OBSERVATIONS OF STEADY FLUX OF PEV ENERGY EXTENSIVE AIR SHOWERS FROM CYGNUS X-3 DURING 1984-86

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ABSTRACT

Data taken with a 24 detector extensive air shower array, operating at Ooty since June 1984, have been used to search for excess of extensive air showers of energy > 2.5 X 10^{14} eV from the direction of binary X-ray source Cygnus X-3. The data show a time-averaged excess in the number of showers from this direction, over the background determined from other regions of the sky having the same declination. The excess is most prominent among older showers having a flatter lateral distribution. A part of this excess shows up significantly in the phase region, 0.6-0.8, in the 4.8 hour periodicity analysis. These observations correspond to an integral flux of $(7.60 \pm 3.15) \times 10^{-13}$ $cm^{-2}s^{-1}$ at energies > 2.5 x 10^{14} eV and of $(1.04 \pm 0.44) \times 10^{-13}$ cm^{-2} s^{-1} at energies > 2.5 x 10^{15} eV. The observations confirm, for the first time, results reported by the Kiel group in 1983 of a directional excess from the direction of Cygnus X-3, without requiring the 4.8 hour periodicity analysis as was necessary in many of the other experiments reporting positive signals. This emphasizes the advantage of good angular resolution for such studies.

To appear in Ap. J. Lett. (1988)

The binary X-ray source Cygnus X-3 has been studied extensively in the gamma ray energy range, few MeV to tens of PeV, using different techniques, after the exciting observations of an excess flux at energies > 10^{12} eV from the direction of Cygnus X-3 by the Crimean group (Vladimirsky et al 1973). Many groups (see Turver 1985 and Watson 1985) later reported observing signals from Cygnus X-3 at TeV energies, but these claims are mostly based on observations of a 4.8 hour periodicity as seen in the X-ray flux. In 1983 the Kiel group (Samorski and Stamm 1983) reported observations of a directional excess of 16.6 showers (4.4σ) above the average off-source background of (14.4 $\pm$ 0.4) showers per bin (4^{o} in right ascension and 3^{o} in declination) for older showers (age > 1.1) at energies above 10^{15} eV. These showers also showed strong correlation in the 4.8 hour periodicity. Surprisingly, these observations showed that the showers from the direction of Cygnus X-3 contained almost as many muons as normal showers, contrary to expectations for photon-initiated showers. Several groups (see Watson 1985 and Protheroe 1987) have since claimed detection of PeV energy gamma rays from Cygnus X-3, based on the 4.8 hr periodicity analysis. These observations, however, do not agree with each other completely in the phase of emission, thus creating some doubts about the advantage of phase analysis for the purpose of establishing Cygnus X-3 as a gamma ray source at TeV and PeV energies. Of course, the absence of observations of a steady flux from Cygnus X-3 and the reliance on phase analysis for detection of a positive signal were essentially due to the poor angular resolution of almost all the air shower arrays operating prior to 1984, except for the Kiel array.

We report here observations carried out with a 24 scintillation detector array at Udhagamandalam (Ooty, for short) in southern India at an altitude of 2200 m (800 g cm^{-2}), and latitude $11^{o}.4$ N. Various tests carried out with this array showed (Apte et al 1985, Tonwar 1985) that for showers of size>$5x10^{4}$ particles incident over the central part of the array, the angular resolution of the array is about $1^{o}.0$ to $1^{o}.5$, depending on shower size. Regular datataking was started in June 1984 with a loose trigger, called NEWS, requiring a single particle in each of the four detectors, N, E, W, and S, placed at the corners of an approximate square of side 10 m near the centre of the array; a further requirement was at least 3 particles in any one of these 4 detectors (Tonwar et al 1985). The shower rate was about 0.13 s^{-1}. During the period, June 27, 1984 (day 179 of the year) to November 12, 1986 (day 316), a total of 7.6 x 10^{6} showers were recorded.

Data analysis of these showers involved two steps:

(i) Computation of the arrival direction cosines for all showers, using the relative arrival time information from all detectors which had a signal larger than about 0.3 of the signal expected from a through-going relativistic muon. Only showers with a signal > 5 particles in at least one of the 4 triggering detectors (N,E,W, and S) were used in the analysis (Apte et al 1988), and

(ii) Computation of the core position, shower size and the lateral distribution parameter s (shower age) for each shower using the χ^2-minimisation method (Sreekantan et al 1983).

Since the determination of direction in individual showers suffers from unpredictble systematic effects in showers whose cores lie on the periphery of the array due to fluctuations in development, some minimum cuts were imposed on the data, to ensure accuracy in angle, shower size and age determination. These cuts are:

Shower size $N_e > 5 \times 10^4$; $R_{core} < 30$ m ; Zenith angle $< 40^o$

The array has poor detection efficiency for showers of size less than 5×10^4 for core distances larger than 10 m with the hardware and software cuts discussed above. A zenith angle cut of 40^o has been imposed to restrict atmospheric depth to less than about 1040 g cm^{-2} . The meridian zenith angle of Cygnus X-3 at Ooty is $29^o.4$, corresponding to an atmospheric depth of 920 g cm^{-2}. This range of 120 g cm^{-2} gives a variation of primary energy by a factor of about 2 for a recorded shower size since the attenuation length of showers of size 10^5 at Ooty altitude is about 150 g cm^{-2},

With these selection criteria, 5.5×10^6 showers were available for search of discrete sources of energy > 10^{14} eV. For examining the Cygnus X-3 region, all showers with declination $\delta = 38^o.9-42^o.9$, were selected and grouped into 90 bins in right ascension (RA), each 4^o wide, with the centre of the 46th bin at RA of $307^o.8$. Thus all showers with RA and declination within $\pm 2^o$ of Cygnus X-3 were binned into the 46th bin (Cygnus X-3 bin). Since data were taken on an almost continuous basis for nearly $2^1/_2$ years, the exposure was nearly equal for all the 90 RA bins. However, a low level normalisation for equal exposure was done using the total number of showers in different RA bins for all values of declination, as the index of exposure. The RA plot for bins 31 to 60 is shown in figure 1a which shows an excess (1.8σ) in the Cygnus X-3 bin. There are

884 events in this bin compared to the 90 bin average of (833 ± 3.0). This excess, while interesting, is not statistically significant by itself.

