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Very high energy gamma-ray astronomy using atmospheric Cerenkov technique

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Abstract. Observations on a celestial object in the gamma-ray window not only reveal the physical conditions prevailing at or near the object but also about the sources of cosmic rays. The observation of very high energy gamma rays could be carried out in the ground level. A brief account of the atmospheric Cerenkov technique to detect γ-rays of energy >100 GeV are given. This article deals mainly with the efforts by the Indian groups involved in the field of very high energy gamma-ray astronomy using this technique. A gamma-ray telescope set-up operating at Pachmarhi making use of this technique is explained. A few of the many interesting results observed by the groups working in India are discussed along with the directions for the future.

Key words : gamma-ray—cosmic ray—atmospheric Cerenkov technique

1. Introduction

Despite several decades of intense research since the discovery of cosmic rays in 1912 their sources remain unrevealed. With the discovery of pulsars, and the experimental finding in the field of X-ray astronomy that the X-ray sources were predominantly associated with accreting binary systems with a compact object like a neutron star or a black hole as one of the members, a fresh interest developed in examining such celestial objects as possible sources of cosmic rays. Several theories had been put forward about the mechanisms that could operate in the vicinity of a fast rotating highly magnetised (~ 10^{12} Gauss) neutron star like the one in the Crab nebula, for accelerating particles to very high energies. It was suggested that the intense magnetic fields of neutron stars in certain binary systems too could act as natural particle accelerators. The very process of generating high energy cosmic rays also causes the emission of high energy γ-rays. The various mechanisms known to be responsible for the production of high energy γ-rays are the interactions of electrons with matter, magnetic fields, ambient low energy photons (by way of inverse Compton scattering) and decays of neutral pions ($\pi^\circ \rightarrow 2\gamma$) generated in cosmic ray nuclear interactions with matter. Unlike cosmic rays, most of which are charged, γ-rays are electrically neutral and hence are unaffected by the weak interstellar magnetic field and therefore preserve the direction of their origin. They travel in straight line from source to us and make it possible to know the direction of the source of cosmic γ-rays. Thus by searching for celestial objects that emit γ-rays one hopes to pinpoint the elusive sources of cosmic rays that generate them. Besides, the γ-ray observations on celestial objects or regions will enable one, either on their own or in conjunction with observations made at radio-optical, X-ray etc. wavelengths to deduce the physical conditions and radiation fields prevailing at or in the regions surrounding the object.

Gamma-ray astronomy, the newest of the astronomies to arrive in the field, covers a very wide electromagnetic spectrum, atleast 12 decades in energy starting from 100 keV to 100 PeV* and higher (refer to Ramanamurthy & Wolfendale 1986; Ginzburg & Dogel' 1989 for a good reading on Gamma-ray astronomy). Almost all the cosmic γ-rays at energies less than about 100 GeV impinging on the Earth are absorbed in the terrestrial atmosphere before reaching the ground or are drowned in a sea of terrestrial γ-rays created in the atmosphere by cosmic ray interactions and are, therefore, accessible for observation only through balloon and satellite borne instruments. The γ-rays of energy $\geq$ 100 GeV could, however, only be studied with great sensitivity from the ground using extensive air shower techniques; this is essentially due to the limitations on the size and exposure of space-borne instruments and the flux of γ-rays which decreases with energy. The basic technique of air showers were developed more than 30 years ago and did not need to await the development of space technology. Yet, the advance of ground based astronomy was rather slow. Only in the last decade or so, the air shower techniques have been really exploited for the purpose of gamma-ray astronomical studies. This development has been driven primarily by several important observations at lower energies using satellites, particularly the European COS-B satellite experiment which discovered 24 celestial sources, including Crab, Vela and Geminga pulsars, emitting γ-rays in the energy range 100 MeV to 1 GeV. The γ-rays in the energy region 100 GeV–100 TeV, conventionally referred to as Very High Energy (VHE) γ-rays are studied through the detection of Cerenkov radiation emitted by the charged particle secondaries in the electro-magnetic cascade shower initiated by the γ-ray in the upper atmosphere. Though the secondary particles are absorbed in the atmosphere, the optical Cerenkov light reaches the ground level with little attenuation. We will elaborate on this technique below. At still higher energies, the Ultra High Energy (UHE) region covering 100 TeV–100 PeV, the γ-rays are energetic enough for the secondary particles to penetrate down to the ground level. An array of charged particle detectors is employed to detect these showers of particles initiated by the UHE γ-ray primary. A reconstruction of the shower-front from the relative timing of the responses of the various detectors yields the direction of arrival. An estimate of energy of the incident γ-ray is made from the densities of particles detected in the detectors. In the past decade, the field of VHE and UHE γ-ray astronomy has been a fast moving and controversial one. The developments are well documented in several reviews. (for *e.g.* see Weekes 1988, 1992; Fegan 1990; Chadwick *et al.* 1990; Rao & Sreekantan 1992).

