TeV γ-ray astronomy using Atmospheric Čerenkov Telescope at Pachmarhi

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ABSTRACT

We present the details of the distributed Atmospheric Čerenkov Telescope Array currently operating at Pachmarhi, India. We use the differences in the lateral distribution of Čerenkov photons between the γ-ray and proton induced showers to cut down the cosmic ray background. Preliminary analysis of data on Crab and Geminga pulsars, taken during 1992 - 1993 indicates that it is possible to reduce background, when a cut designed to preferentially select showers with a flat lateral distribution of Čerenkov photons, is made.

1. INTRODUCTION

To search for persistent weak emission of TeV γ-rays from celestial sources one has to reduce the background due to hadronic cosmic ray showers. Monte-Carlo simulations have shown that differences between hadron induced and γ ray initiated cascades could be exploited to reject cosmic ray initiated showers (Hillas 1985, Hillas and Patterson 1987, Rao and Sinha 1988). The simulations have shown that electromagnetic cascades are flatter in the lateral distribution of Čerenkov photons and more compact in the angular size of the Čerenkov images than those initiated by cosmic ray primaries.

Several groups have used some of the above parameters to reject the background and enhance the signal (Weekes 1989, Baillon *et al.* 1994, Tumer *et al.* 1985 and Goret *et al.* . 1993). The Whipple group has detected steady emission of TeV γ-rays from Crab nebula using Čerenkov imaging technique (Vacanti *et al.* 1991 and Punch *et al.* 1992) and have established this source as a 'standard candle' of TeV $\gamma-$rays. However, not enough attention has been given to the lateral distribution aspect of the atmospheric Čerenkov radiation to reject cosmic ray initiated background. The lateral distribution of Čerenkov photons have a "hump" at distances of 120-140 m from the shower core in γ-ray initated cascades only (Rao and Sinha 1988). Further, the shower to shower fluctuations in the lateral distribution of Čerenkov photons is much less for a γ-ray initiated shower compared to cosmic ray initiated showers, which

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are rather 'bumpy' due to the contribution of Čerenkov light from muons. The average lateral distribution of Čerenkov photon densities, as calculated by Hillas and Patterson (Hillas and Patterson 1990), clearly show a flat distribution up to the "hump" region for γ-ray initiated showers and a steeper distribution for proton initiated ones. Rao and Sinha (Rao and Sinha 1988) have shown that the signal to noise ratio could at least be improved twice by exploiting these very differences. Calculations made for various array configurations showed (Vishwanath *et al.* 1993) that unambiguous identification of γ-ray initiated showers could be made with a large number of detectors sampling the Čerenkov photons. Accordingly, the set-up at Pachmarhi is being modified and augumented. In this paper, we describe our set-up, method of obervation and data analysis techniques. Data taken during 1992-93 on Crab pulsar is used as a training ground for an analysis technique which rejects background using differences in the lateral distribution of Čerenkov photons between γ-ray and proton initiated showers. Preliminary results on Crab and Geminga pulsars are also reported.

2. TELESCOPE SET-UP

The Atmospheric Čerenkov Telescope Array at Pachmarhi, India (longitude: $78° \; 26' \; E$, latitude: $22° \; 28' \; N$ and altitude: 1075 m a.s.l.) consists of an array of parabolic reflectors of 0.9 m and 1.5 m in diameter spread over an area of $85 \; m \times 100 \; m$. The reflectors are equatorially mounted and independently steerable both in E-W and N-S directions. The reflector orientation and tracking are controlled by a computer automated system to an accuracy of $\pm 0°.1$. A fast photomultiplier (Burle 8575) mounted at the focal plane of each reflector behind a 2° diameter mask is used to detect Čerenkov photons.

Prior to 1992, we had 20 reflectors, each having its own mount. The number of reflectors is steadily and constantly increased to improve the signal/noise ratio over the years. At present, the array is configured to consist of 13 banks of reflectors of 2.5 m^2 total area each as shown in figure 1. Pulses from photomultipliers of a given bank were linearly added together. The telescope set-up is being further upgraded to have 25 banks, each having a total reflector area of 4.4 m^2. The mirror mount was also re-designed so as to hold 7 reflectors in a mount. In its final form the banks will be arranged in a 5×5 matrix with a spacing of 20 to 25 m.

3. OBSERVATIONS

The modification and expansion of the array was started in Jan 1992. While development work was given priority, observations were carried out on isolated pulsars like Crab and Geminga mainly to train the analysis procedures and test the trigger electronics.

