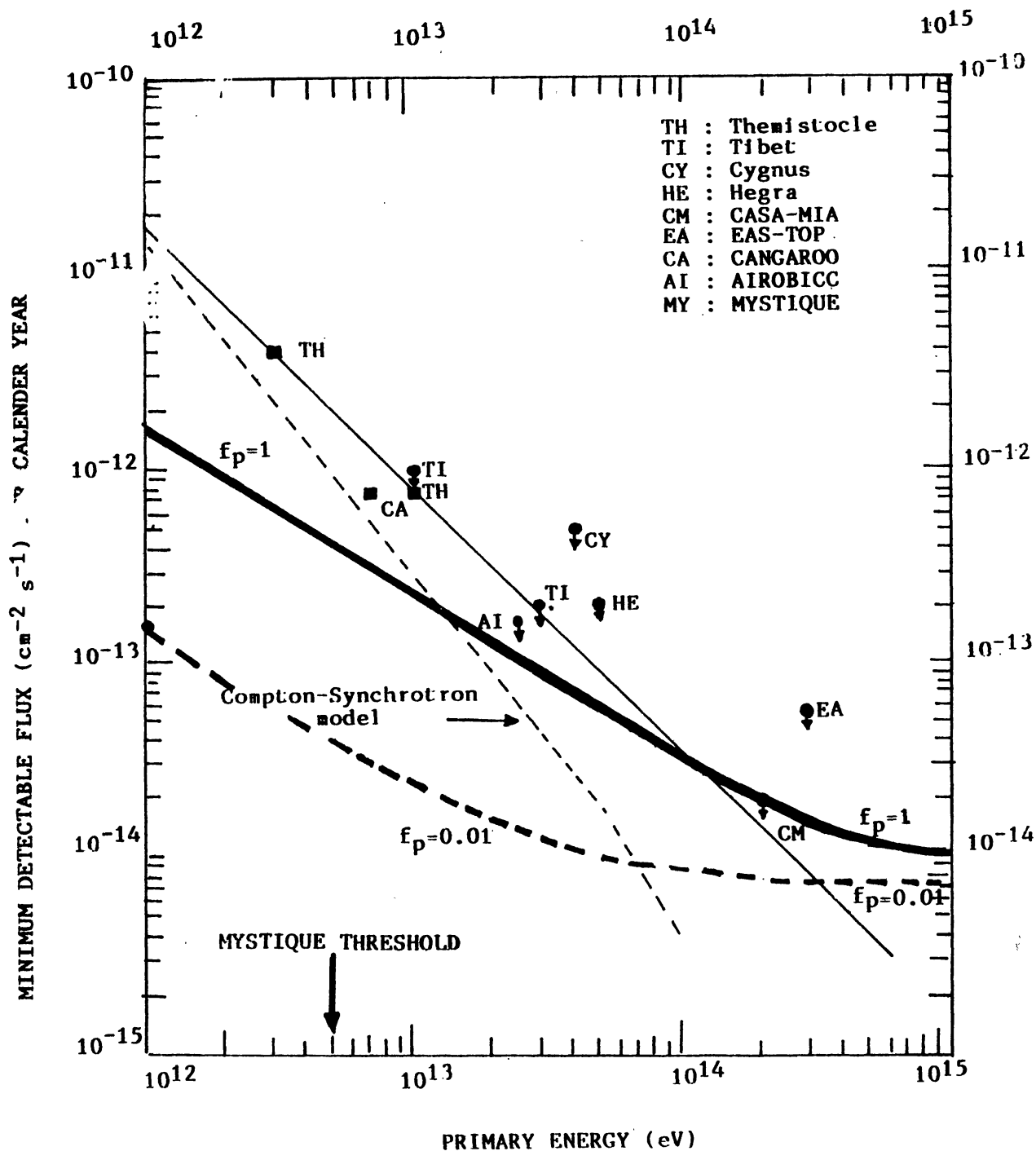
Figure 14. The projected sensitivity plot of the MYSTIQUE array evaluated for two situations : (i) when the background cosmic-rays are rejected by considering only the intrinsic angular resolution of the array (expected value of ~ 0.25°) and (ii) when further rejection of this background is sought by extrinsically exploiting the differences in the lateral distribution and temporal features of recorded Cerenkov events.