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*1 TeV = 10^{12} eV and 1 PeV = 10^{15} eV.

2. The atmospheric Cerenkov technique (ACT)

When a celestial γ-ray of sufficiently high energy (> 100 GeV) enters the terrestrial atmosphere it produces an electro-magnetic cascade called extensive air shower (EAS). A high energy photon generates an $e^+ - e^-$ pair in the Coulomb field of a target nucleus. The electrons or positrons, in turn, generates high energy photons by bremsstrahlung. These twin processes repeat several times further. The VHE γ-rays do not create secondary particles with sufficient energy for the cascade to reach ground level. They are absorbed in the upper atmosphere, essentially by losing energy by ionization. However, the secondary electrons and positrons in the early stages of shower development are of such high energy that their velocities exceed the local phase velocity of light in air and therefore emit optical Cerenkov radiation which reaches ground level with little attenuation. These Cerenkov photons are emitted typically within a cone of half angle ~1°.3 with respect to the electron (or positron) direction. Also the electrons and positrons themselves undergo Coulomb scattering in the atmosphere. As a result, the Cerenkov photons are not focused at a single point on the ground but are diffused to distances up to ~150 m from the axis of the shower. For example, a 300 GeV γ-ray produces a few million Cerenkov photons within a cone of half angle ~ 2° with respect to the direction of the incident γ-ray. The light flash as detected at ground level lasts only about 10 ns. The average density of photons is about $7/m^2$, so feeble light that observations have to be necessarily carried out only during moonless nights under cloudless sky. Because of the large lateral spread of the Cerenkov light pool, the collection area for a celestial γ-ray is ~ 4 orders of magnitude larger than the geometrical area of the detector, which is a chief advantage of this ground based method over the satellite or balloon borne detectors. Thus at VHE energies, the atmospheric Cerenkov technique (ACT) provides the only viable method in spite of the constraint of a low duty cycle (< 10%) imposed on this technique by the need to operate only during clear moonless nights. The prediction that the Cerenkov light pulses from cosmic ray showers should be detectable at the surface of Earth was made by Blackett (1948) and later confirmed by observations by Galbraith & Jelly (1953).

The VHE γ-ray telescope consists of an array of large area parabolic reflectors, deployed either as a compact set-up or distributed array. Each reflector collects and focuses the Cerenkov photons on to the cathode of a fast photomultiplier (PMT) mounted at the focus of the mirror. The γ-ray signal has to be detected against the background of night sky photons amounting to ~ 6.4×10^7 photons/cm^2 s sr. In addition, the Cerenkov light from the γ-ray shower has to be distinguished from the more numerous cosmic ray showers which also produce atmospheric Cerenkov light and have signatures very similar to the γ-ray initiated events. Night sky background photons arrive randomly in time. They are first reduced by limiting the field of view of the PMT to a very small solid angle around the celestial object of interest and eliminated almost entirely by demanding fast coincidences between a few PMT's with small integration times. However, it is more difficult to discriminate against cosmic ray showers though in general their Cerenkov light pool is more diffuse because of the production of pions and other particles at finite angles with respect to the axis of the shower. Cosmic ray showers are isotropic in space and arrive randomly in time. Making use of these facts, γ-ray signal is identified as a spike in spatial and/or in temporal distribution of all events over and above the normal statistical fluctuations. The fraction of γ-rays is typically a few percent of the background cosmic ray events.