Data were taken during clear moonless nights. The source was acquired and tracked by an automated computer-controlled tracking system. Pointing and tracking accuracy of all telescopes was within $\pm 6'$. Typically, a source was tracked for about 1 to 5 hours over the hour angle range of $-38°$ to $+38°$. Event triggers were generated by a majority logic of various combinations of reflector banks and pulse height threshold levels. Each trigger was tagged for its identification. The minimal trigger corresponds to a threshold energy of 600 GeV for γ-rays. Event arrival times were derived from a Global Position Satellite receiver having a time keeping accuracy of ± 100 ns. Each event data consists of the event arrival time to an accuracy of ± 1 μs, amplitude and relative time of arrival of pulses at each bank, trigger information and other relevant house-keeping informations which are recorded on a magnetic tape by a real time data acquisition system (Bhat *et al.* 1990).

Genuine coincidence rates, chance coincidence rates and all the bank rates were monitored through out a run.

4. ANALYSIS

The observed event times are reduced to that at the solar system barycenter using the JPL ephemeris. The phase of each event is computed using contemporaneous pulsar elements and a phasogram is constructed. Two cuts, one based on the arrival direction of the shower and the other based on the flatness of the lateral density distribution of Čerenkov photons, are applied to reduce the content of cosmic ray initiated showers in the data.

We demand that atleast 5 banks trigger for determining the arrival direction of a shower from the time to digital converter (TDC) information, approximating the shower front to a plane. The angular resolution of the system is obtained by the split array method and is about $0°.75$. ($0°.6$ for ≥ 7 triggered banks). The number of events as a function of the space angle between the two sets of direction measurements is shown in figure 2.

We define a parameter F, called the Flatness parameter, as

$$F = \frac{1}{N < \rho >} \sum_{i=1}^{N} (\rho_i - < \rho >)^2$$

Where N is the total number of banks triggerred and $< \rho >$ is the average of the $\rho_i's$, the number of photons in individual banks. F is then computed for every shower. The value of this parameter is expected to be small for showers with a flat and less "bumpy" lateral distribution. This is a χ^2 like parameter except that its distribution is unlike that of χ^2 since the population of photon densities is not drawn from a normal distribution. The Monte-Carlo calculations (Vishwanath *et al.* 1994) show that a selection of low values of F ($F \leq 0.4$) descriminates γ-rays against cosmic ray background. The actual value of F at which a cut is imposed seems to depend on the assumed fluctuations in the lateral distribution, the geometry of the array and N.

5. RESULTS

We have observed Crab pulsar for about 46^h from Jan. to Mar. 199 (I), for 92^h from Oct. 1992 to Mar. 1993 (II) and for 20^h in 1993-94 (III). Geminga pulsar was observed for 76^h in 1992-93 (II) and for 40^h in 1993-94 (III). Preliminary analysis has been done for the first two sets of data while it is continuing for the third set. 9 banks were operating during data set I, 8 banks during data set II and 12 banks during data set III. The angle information could not be obtained for data set I due to lack of TDC information. Two of the TDC channels were malfunctioning during data set II and hence at times we had TDC informations in only 6, 7 or 8 Banks.

The phase plots before and after applying the F cut ($F \leq 0.3$) for the data set I are shown in fig. 3a and 3b respectively. It is seen that the deviation in the bin corresponding to the radio main-pulse phase is enhanced with this cut. 77 % events got rejected with $F \leq 0.3$ cut. The observed number of events in the bin corresponding to radio main-pulse phase is 7912 when 7742 events are expected in the uncut data. The corresponding numbers with the F-cut are 1958 and 1739. This deviation of the observed number from the expected corresponds to a Li-Ma significance of 5σ. No significant deviation in the number of observed events is seen in the inter-pulse position.

In the II set of data events with a space angle θ between the source and the shower axis $\leq 1°.5$ and ≥ 5 triggered banks are accepted. The 20 bin phasogram is shown in fig. 4a. An angle cut of $\theta \leq 0°.75$ is then applied resulting in the rejection of about 75% of data. An F-Cut of $F \leq 0.4$ is then applied which rejected about 50% of remaining data. The over-all rejection by both the cuts was about 87%. The phasograms for data with $F \leq 0.4$, $\theta \leq 0°.75$, $F \leq 0.4$ and $\theta \leq 0°.75$ cut are shown in figures 4b to 4d. It should be recalled that the F-cut is sensitive to the number of banks used and the geometry of the array. Excess of events over the background (defined as the mean in the phase region between 0.5 to 0.95, the 'unpulsed' region) is seen in the main, inter pulse and the region in between them in fig. 4d The Li-Ma significance of these excess events are 4.1σ, 4.6σ and 2.5σ respectively.