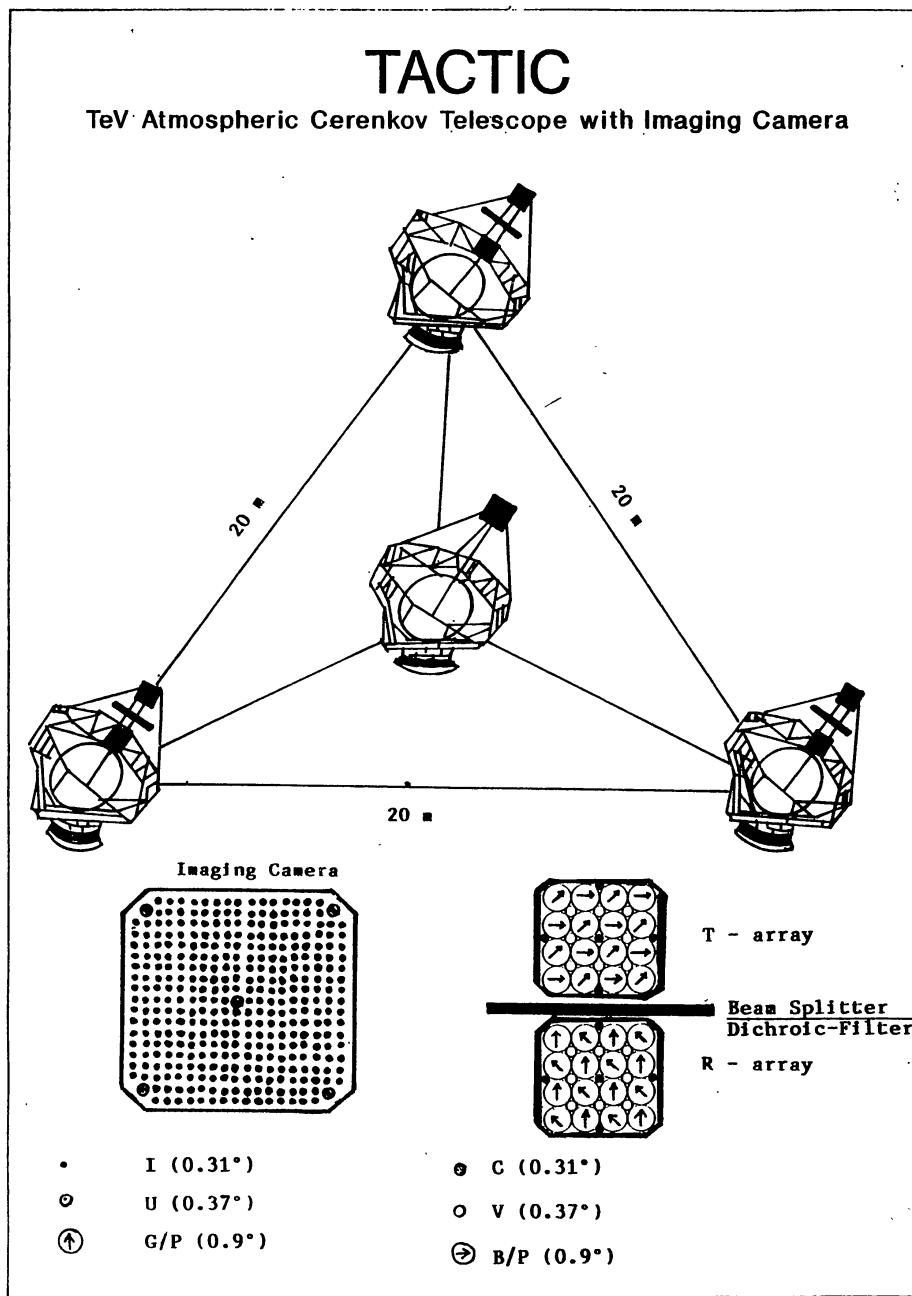
Figure15. (a). A block-diagram representation of the TACTIC array, presently under installation at Mt. Abu, for high-sensitivity spectral and temporal investigations on γ-ray sources in the photon energy range of ~ 0.5-10TeV. The array would also investigate UHE cosmic-ray elemental composition (50-500 TeV per particle) in a supplementary mode of operations, going to be employed under partially moonlit conditions when normal γ-ray sources studies are not conventionally performed.