The cosmic ray rate is proportional to the product of the collection area, A, and to the solid angle of view, Ω, while the γ-ray rate is proportional to A. For an observation time, T, the signal to noise ratio, then, is given by $\Phi_\gamma AT/\sqrt{\Phi_{cr} AT\,\Omega\,(1-R)}$ where R is the background cosmic ray shower rejection factor and Φ_γ, Φ_{cr} are the fluxes of γ-rays and cosmic rays respectively. Typically, $\Phi_\gamma \approx 10^{-2}\ \Phi_{cr}\,\Omega$ and $R = 0$ for no rejection of background showers. The signal could be enhanced further by a factor of 3 to 10 in the case of pulsating sources like pulsars and X-ray binary systems if γ-rays are emitted at particular phases of the rotation of the emitting object. By folding the event arrival times (duly corrected for the Doppler effects introduced at the observer due to the rotation and orbital motion of Earth as well as the source due to the orbital motion of binary system) modulo the pulsar or binary orbital period, a phasogram of the light curve is constructed. The γ-rays populate only particular phases of the phasogram and stand out against the cosmic ray background which is distributed uniformly at all phases. Any search for pulsed γ-rays entails recording the event arrival times to great accuracy ($\Delta t/t \leq 10^{-10}$) to allow one to construct a phasogram avoiding a smear of the signal resulting from phase walk.

3. Observations

It is Shklovsky (1953) who first inferred the presence of electrons of tens of TeV energy in the Crab Nebula, gyrating around the magnetic fields (10^{-4} to 10^{-3} G) in the filaments of Crab to explain the optical continuum from the Crab Nabula. Soon this idea was confirmed by observations on the polarisations of photons at radio, optical and X-rays. Cocconi (1960) argued that, if electrons in the Crab are the end products of the decay chain $\pi^\pm \to \mu^\pm \to e^\pm$ (the pions being produced in the interactions of a high energy proton beam with the ambient matter), there must be also an emission of TeV γ-rays by the Crab through the decays of $\pi^\circ \to 2\gamma$. He predicted fluxes of VHE γ-rays at a level of $\sim 10^{-10}\ \gamma/\mathrm{cm}^2\ \mathrm{s}$ — high enough for the experimenters to follow up his suggestion and make observations. The first systematic observations to search for γ-ray sources using ACT were undertaken in the erstwhile USSR in 1960 by Chudakov *et al.* (1960). These observations, however, did not yield statistically significant results on the γ-ray fluxes from point sources; they set upper limits on the fluxes of γ-rays of energy > 5 TeV from several radio sources at a level of $\sim (2-5) \times 10^{-11}$ photons/cm^2 s. Other telescopes were subsequently developed by groups all over the world including two groups in India, the group from Tata Institute of Fundamental Research (TIFR) lead by Profs. B.V. Sreekantan and P.V. Ramanamurthy, and the group lead by Dr H. Razdan from Bhabha Atomic Research Centre (BARC), for detecting TeV γ-rays from celestial objects.

The TIFR group set up at Ooty (now called Udhagamandalam) in Southern India (76°.71E, 11°.42N, 2.3 km altitude) an atmospheric Cerenkov telescope with two search light mirrors mounted on an orienting platform in 1969, immediately after the discovery of a pulsar in the Crab Nebula. Over the years the number of mirrors were increased and the detection methods have been steadily improved. For several years, a TeV γ-ray telescope with a total mirror area of about 20 m^2 was operated in and around Ooty. A very systematic search for pulsed emission of γ-rays was made on a number of pulsars. Crab and Vela pulsars showed positive signals on several occasions. After operating the telescope for over 16 years in Ooty the mirrors were moved in the year 1986 to Pachmarhi in

Madhya Pradesh, where the sky conditions for night sky observations are better than that at Ooty.