Showers with $N_e > 5 \times 10^4$ at Ooty have a broad age distribution (Apte et al 1988) with a median value of 1.09. For reasons discussed later we put an age cut of 1.4 to enrich the data with old showers (Samorski and Stamm 1983) and figure 1b shows the RA plot for these showers. Nearly 1/3rd of the showers satisfy this condition. The statistical significance of the excess in the Cygnus X-3 bin increases to nearly 3.4σ , with 300 events in this bin compared to the 90 bin average of (247 ± 1.6). Showers in figure 1b were further subdivided into four differential shower size bins: $5\times10^4<N_e<10^5$ (A), $10^5<N_e<2\times10^5$ (B), $2\times10^5<N_e<5\times10^5$ (C), and $N_e>5\times10^5$ (D). It is significant that Cygnus X-3 bins in these 4 independent data samples show excesses of 3.1, 0.8, 0.2, and 3.8σ respectively, relative to the background in each group. The RA distributions for subgroups A and D are shown in figures 1c and 1d respectively. The probability that these excesses in the Cygnus X-3 bin could arise due to random fluctuations is less than 10^{-5}, when we took into account the 4 size groups and two age groupings (all ages and age>1.4) considered.

The occurrence time (UT) for each shower was known with an accuracy of 1 ms. For phase analysis, the observed times of showers in the Cygnus X-3 bin were converted to arrival times at the Solar system barycenter. The phase histogram for showers in the Cygnus X-3 bin and size > 5×10^4, computed using the Cygnus X-3 ephemeris (van der Klis and Bonnet-Bidaud 1981, van der Klis 1984; $P=0.199968338$ d, $\dot{P}=1.02 \times 10^{-9}$ d/d, and $T_o=244\ 0949.8965$

JD), is shown in figure 2a. Interestingly, the phase interval, 0.60-0.75, shows a somewhat significant excess (about 2σ), compared to the expected background which is calculated by dividing the total number of showers by 20. The numbers actually plotted in the figure are normalised for exposure which was almost uniform for all 20 bins to within a few percent due to the rather long and almost continuous run of 868 days (179/1984-316/1986). It is to be noted that the phase region, 0.6-0.8, is a preferred region for emission, both at the TeV and PeV energies (Watson 1985 and Protheroe 1987). The phase distribution for older (age>1.4) showers, shown in figure 2b shows similar features. Since the time-averaged signal seems to be strongest among larger size showers (figure 1d), it is of interest to see the phase plots for showers with size>$5x10^5$, without and with age selection. These plots are shown in figures 2c and 2d respectively. The phase region, 0.6-0.8, shows an excess of nearly 3σ in figure 2c while the excess is only about 2σ in figure 2d.

The background values shown in figures 2a-d by dashed lines are conservative estimates since these include contribution due to the source. There are two other ways of estimating background for these plots. One way is to subtract possible source contribution (for example, events in the phase region 0.6-0.8) from the total number and then divide the remaining events by 16. This would increase the statistical significance of the excess seen in phase region 0.6-0.8 in plots 2a-d, for example, the excess seen in figure 2c increases from 3σ to 4σ above the background. A more realistic way of estimating background is to use the average number of showers expected in the Cygnus X-3 bin from data of other RA regions and divide it by 20. Using the average background values shown in figures 1a-d, new background values obtained for figures 2a-d are shown by dot-dash lines. This results in a dramatic increase in the statistical significance of the excess seen in phase region 0.6-0.8, for example, the excess in figure 2c is now 4.7σ. Also, now there seems to be some evidence for emission in the phase region 0.20-0.35 which is another region where excess has been observed in other experiments, both at TeV and PeV energies (Watson 1985). On the basis of present data alone it is difficult to make an accurate estimate of the fraction of flux that is pulsed with the 4.8 hour period, but a comparison of the excess seen in figures 1b and 1d with the excess seen in phase region 0.6-0.8 in figures 2b and 2d, suggests that about 50% of the time-averaged flux is emitted in this phase interval. Combining the probability of observing the excess seen in the phase plots ($<10^{-3}$) with the probability of observing the excess in the RA plots for various size groups, it is estimated that the probability that these various excesses are due to chance is only about 1 in 10^8.

The shower size thresholds of 5×10^4 and 5×10^5 correspond approximately to primary energy thresholds of 2.5×10^{14} and 2.5×10^{15} eV respectively, for the average zenith angle of observation of 33^o and Ooty altitude for photon-initiated showers. The collection area is 2.8×10^7 cm^2 for higher size showers and somewhat less for lower size showers due to some inefficiency of triggering at larger distances. The observation time for Cygnus X-3 during the period 179/1984-312/1986 was 9.4×10^6 s for Cygnus X-3 within 40^o of zenith. Using these numbers and the observed excess number of older ($s>1.4$) showers from the direction of Cygnus X-3 and taking into account the average angle of observation and triggering inefficiencies, the integral time averaged flux of gamma rays from Cygnus X-3 are obtained as

$F(E > 2.5\times10^{14}\ \mathrm{eV}) = (7.16\pm3.15)\times10^{-13}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, and

$F(E > 2.5\times10^{15}\ \mathrm{eV}) = (1.04\pm0.44)\times10^{-13}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$.

A comparison of flux values or upper limits given by different experiments (Protheroe 1987) is not very meaningful due to widely different values of angular resolution and effective aperture, leading to different signal to background ratios, particularly at PeV energies. A comparison is also difficult due to significant variation in the flux over periods of few months. Ooty observations, divided into 5 periods, each of approximately 6 months duration, show that the flux has varied by a factor of about 2 to 3 over this period. For example, the 3.8σ excess seen in figure 1d results from a combination of signals of 3.5,0.6,2.0,2.0, and 1.1σ over these 5 time periods. Though the signal is almost absent in the second period (345/1984-146/1985) in showers of size$>5\times10^5$, the situation is different for showers of lower primary energies. Analysis of these data for short term variability and possible bursts (Baltrusaitis et al 1987) is in progress.