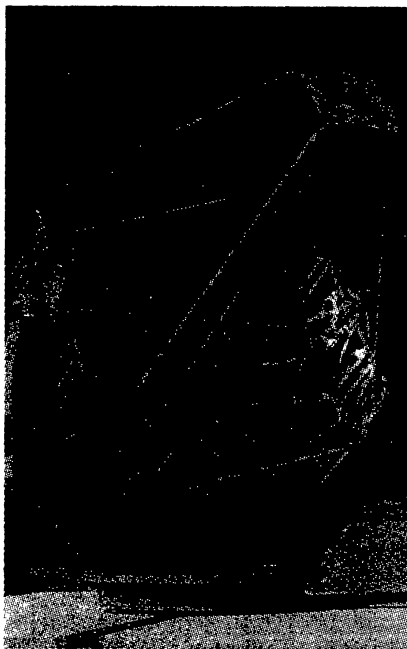
Figure15. (b). A photograph of the TACTIC Imaging Elemei already operational in our provisional observatory site in Mt. Abu. The 349-pixel fast-photomultiplier-based camera is shown mounted in the focal plane. At present, its central 81 pixels (9 X 9 array, FOV ~3°-dia.) have been activated.
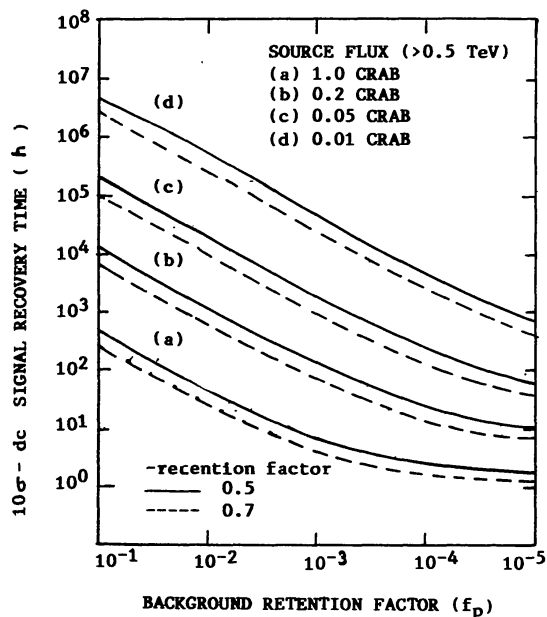
Figure 16. The sensitivity of the TACTIC array as a function of the expected background rejection factor for this instrument and the source brightness level in the TeV energy range. The sensitivity is quantified in terms of the time required by the TACTIC to retrieve a d.c. source signal at $\geq 10\sigma$ confidence level – this value is expected to be ~ 10 hours in case of the Crab Nebula.

5. Epilogue

Looking back at how things have shaped up from our perspective during the past 25 years, it has been a fairly long, but nonetheless satisfying journey on the whole. Starting on our own in the isolated splendour of Gulmarg in a new field, it is quite reassuring to see today, working around us, a fairly big pool of resourceful and enthusiastic young research workers who have acquired mastery over the sophisticated detection techniques being deployed in the field presently and have got a feel for them at the nuts-and-bolts level. It is satisfying to note that our group has kept itself abreast with the technology revolution that has been witnessed during the intervening period in computer hardware and software as well as in electronics and instrumentation and are fully geared today to successfully implement the high-technology project GRACE – it will deploy hundreds of fast photomultiplier channels, flash-ADC-based transient-event recorders with GHz sampling rates and transputer-based, real-time data-acquisition systems. In addition, it also envisages use of a modern satellite communication-link for remote handling and control of the telescope from Mumbai at a distance of $\sim 600km$ from the observatory location in Mt. Abu. Evidently, this revolution in technology upgradation presents a sharp contrast, to what by today's standards, would be dubbed as an archaic supernova monitoring system with which we had started in Gulmarg nearly 2 decades ago – it used a couple of photomultiplier detectors and a 35mm photographic camera-based event recording unit.

Another satisfying development, witnessed on the world-scene over the years, has been the gradual consolidation of the ground-based γ-ray astronomy field from its exploratory phase to a level where it is now possible to have reproducibility of results and log upto $\sim 60\sigma$ confidence level signals in a matter of hours, as has been the recent happy experience of the Whipple group, while observing the Markerian 421 (a nearby active galactic nucleus) with their Cerenkov Imaging Telescope. This reassuring state of affairs guarantees an extremely productive and stimulating phase for the γ-ray astronomy field in the coming years, during which period, hopefully, we may finally have the long sought-after answers to some of the outstanding cosmic riddles, including the physics behind the phenomenal release of high-energy particle streams in AGN's and other compact systems in the universe, the origin and acceleration of cosmic-rays and independent measurements of the photon densities of the metagalactic radiation fields and, possibly, of an even more precise value of the Hubble constant. Given this reassuringly bright outlook for the future progress in the field and the coming up of the GRACE facility in the country, it is reasonable to expect that our 25-year long investment in the field so far will start paying richer dividends here onwards and the coming generations of the Indian astronomers will make substantial contributions in a field which has just started opening up its treasure-trove!

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