The atmospheric Cerenkov telescope currently operating at Pachmarhi (22°.47N, 78°.43 E, 1075 m altitude) is shown in the photograph. It consists of 8 large parabolic reflectors (1.5 m dia) and 12 small size ones (0.9 m dia) all mounted equatorially. Each reflector could be moved independently both in the E-W and N-S directions and are controlled from a remote central room through electronic signals. A fast PMT, RCA 8575, is mounted at the focus of each reflector (behind a mask of ~ 2° to limit the field of view) to convert the Cerenkov light flash into an electrical pulse. These pulses are brought to the central room through coaxial cables, discriminated, put into majority logic and various triggers are generated. For every event, the event arrival time correct to a microsecond, analog pulse height from each group of PMT's and relative time delays between various mirrors etc. together with various housekeeping informations are recorded (Bhat *et al.* 1990a) on line on magnetic tapes using an indigenously designed system built around a Q-bus based PDP-11/23 processor (system dead time ~ 1 ms). A versatile software package was developed to control the above data acquisition system as well as monitor the performance of invididual channels. Accurate time keeping to within an error of ± 30 μs with respect to UT is achieved through a satellite time receiver system. A given source is usually tracked for a maximum of 6 hours per night as it moves through the hour angle range, from 45°E to 45°W. Data were collected on several isolated pulsars (Crab, Vela, Geminga, PSR0355 + 54), X-ray binaries (Cyg X-3, Her X-1, 4U0115 + 63), the eclipsing millisec binary pulsar PSR 1957 + 20 and several other celestial sources.

Photograph : An aerial view of the array of gamma-ray telescopes at Pachmarhi.

The BARC group started observing the night sky in the mid seventies at Gulmarg in Kashmir (34°.5N, 74°.3E, 2743 m altitude) using two bare faced photomultipliers (EMI 9545 B) separated by 1 m and pointing upwards in the sky (which can be likened to a wide-angle telescope with a viewing angle of 50° w.r.t. the zenith) in the drift scan mode. In this mode the telescope is kept stationary, and the sky is scanned as Earth rotates. They reported (Bhat *et al.* 1980a) a non-random component in the arrival times of cosmic ray events for time separation of < 40 s. Later, following the TIFR group, they too installed (Koul *et al.* 1989) a similar set-up at Gulmarg, consisting of 6 equatorially mounted parabolic search light mirrors of 0.9 m diameter divided into two banks of 3 mirrors each. Using this system they have observed a few X-ray binaries (Cyg X-3, Her X-1, 4U0115 + 63), pulsars (Geminga), catalysmic variables (Am Her) and other sources.

4. Results

During the many years of observation, by various groups, several celestial objects were looked at in their attempt to detect γ-ray emission. The radio pulsars Crab and Vela, X-ray binaries Her X-1 and Cyg X-3 and the supernovae remnant Crab Nebula were the most intensely studied objects. In the following I shall highlight results from some of the observations conducted by the TIFR and BARC groups. I have chosen a few results for illustration purposes only, those with which I am either more familiar or personally involved with, with a bias towards the later. For an exhaustive survey of results one may refer to the recent reviews on this subject (see for *e.g.* Weekes 1992; Rao & Sreekantan 1992).

The Crab pulsar was observed by the TIFR group since 1977 on a regular basis with progressively increasing sensitivity. Evidence for the time-averaged emission of pulsed VHE-rays were seen in some years' data at a flux level of I_γ (> 6.4 TeV) = $(8 \pm 2) \times 10^{-12}$ photons/cm^2 s but not in the rest of data. This could very well mean that the signal is variable and/or sporadic, a general feature as experienced by all groups involved in the search of VHE γ-ray sources. This feature has come to be known in the literature as episodal emission as opposed to steady (pulsating or otherwise) emission. The more recent observations have detected transient emissions of a few minutes duration essentially because special efforts were made to search for them since the early eighties. An episode of 15 minute duration was recorded by the TIFR group (Bhat *et al.* 1986) on January 23, 1985 at 17:11 UT from the Crab pulsar. The light curve shows a narrow pulse, a 5 σ excess, at the position of radio main-pulse. An important feature of this observation is that two independent telescopes tracking the Crab pulsar from locations at Ooty separated by 11 km showed the signal while a third telescope adjacent to one of them but pointing towards a background region, 8° away from the Crab pulsar, did not show any effect, thus strengthening the inference of a transient pulsed emission of TeV γ-rays by the Crab pulsar. A similar burst from the Crab pulsar has been observed (Acharya *et al.* 1992) with $a > 6\sigma$ signal at the radio main-pulse position of January 2, 1989 at 18:07 UT while operating at Pachmarhi with an altogether different set-up. This burst was seen in all the 5 quasi-independent telescopes and lasted for 5 minutes. The light curves of these two bursts are identical and are shown in figure 1. The time-averaged fluxes of γ-rays over the burst periods are comparable to each other and are equal to $(2.5 \pm 0.6) \times 10^{-10}$ photons/cm^2 s and