As in the Kiel experiment, the signal due to Cygnus X-3 in our experiment also is most prominent among older showers. Does this suggest photons as the primaries of these showers? There is some controversy (Watson 1985, Protheroe 1987) about photon showers having flatter lateral distribution relative to proton showers of same shower size. Some calculations (e.g.

Hillas 1985, Fenyves 1985, Cheung and Mackeown 1987) have suggested that the expected age distributions for cosmic ray (proton) and photon initiated showers overlap considerably, thus eliminating age as a discriminating parameter. However, we would like to emphasize that none of these calculations reproduce the age distributions of normal showers observed experimentally. In fact, the expected average age for showers of size 10^5, according to these calculations, at mountain altitudes or sea level, is larger than 1.2, while the observed values is 1.0-1.1. This may be connected with large fluctuations in development of proton initiated showers coupled with the very steep primary energy spectrum for protons. Calculations by Cheung and Mackeown (1987) show that photon initiated showers have a narrower age distribution compared to showers initiated by protons, presumably due to the smaller value of radiation length (37 g cm^{-2}) in air compared to interaction length for protons or pions (80-120 g cm^{-2}); also they show a small but gradual shift, towards larger values of the average age, for deeper levels in atmosphere. For the average value of the zenith angle of 33^o for observations on Cygnus X-3 at Ooty, the effective atmospheric depth is 954 g cm^{-2} and the expected longitudinal age of showers of size 10^5 initiated by photons of energy $5x10^{14}$ eV from Cascade theory (Approximation B) is about 1.5. Thus our observation of a signal among older (age>1.4) showers from the direction of Cygnus X-3 can not rule out the possibility of these being due to gamma rays. The problem with the gamma ray hypothesis, however, is that the number of muons observed in the Kiel experiment in older showers from the direction of Cygnus X-3 was not significantly different compared to normal showers. Calculations (see, for example, Halzen et al 1986) show the number of muons in photon showers to be smaller, at least by a factor of 10, compared to proton showers. Another problem is that photons of PeV energy suffer severe attenuation through pair production interaction with the optical and infrared photons near the sources (Appa Rao 1984) and microwave photons in the intervening space (Cawley and Weekes 1984). Thus the precise nature of the radiation responsible for the signal seen at TeV and PeV energies remains a puzzle.

Various scenarios have been proposed for understanding the high energy emission from Cygnus X-3 and the shape of the observed light curve. Most of the models proposed (see Protheroe and Stanev 1987) assume the source to be a close binary involving a young neutron star/pulsar which is eclipsed periodically by a companion star. Particles accelerated in the vicinity of the neutron star are assumed to collide with the matter surrounding the companion and give rise to secondaries that under favourable viewing angles are seen by terrestrial detectors. Detailed information on the light curve for the source is very necessary for a good understanding of the emission region and the mechanism for particle acceleration near the source. However, many features of the observed light curve are still quite confusing and more observational data is needed, preferably through independent experiments with similar energy thresholds providing simultaneous data.

ACKNOWLEDGEMENTS

It is a pleasure to thank A.R. Apte, S.G. Bhargavi, C. Ravindran, T. Selvankumaran, and V. Uma for their scientific assistance in running the experiment and A. Pushpanathan and P. Sivaram for technical help.

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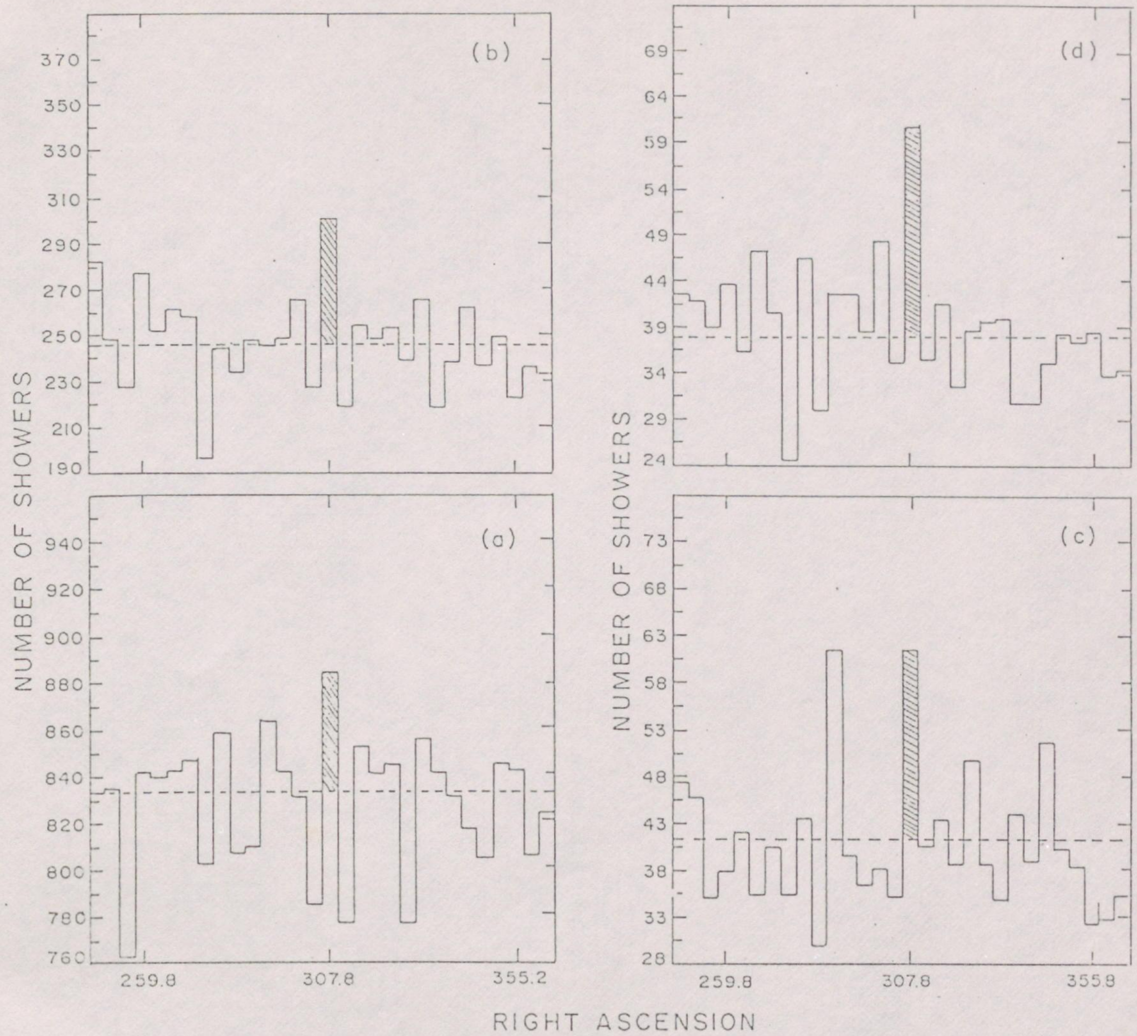