Same cuts were also applied to the Geminga data as the available number of banks were more or less same in data taken of these objects. The resulting light curve with 30 phase bins for data with basic cuts and that with $F \leq 0.4$, $\theta \leq 0°.75$, $F \leq 0.4$ and $\theta \leq 0°.75$ cut data are shown in figures 5a to 5d. A 5.0σ deviation is seen in fig. 5d in the pulse position P1 ("the I pulse of EGRET data") while the Li-Ma significance of the deviation in the P2 pulse position ("the II pulse in EGRET data") is 2.6σ.

6. DISCUSSION

It is evident that a cut based on the lateral distribution of Čerenkov photons enhances the γ-ray signal in addition to the cut on the direction of arrival of the shower. It is intuitively obvious that if there are γ-rays and if they have a flat lateral distribution of photons, a cut like this should reject background and hence enhance the signal.

Preliminary analysis of data on Crab pulsar taken in 1992-93 indicates emission in the position of radio main pulse, inter pulse and inbetween. The basic chance probability is multiplied by 9, the number of F-cuts tried, and 5 (7 for data set I), the possible trials in deriving the value of F if restricted to a specified number of banks. The final probability that the signal at the Main pulse position in the I data set is due to chance is 4×10^{-5}. The combined probability of a chance fluctuation in 3 emission regions in the data set II is $\approx 1.5 \times 10^{-8}$. It should be noted that the Whipple experiment (Vacanti *et al.* 1991) and ASGAT experiment (Goret *et al.* 1993) did not see any pulsed emission from Crab pulsar.

In the data of Geminga pulsar too, the signal shows up when the same cuts as that for Crab pulsar are applied. The corresponding chance probability is $\approx 7 \times 10^{-6}$, taking all degrees of freedom into account. This result confirms the earlier detection by the Tata and Durham groups using their archival data (Vishwanath *et al.* 1993, Bowden *et al.* 1993). However, the Whipple group did not see any pulsed emission from this object (Akerlof *et al.* 1993).

The data were split into smaller sets to examine the time-variability in the emission of TeV γ-rays. No evidence for a significant variability is observed. Both Crab and Geminga pulsars seem to emit steady pulsed TeV γ-rays during 1992-93, the period corresponding to the data set examined. Our analysis to estimate absolute fluxes, by understanding various effects of the cuts imposed, is in progress. We are also in the process of looking for other sensitive parameters to reject maximum background events while retaining a good number of γ-ray events.

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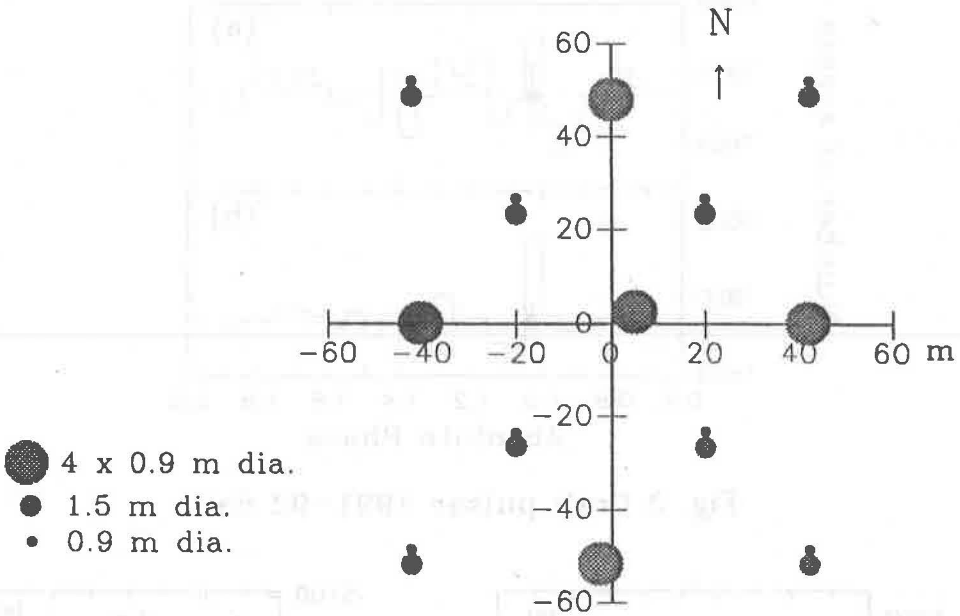
Fig. 1 ACT ARRAY at PACHMARHI ($78^0.42$ E ; $22^0.46$ N ; 1075 m above m.s.l.)