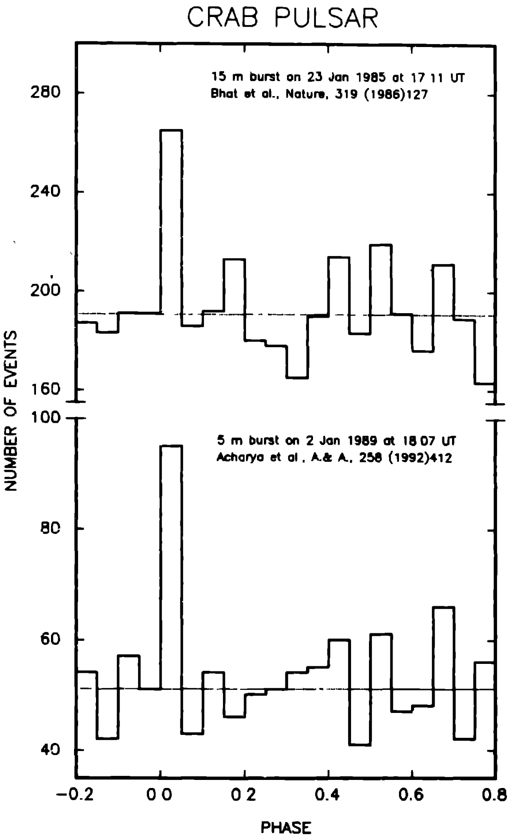

Figure 1. The gamma-ray light curve of Crab pulsar during two episodic emissions. The upper phasogram is obtained during a 15 minute burst at 17:11 UT on 1985 Janaury 23 and the bottom one during a 5 minute burst at 18:07 UT on 1989 January 2. The dotted line represents the average for the whole phasogram in both cases. The radio main-pulse position corresponds to zero phase.

(1.4 ± 0.2) × 10^{-10} photons/cm^2 s at respective threshold energies of 1.2 TeV and 2.8 TeV. Variability of the signal on a shorter time scale was studied by Vishwanath (1987) who subdivided the data into several mini-runs of 1 minute duration each and examined their phasograms. He found evidence for emissions over time scales of minutes and possibly hours. The TeV γ-ray light curves obtained from the Crab pulsar were found to vary from a narrow single pulse occuring at, either the main or the interpulse of the radio emission, to both pulses or a broad pulse structure covering almost half the period with emission in between the main and interpulses.

Vela pulsar located 500 pc away from the solar system could only be observed from sites located in the southern hemisphere or close to the equator. This pulsar was observed by the TIFR group while operating at Ooty on 6 observing seasons spanning 8 years. A coherent emission of pulsed VHE γ-rays were seen in almost every years' data at differing significance levels. The early observations (Bhat *et al.* 1980b) did not have absolute phase information but detected two narrow peaks separated by ~ 0.42 in phase, a characteristic feature noticed at other wavelengths. Information on absolute phase was available for the later years' observations. The data from these observation showed a small but persistant emission at the same phase. The signal to noise ratio improved significantly when lower energy events were preferentially selected (Bhat *et al.* 1987).

The resultant TeV γ-ray phasogram from Vela shows a 4.0σ peak aligned with the optical first pulse position. A weak second pulse (1.5σ) separated by 0.43 in phase from the main pulse was also noticed. The integral energy spectrum of the γ-ray signal, seen over the years at different energy thresholds (from 4.9 TeV to 10.4 TeV), was found to follow a power law of type $E^{-(2.5 \pm 0.3)}$. The time averaged integral flux, based on excess counts in the two peaks, is $(1.5 \pm 0.3) \times 10^{-11}$ photons/cm^2 s at $E_\gamma > 4.5$ TeV.