Figure 1 : Distribution of arrival direction in right ascension for showers having declinations, $38^{o}.9< \quad <42^{o}.9$: (a) shower size $N_e>5x10^4$, all ages ; (b) $N_e>5x10^4$, age>1.4 ; (c) $5x10^4<N_e<10^5$, age>1.4 ;(d) $N_e>5x10^5$, age>1.4 . Note that average values shown by dashed lines are based on all 90 RA bins while only 30 bins are plotted in figure

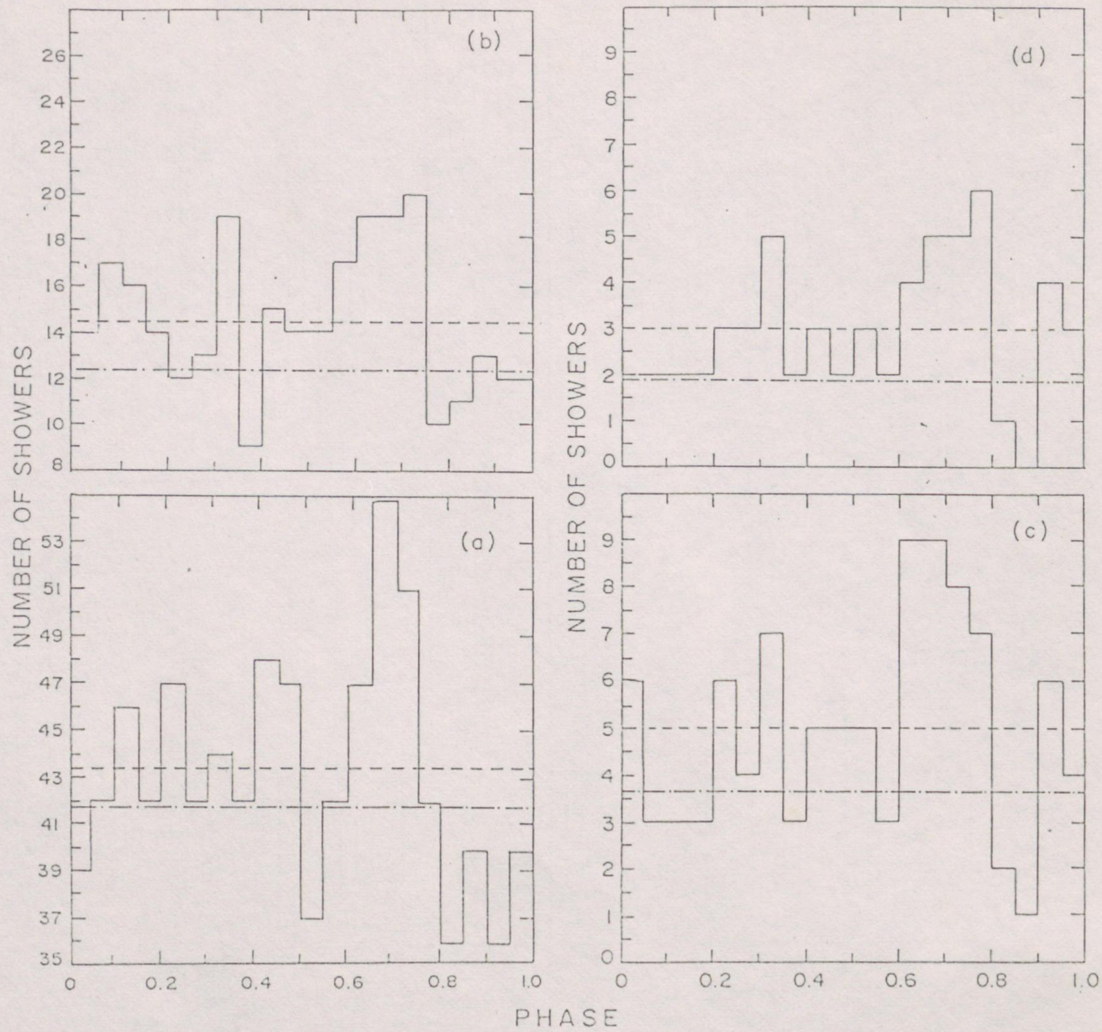

Figure 2 : Phase histograms for 4.8 hour periodicity for showers in the Cygnus X-3 bin:

(a) shower size $N_e > 5x10^4$, all ages ; (b) $N_e > 5x10^4$, age>1.4 ; (c) $N_e > 5x10^5$, all ages ; (d) $N_e > 5x10^5$, age>1.4. Dashed lines are averages based on the number of showers in the Cygnus X-3 bin and the dash-dot lines are based on the average number of showers in all RA bins with same declination

A LARGE VERY HIGH ENERGY GAMMA RAY BURST FROM HERCULES X-1

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ABSTRACT

We observed a large TeV gamma ray burst from Hercules X-1 in our Atmospheric Cerenkov array at Pachmarhi, India. The burst lasted from 2147 UT to 2201 UT on April 11, 1986. The number of gamma ray events during the burst amounted to ~ 54 % of the Cosmic Ray flux, resulting in a 42 σ effect. This is the largest TeV gamma ray signal seen from any source till now. The time averaged flux for the burst period is 1.8×10^{-8} photons cm^{-2} sec^{-1} above a threshold energy of 0.4 TeV, which results in a luminosity of 1.8×10^{37} ergs sec^{-1}. The burst took place at the end of the " High On " state in the 35 day cycle of the Her X-1 binary system indicating accretion disc as the possible production site.