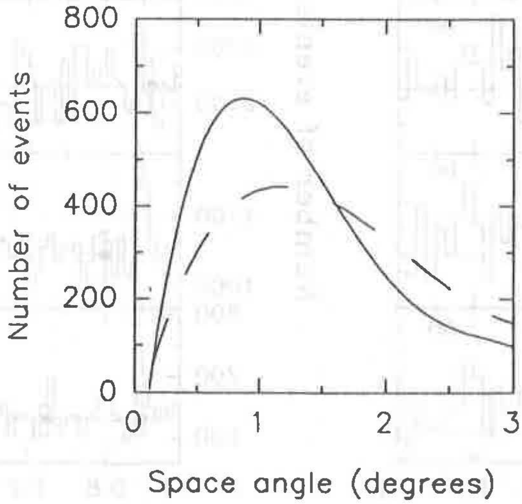


Fig. 2 Angular response of the array. Full line for 8 banks and dashed line for 6 banks

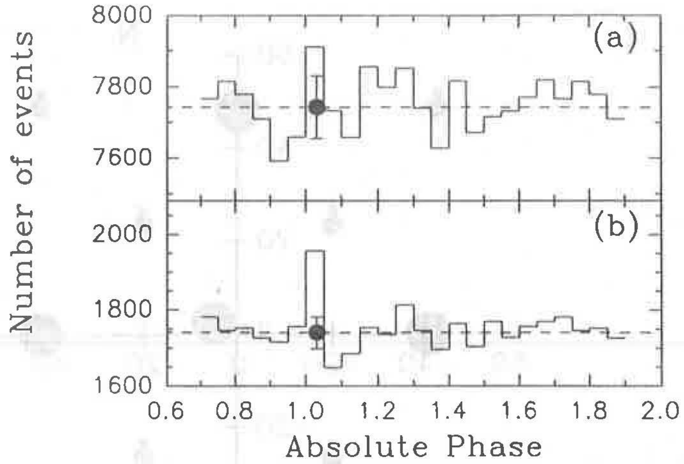


Fig. 3 Crab pulsar 1991−92 data

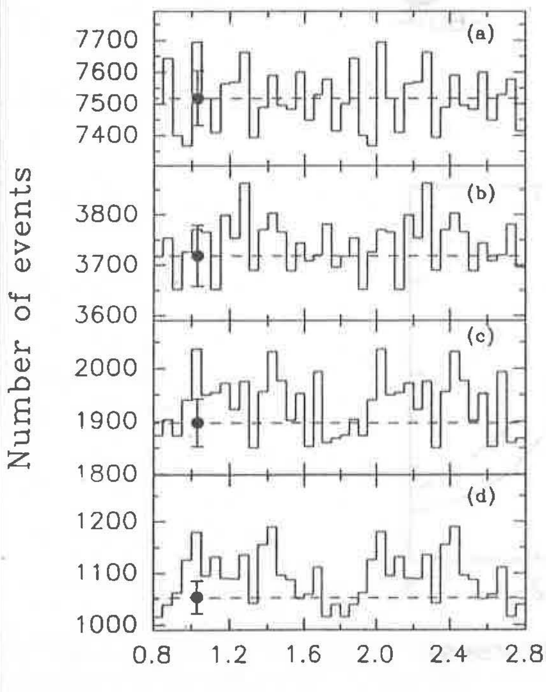


Fig. 4 Crab pulsar 1992−93 data

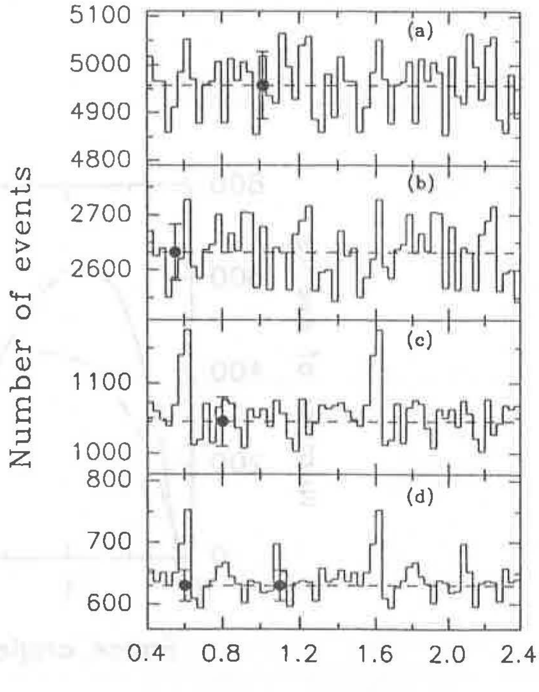


Fig. 5 Geminga, 1992−93 data