PSR0355 + 54 is a short period (p = 156 ms) radio pulsar characterised by its extremely low timing noise and occasional large glitches. This pulsar was observed by the TIFR group in 1987 for a total of about 25 hours. A steady pulsed emission was seen from this pulsar (Bhat *et al.* 1990b). The light curve, shown in figure 2 has a 4.3σ signal at a phase 0.53 with respect to the radio pulse. The probability that this signal is due to the statistical fluctuation of the background is 8.7×10^{-4} taking all the degrees of freedom into account. The time averaged integral flux from this source works out to be, $I_\gamma(E_\gamma > 1.3 \text{ TeV}) = (7.9 \pm 2.0) \times 10^{-12}\ \gamma/\text{cm}^2$ s which corresponds to a TeV γ-ray luminosity (assuming isotropic emission of γ-rays with a differential energy spectrum $\propto E^{-2}$) of 3.1×10^{34} erg/s, a figure comparable to the total spin down power of the pulsar. Observation on this source was followed up in subsequent years, but at higher thresholds. The signal continues to be present in the same phase bin as before but with lesser significance as expected.

X-ray emitting accreting binary pulsars are another interesting catagory of sources of high energy radiation. Most often, the observed γ-ray emission is sporadic and is generally modulated with the rotation period of the neutron star. Hercules X-1 is a favourite candidate source to look at, as it is one of the best known low mass X-ray binaries and often considered the prototype. The X-ray emission from this source exhibits 3 distinct periodicities: 1.24 s due to rotation of the neutron star, 1.7 d due to orbital motion of the binary system and 35 d probably due to precession of the neutron star. The TIFR group observed (Vishwanath *et al.* 1989) one 14 minute episode on April 11, 1986 in a total of 15 hours' of data collected in the year 1986 on Her X-1. An enormous (~ 54%) increase in the trigger rate was noticed

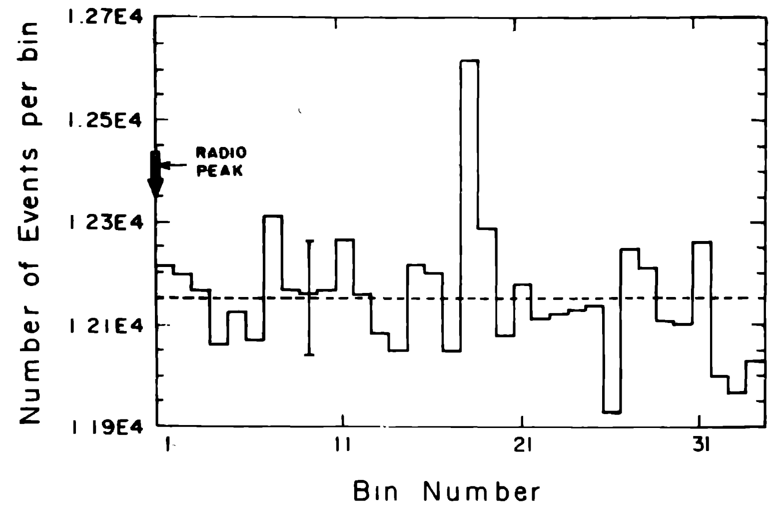

Figure 2. The gamma-ray phasogram of PSR 0355 + 54 based on 428,639 events collected during ~ 25 hours of observation. The signal at a significance level of 4.3σ and occuring in the 18th bin is at a phase 0.53 w.r.t. the radio peak. The one sigma error on the background is indicated as an error bar on the mean.