Revised Version
Submitted to AP.J.
15/8/88

I. INTRODUCTION

Her X-1 was first discovered as a TeV gamma ray source by the Durham group (Dowthwaite et al. 1984). A 3-minute outburst was seen in April 1983 in which there was a 33 % excess in the rate. The events in the burst were found to be modulated at the 1.237 sec pulsar period , approximately coincidental with the X-ray period. Later there were several detections of pulsed emission from this source by the Whipple group between 1984 and 1986 (Lamb et al. 1988, Gorham et al. 1986a, Gorham et al. 1986b). The Haleakla group also observed an outburst in 1986 at a pulsation frequency similar to that of the Whipple group (Resvanis et al . 1988). Thus, three independent groups have detected pulsations at TeV energies from Her X-1. At PeV energies pulsed emission was seen in 1983 by the Fly's eye group (Baltrusaitis et al. 1985) and in 1986 by the Los Alamos group (Protheroe 1987). The Los Alamos group detected also a rate increase. In this paper, we report on the results of our 1986 observations at Pachmarhi during which a 14 minute burst from Her X-1 was detected. During the burst, there was an increase of ~ 50 % in the number of events.

II. OBSERVATIONS

The Atmospheric Cerenkov array, which was operated at Ootacamund till 1985 March, was shifted to Pachmarhi (longitude : $78^{\circ}.26$ E, latitude : $22^{\circ}.28$ N and altitude 1075 m above sea level) in March 1986. The array, also described elsewhere (Bhat et al. 1987, Gupta et al. 1985), consists of 10 small (diameter 0.9 m) and 8 large (diameter 1.5 m) parabolic mirrors. The mirrors were put close together and used in a compact rectangular array configuration with sides of 14.5 m x 7.2 m. Each mirror was mounted on independent drives capable of tracking the source. At the begining ofthe run, the mirrors were manually aligned to a bright star near the source and then electronically moved to the source. During the runs, the scalers counting the pulses fed to the motors assured the tracking electronics was functioning well. Further, the mirrors were often brought back to the guiding bright star at the end of the run to check for any tracking errors. By tracking a bright star over a period of 5-6 hours, the tracking accuracy was found to be within ± $0\overset{\circ}{.}25$.

A mask with the aperture corresponding to a cone of half angle 2° ,was placed at the focal plane of each mirror. A fast PMT (RCA 8575) was mounted behind the mask on each mirror. The pulses from the PMTs were linearly added with fan-in units to form 6 banks. Banks I, II, III and IV were formed from four sets of big mirrors, each set consisting of two mirrors. Banks V and VI had two sets of small mirrors, each set comprising five mirrors. Outputs from these banks were fed to a set of discriminators each of which generated a 20 nsecs logic pulse. The logic pulses from this set of discriminators were fed to another identical set of discriminators after being delayed by 0,30,60,90,120 and 150 nanosecs respectively . These discriminators also produced logic pulses of width 20 nsecs. The thresholds of both sets of discriminators were kept at 30 mV. While the inputs(amplitude = 800 mV) to the second set of discriminators got attenauated slightly becasue of the delay cables (the maximum attenuation was ~ 10 %), the low bias assured that all the pulses triggering the first set would trigger the second set also. The outputs of both the sets of discriminators were fed to two identical multiplicity logic units(Lecroy 380 A). It was required that there should be pulses from at least 4 discriminators for both the multiplicity logic units to generate an output. The first multiplicity logic unit generated the master trigger pulse, whereas the second unit generated the chance coincidence pulse. The choice of the delay lines ensured that the second multiplicity logic would not give any output for a ′ genuine ′ trigger. The high voltages on the PMTs were adjusted to give a bank rate of ~ 250 kHz, which resulted in chance rate amounting to 5-10 % of the trigger rate. The current from the PMTs had not been compensated for background light variations . Therefore, the atmospheric transparency would introduce some variation in the bank rates and thus in the trigger and chance rates. Both the trigger events and the chance events were counted on five digit scalers. The time of occurence of each event was derived from an accurate (± 30 μsecs with respect to UTC) clock. The OR output of the multiplicity logic, which provided a 50 mV output pulse for each input pulse, was discriminated and whenever all the 6 banks were triggered, a latch was derived. This signified the higher energy showers. The high voltage was kept constant throughout the run. Following information was recorded on tape for each event : (a) the time to an accuracy of ± 0.5 msec (b) the readings from the trigger counter and the chance counter and (c) the latch. The trigger and the chance event counters were also monitored every ten minutes and recorded in the run-log monitor. The average one minute rate for consecutive ten minute intervals was derived from these readings. The run-log monitor was used to keep a check on the progress of the experiment. It also provided an independent and quick look at the data. The average trigger rate was 800 min^{-1} , which translated to a threshold of 400 GeV for gamma ray primaries.

III. ANALYSIS

10 runs on Her X-1 were taken between 5th and 14th April, 1986. The run-log monitor was inspected for significant increases in trigger rate on 10 minute time-scales. Only run # 9, taken on April 11, 1986 showed a large increase. This had been noticed during the run itself. Fig. 1 shows the variation of trigger rate(min^{-1}) and the chance rate from the beginning to the end of the run. The gradual increase in rate as the hour-angle (hence zenith angle) of the source decreased is compatible with the expected lowering of the threshold energy. However,the trigger rate shot up after 2140 UT and stayed high for 30 minutes. During the period 2120 UT to 2220 UT, the mean trigger rates (min^{-1}) in the successive 10 minute intervals are : 872, 880, 1107, 1332, 1150 and 995. The corresponding chance coincidence rates are : 60,60, 58, 64, 46 and 84. The tape had to be changed at 2224 UT and there was no further data taking for the next 8 minutes (2224 - 2232 UT). The trigger rate for the next ten minute interval (2232 - 2242 UT) was 1125 with a chance rate of 68. We terminated the run at 2300 UT due to the onset of dawn. Thus the average observed rate for the burst period was 1187 min^{-1} as against an expected rate (by interpolation) of 926 min^{-1} . Only three other runs had rates of 700 ± 50 at the beginning of the run (at ~ 30^{o} E) indicating sky

conditions similar to that on April 11th. All these runs showed rates of 850 ± 50 at ~ 15^{o} E and 1000 ± 50 around transit. Thus, the events on the night of the burst had the same zenith angle dependence as on other nights. Indeed, the zenith angle dependence of trigger rate during all the four runs were identical within statistics.