while there was none in the chance trigger rate as shown in figure 3. The excess of trigger events over the baseline were interpreted as due to γ-rays. The time averaged flux during burst is = (1.8 ± 0.4) × 10^{-8} γ/cm² s at $E_\gamma > 0.4$ TeV. The luminosity of the source works out to be 1.8 × 10^{37} erg/s for an isotropic emission and an exponent of –3 for differential energy spectrum. Several frequent gaps in the event time data stream, due to misbehaviour of the data recording system precluded the 1.24 s periodicity analysis. The 1.7 d and 35 d phases at the time of the burst are 0.19 and 0.31 respectively. Subsequent observations did not show any sign of emission over a time scale of few minutes. The BARC group has observed (Rawat *et al.* 1991) this object in an ON-OFF mode, wherein a Her X-1 scan of 30 minute duration covering a certain zenith angle range was immediately followed by an OFF source scan of same duration, spanning the same zenith angle range. No evidence of steady emission form Her X-1 was seen in the entire 16 hours' data collected during June 1988. Based on the average ON/OFF ratio of 1.01 ± 0.01, a 99% confidence level upper limit on the steady flux of γ-rays of energy ≥ 3 TeV from Her X-1 is placed at 3.6 × 10^{-11} γ/cm² s. However, one 15 minute long duration of episodic emission was noticed to occur on June 12, 1988 at 21:05 UT when the data were subjected to neutron star periodicity analysis. The observed pulsation period is consistant with the contemporary X-ray period. The 35 d cycle phase for the episode is 0.02, a phase close to the on-set time of 'high on' state in the X-ray flux and the 1.7 d orbital phase is 0.66. The time averaged flux works out to be (4.7 ± 1.2) × 10^{-10} γ/cm² s at ≥ 3 TeV which corresponds to a source luminosity of ~ 10^{35} erg/s.

The binary system, Cygnus X-3, in the constellation of Cygnus is known to flare up occasionally producing an increase by a few orders of magnitude in the radio flux density.

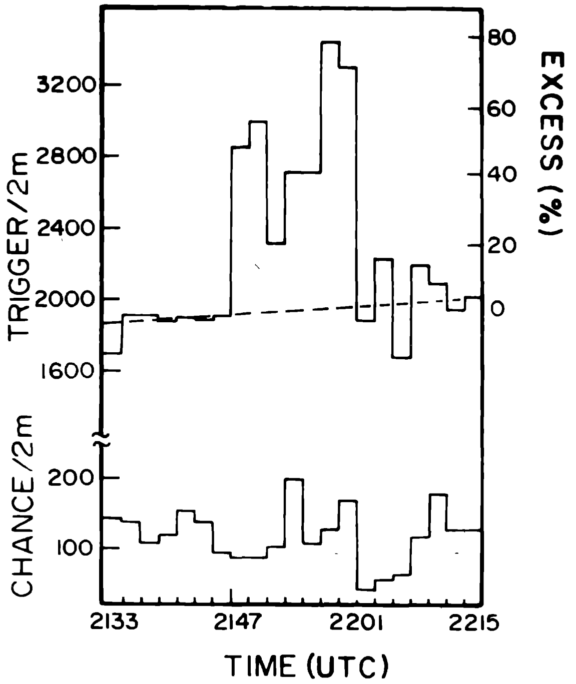

Figure 3. The trigger rate and the chance coincidence rate per 2 minutes on 1986 April 11, during observations on Her X-1. The broken line represents the expected trigger rate due to cosmic ray showers. The right-hand side scale shows the excess over the cosmic ray background rate as a percentage of the background rate.

A peak flux density ranging from 3 to 22 Jy were observed on various occasions at various radio frequencies. The BARC group trained their telescope at Cyg X-3 during one of the outstanding radio flares in October 1985. Two episodes of higher event rates, each lasting for a few minutes (≤ 7 minutes) on 10 and 12 October, during the immediate post radioflare period were observed (Rawat *et al.* 1989). No correlation with the 4.8 h orbital period is seen in both cases. They report a time averaged flux of $(1.2 \pm 0.2) \times 10^{-11}$ γ/cm^2 s at a photon energy of ≥ 6 TeV.

Am Hercules is a prototype cataclysmic variable (CV) binary system comprising a synchronously rotating ($p = 3.1$ h) magnetic white dwarf and accreting matter from a Roche lobe filling late type main sequence star. A possible emission of TeV γ-rays of energy > 2TeV from this source with a phase averaged flux of $(5.6 \pm 2.1) \times 10^{-11}$ γ/cm^2 s is observed by the BARC group (Bhat *et al.* 1991). The γ-ray light curve is found to exhibit two broad emission peaks at magnetic phases around (0.1 ± 0.2) and (0.6 ± 0.2) and is similar to the observed phase dependence of the circularly polarised light emitted by the source.