More detailed information on the burst time and event rates were obtained from the tape data. The increase in the rate was found to be essentially between 2147 UT and 2201 UT. Fig. 2 shows the number of trigger and chance coincidence events in two minute time bins. The increase is for 14 minutes, with the largest rate being seen in the last four minutes of the increase. If we characterize the three time regions - 2133 to 2147 UT, 2147 to 2201 UT, and 2201 to 2215 UT - as A,B and C respectively, the number of events from the tape in these three intervals were 13254, 20367 and 13826 respectively. The number of chance events were 905, 873 and 790 respectively. The actual number of atmospheric Cerenkov events is obtained by subtracting the chance events from the total number of events. The fractional increase in the actual event rate during the burst period is 53.6 %. The expected number of events in interval B from a mean of those in intervals A and C is 12692 ± 89 while 19494 were seen. This results in a 42 σ effect. We note that this is the largest effect seen so far in Very High Energy Gamma Ray Astronomy. Fig. 2 also shows the rate of excess events (as a percentage of the background rate) as a function of time.

It is important to note that the chance coincidence rate , as shown in fig 2, did not increase during the burst when the total trigger rate went up. The chance rate showed a variation between 5-8 % before the burst, 3-8 % during the burst and 2-8 % after the burst. The fraction of chance events during the burst was 4.3 % , whereas outside the burst it was 6.2 % . It is clear , then, that the excess trigger rate during the burst cannot be ascribed to any extraneous light source or electrical noise. We attribute the excess events during the period 2147 to 2201 UT to gamma rays from Her X-1 system.

The time averaged flux for the entire burst period is estimated to be $1.80 \pm 0.04 \times 10^{-8}$ photons $cm^{-2}sec^{-1}$. This gives a luminosity of $1.80 \pm 0.04 \times 10^{37}$ ergs sec^{-1}, assuming a gamma ray threshold energy of 400 GeV and a differential spectrum with an exponent of -3. The errors given here are statistical only. In addition, there can be systematic errors of a factor of 2, arising from uncertainties in the collection area and threshold energy. The burst-average flux seen here is a factor of 100 higher than the burst-average flux seen in earlier observations.

For a study of time structure of the events, millisecond accuracy is needed for the event arrival time. At this stage, it may be mentioned that because of recording problems, a stretch of 14 out of 41 events was lost in each data record. Missing bit problems resulted in further loss of events. Finally, 57% and 55% of the events could be recovered for the quiescent and active periods respectively. The number of recovered events in the three time intervals A,B and C were 7398, 11119 and 7963 respectively. Thus, the recovered events show only a 28 σ effect. As mentioned earlier, an approximate idea of the energy of each shower was obtained from the number of banks making up the trigger. The number of lower energy (only 4 or 5 banks present) events in the three time intervals A, B and C were 4137, 7885 and 5595 respectively. Thus, the excess of lower energy events(3019) is ~ 88 % of the observed excess of all events (3439). This, then, indicates that the gamma rays during the burst have a steep energy spectrum.

Fig. 3 shows the distribution of time separation between consecutive events for the burst period(the solid histogram) and the quiet period (the dotted histogram). From the observed number of events before the recovery, the average time interval between events is expected to be 41 msecs and 62 msecs during the burst and the quiet periods respectively. The solid line in Fig.3 is the expected time separation distribution obtained from the observed distribution of events during the burst(Fig 2). The dotted line shows the expected fit for the quiet period. The agreement between the observed and the expected distributions is quite good. The increase in the frequency of closely spaced events during the burst duration as compared to the quiet period is clearly seen in the figure.

A search for periodic emission during the burst was carried out around 0.8079 Hz, the known X-ray pulsation frequency (Ogelman et al.

1985 and Lamb et al. 1988). 39 steps on either side of the X-ray period (step size = 0.000595 seconds) were used resulting in a search range from 0.8233 Hz to 0.7931 Hz for the frequency. For all test periods, an appropriate Doppler correction was applied on the basis of the binary elements given by Ogelman et al. The data showed peaks with Rayleigh Power > 10 at three frequencies corresponding to 0.8010 Hz, 0.8071 Hz and 0.8197 Hz. To assess the probability of seeing such high values of Rayleigh Power, a Monte Carlo simulation was done with the observed event seperations (as in Fig. 3) as input. Further, the loss of events as in the recovery of data was also simulated. The Rayleigh Power analysis was done using the same range of periods as for the data. The probability of any one period showing Rayleigh Power > 10 in the Monte Carlo simulations was found to be as high as ~ 5 % .Therefore, the peaks in the Rayleigh power analysis of data could not be ruled out confidently as not due to the artefacts of the data . Thus, because of the loss of events, it is not possible to opine definitively on the nature of the periodic emission. We would like to emphasize however that this does not in any way affect our observation of the rate increase itself.

IV. DISCUSSION

At first, we discuss whether this observation could be due to a freak optical phenomenon. The response of our telescope to optical phenomena was tested out with stars of different magnitude. A drift scan with a bright star (α Andromeda, $m_v = 2.3$) showed that the normal trigger rate of 600 min^{-1} doubled with the star at the centre of the telescopes, while the chance rate of 80 min^{-1} increased by a factor of eight in the same time period. The variation in the optical light output from HZ-Her the companion star, is known to be not large : during the entire orbital cycle, the visual magnitude changes from 13 to 11 (Middleditch and Nelson, 1976). We have observed many times over last 8 years that lightning increases both the trigger rate and the chance rate in the system by 100 - 200 counts per minute. However, the difference between the trigger and chance coincidence rates was barely noticeable. For lightning or optical flashes from the source to mimic the phenomenon seen here, it has to have temporal characteristics similar to the atmospheric Cerenkov pulses (or it should last for less than 90 nanoseconds for the chance coincidence unit not to generate any output) and has to be sustained for 14 minutes. We also note that during the episode it was visually verified that there was no obvious indication of any extraneous source of light. We also consider here whether the increase seen here could be due to electronics problems. We first note that all the discriminators feeding the multiplicity logic units had the same width of 20 nanoseconds. Further, all pulses which trigger the first set of discriminators trigger the second set also. The two multiplicity logic units are identical for all purposes. The performance of these two units and the whole electronics was routinely tested by giving pulse generator pulses to the fan-in units. In this context, one should also state that a very similar system was operated at Ootacamund for at least six years and at Pachmarhi for over 2 years; and no phenomenon similar to this burst was ever seen either before or after the occurence of the burst reported here. Thus, the conclusion is that the increase seen in this observation is genuinely due to gamma rays from Her X-1.

The burst occured at an orbital phase ($\phi_{1.7\ d}$) of 0.19 and the 35 day phase (ϕ_{35d}) was 0.31. Among the detections from other groups, several detections are at the orbital phase of either 0.2 or 0.7. The Durham detection, as well as the 1986 Whipple detection(Lamb et al) showing the largest pulsed effect so far , are at the 35 day phase of ~ 0.0 . The burst detected by us and the Whipple detection are separated by ~ 1.74 cycles of the 35 day period. It is significant that Eichler and Vestrand (Eichler and Vestrand, 1984) predict very high energy gamma ray emission at either the onset or the decline of the" High On" state in the 35 day period. According to them, the accretion disk presents the right amount of target thickness at these phases for the high energy protons emitted from the neutron star. The burst seen by us coincides with the decline of the 35 day " High On " state. It is possible that while the source has been detected at other phases, the onset and the decline of the "High On " state provide the right amount of target material for copious production of gamma rays. We should however note that the 35 day period has not been completely understood. There are recent indications that the conventional understanding of this periodicity as due to the obscuration by the disc may not be correct (Trumper, 1986).

In conclusion, we have observed a very large increase in the number of events from the direction of Her X-1 over a 14 minute interval (2147 UT to 2201 UT) on April 11,1986. Barring unknown scenarioes, this increase can only be due to TeV gamma rays from Her X-1. We note that this is the largest signal seen till now at these energies. Because of the gaps in our data we cannot opine on the pulsed nature of the emission.

We wish to thank Dr. K.Sivaprasad for fruitful discussions, Mr. A.R.Apte for setting up the array , and Messers. G.P.Satyanarayana and A.I. D'Souza for help with the observations. The help given by Prof. T.S.Murthy of the Madhya Pradesh Council of Science and Technology and Messers. N.R.Krishnan, Vinay Shankar and Samar Singh of the Madhya Pradesh Government for setting up the observatory at Pachmarhi is gratefully acknowledged.

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FIGURE CAPTIONS

1. The increase in trigger rate with time on April 11, 1986. The rates were derived from the 10 minute on-line readings of the event counters. The dashed line is an eye fit to the gradual increase in rate which is compatible with the expected lowering of threshold energy with the decrease of the hour angle of the source. The source medridian transit is around 2230.
2. The trigger rate and the chance coincidence rate per two minutes from the data tape. The right hand side shows the excess over the Cosmic ray background rate as a %age of the background rate.
3. The frequency of time separation of events in the burst period (the solid histogram) and the quiet period (the dashed histogram). The two lines are the expectations from the observed rates.