5. Conclusions and future prospects

As a result of intense observational efforts all over the world it has been possible to establish a few celestial sources among the radio pulsars, X-ray binaries, Supernova remnants, cataclysmic variable etc. as emitters of VHE γ-rays. With a few exceptions [for *e.g.* detection of steady emission of TeV γ-rays from Crab by the Whipple group (Vacanti *et al.* 1991) and steadily pulsating TeV γ-rays from PSR0355 + 54 by the TIFR group] most claims of detection of TeV γ-ray emissions relate to sporadic emissions lasting for a few to several tens of minutes. Some of them were observed only once and only by one group and await confirmation. Weak fluxes coupled with the variable or sporadic emission of γ-rays renders this branch of astronomy a difficult one. To establish the sporadic nature of emission (bursts), a simultaneous recording of the same outburst with the same characteristics by two or more independent telescopes is a must. A modest beginning is made in this respect. The observation of a TeV γ-ray burst from Crab pulsar simultaneously by the two widely separated telescopes at Ooty and observing a similar outburst (4 years later at Pachmarhi) with a similar light curve from the same source is one such example. The break-through achieved by the Whipple group in reducing the cosmic ray background considerably through imaging technique (Vacanti *et al.* 1991) developed through vigorous Monte-Carlo simulation of γ-ray and proton induced showers has given tremendous hope for the future. They have detected (Punch *et al.* 1992) a 34σ steady (unpulsed) signal from Crab nebula by achieving a background cosmic ray shower rejection factor, $R \approx 0.98$ and have established this source as a steady emitter of TeV γ-rays with an integral flux of $F_\gamma(> E) = 1.9 \times 10^{-11} E_{\text{TeV}}^{-1.4}$ γ/cm^2 s, which could be used as a steady candle. No other such steady candle of steady pulsed emissions exist as yet. Several highly sensitive experiments with large background rejection factors and source location accuracy of ~ 7' are planned world-wide including one telescope at the South Pole in the coming years. The present TIFR array at Pachmarhi is being expanded to include 20 more mirrors and reduce the energy threshold. There are further plans to increase it by 4 fold and deploy them in various modes like compact, distributed and well separated independent telescope modes in the near future. The new array will also make use of differences in the lateral distribution of Cerenkov light between photons and proton initiated showers to improve the signal/noise ratio. The BARC group intends to shift their set-up to a new location at Mt. Abu and install a system with imaging capability. Overlapping observations should now be possible between Pachmarhi and Mt. Abu set-ups and establish the authenticity or otherwise of episodic emissions. The new satellite, Compton Gamma Ray Observatory (CGRO), launched by NASA on April 5, 1991 has opened up a new possibility of simultaneous or contemporaneous observations with the ground based observations of a given source. Detectors on board the CGRO have detected γ-ray emissions from a number of galactic and extragalactic objects including the pulsars Crab and Geminga, the quasars 3C273 and 3C279 and a giant elliptical galaxy Markarian 421 having a nucleus of the BL Lacertae type, thus adding a new class of objects (BL Lac objects) as γ-ray emitters at low energies ($<$ 10 GeV). Spurred by the CGRO observation on Mk 421, the whipple group (Punch *et al.* 1992) trained their telescope at this distant (redshift, $z = 0.031$) object and obtained a positive evidence for steady emission of TeV γ-rays from the source. With these successes, the field of very high energy gamma-ray astronomy, dealing with photons of TeV energies, is looking up. Combined with observations at the other wavelengths of the electromagnetic spectrum (radio, IR, optical, UV, X-rays, GeV energy γ-rays and PeV energy γ-rays), the TeV gamma-ray astronomical observations will help in understanding the nature and processes going on in the environs of specific astrophysical objects. The TeV gamma ray observations are poised to make important contributions to high energy astrophysics in the years to come.

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