FIG. 1

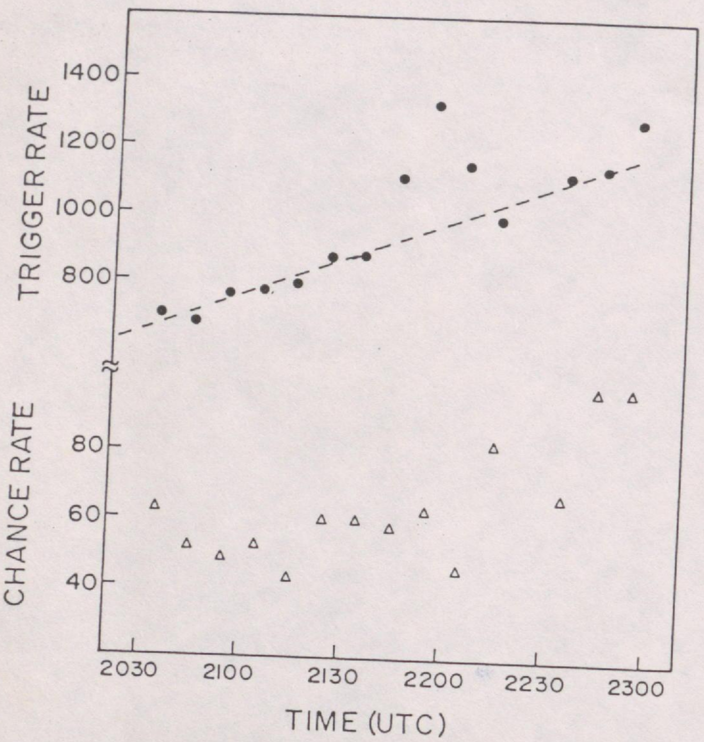


FIG. 3

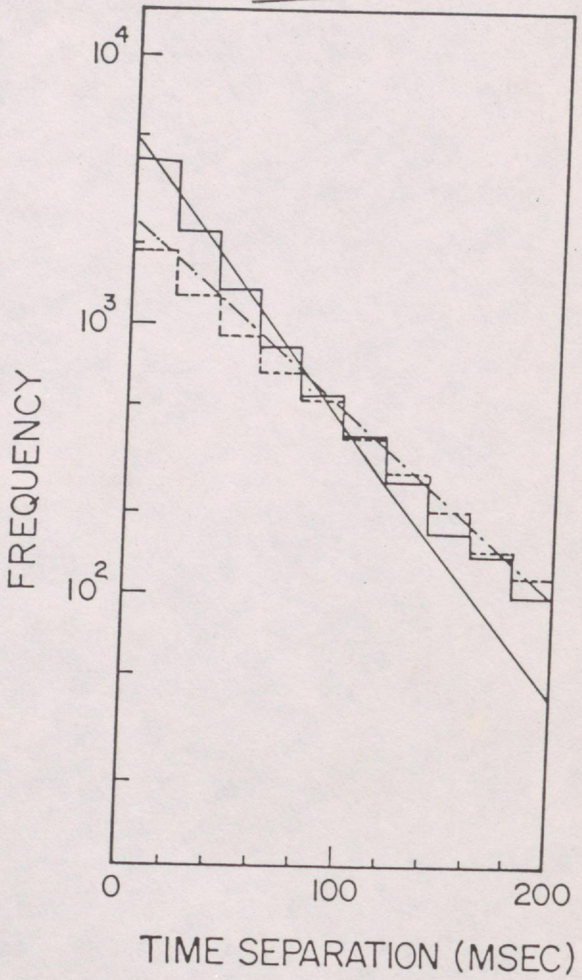
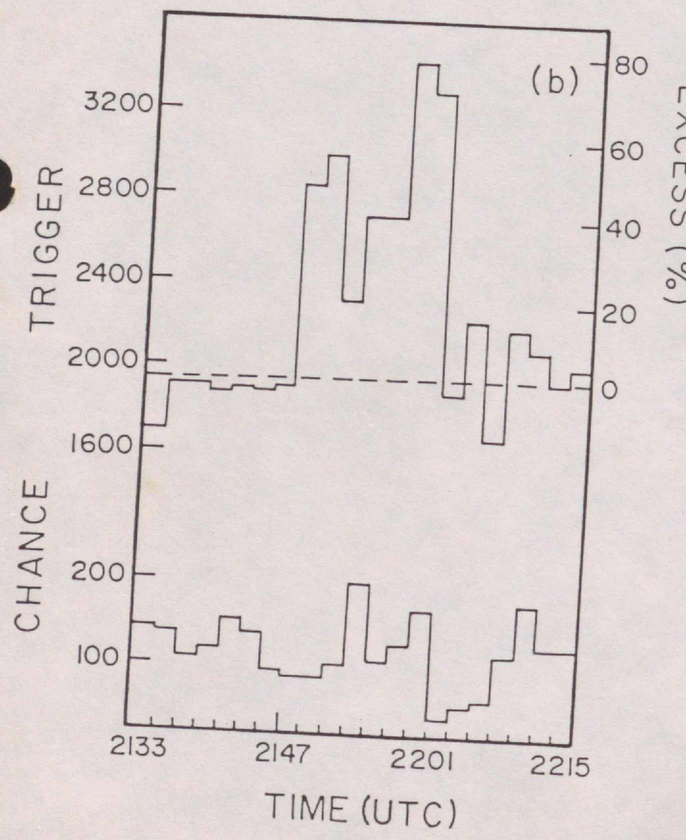


FIG 2



THE ASTROPHYSICAL JOURNAL, 330:L107–L111, 1988 July 15

OBSERVATIONS OF STEADY FLUX OF PeV–ENERGY EXTENSIVE AIR SHOWERS FROM CYGNUS X-3 DURING 1984–1986

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Received 1988 March 14; accepted 1988 April 13

ABSTRACT

Data taken with a 24 detector extensive air shower array, operating at Ooty since 1984 June, have been used to search for excess of extensive air showers of energy $>2.5 \times 10^{14}$ eV from the direction of binary X-ray source Cygnus X-3. The data show a time-averaged excess in the number of showers from this direction, over the background determined from other regions of the sky having the same declination. The excess is most prominent among older showers having a flatter lateral distribution. A part of this excess shows up significantly in the phase region, 0.6–0.8, in the 4.8 hr periodicity analysis. These observations correspond to an integral flux of $(7.16 \pm 3.15) \times 10^{-13}$ cm^{-2} s^{-1} at energies $>2.5 \times 10^{14}$ eV and of $(1.04 \pm 0.44) \times 10^{-13}$ cm^{-2} s^{-1} at energies $>2.5 \times 10^{15}$ eV. The observations confirm, for the first time, results reported by the Kiel group in 1983 of a directional excess from the direction of Cygnus X-3, without requiring the 4.8 hr periodicity analysis as was necessary in many of the other experiments reporting positive signals. This emphasizes the advantage of good angular resolution for such studies.

Subject headings: gamma rays: general — X-rays: sources

The binary X-ray source Cygnus X-3 has been studied extensively in the gamma-ray energy range, few MeV to tens of PeV, using different techniques, after the exciting observations of an excess flux at energies $>10^{12}$ eV from the direction of Cygnus X-3 by the Crimean group (Vladimirsky and Stepanian 1973). Many groups (see Turver 1985; Watson 1985) later reported observing signals from Cygnus X-3 at TeV energies, but these claims are mostly based on observations of a 4.8 hr periodicity as seen in the X-ray flux. In 1983 the Kiel group (Samorski and Stamm 1983) reported observations of a directional excess of 16.6 showers (4.4 σ) above the average off-source background of (14.4 ± 0.4) showers per bin (4° in right ascension and 3° in declination) for older showers (age >1.1) at energies above 10^{15} eV. These showers also showed strong correlation in the 4.8 hr periodicity. Surprisingly, these observations showed that the showers from the direction of Cygnus X-3 contained almost as many muons as normal showers, contrary to expectations for photon-initiated showers. Several groups (see Watson 1985; Protheroe 1987) have since claimed detection of PeV energy gamma rays from Cygnus X-3, based on the 4.8 hr periodicity analysis. These observations, however, do not agree with each other completely in the phase of emission, thus creating some doubts about the advantage of phase analysis for the purpose of establishing Cygnus X-3 as a gamma-ray source at TeV and PeV energies. Of course, the absence of observations of a steady flux from Cygnus X-3 and the reliance on phase analysis for detection of a positive signal were essentially due to the poor angular resolution of almost all the air shower arrays operating prior to 1984, except for the Kiel array.

We report here observations carried out with a 24 scintillation detector array at Udhagamandalam (Ooty, for short) in southern India at an altitude of 2200 m (800 g cm^{-2}), and latitude 11°.4 N. Various tests carried out with this array showed (Apte *et al.* 1985; Tonwar 1985) that for showers of size $>5 \times 10^4$ particles incident over the central part of the array, the angular resolution of the array is about 1°.0–1°.5, depending on shower size. Regular datataking was started in 1984 June with a loose trigger, called NEWS, requiring a single particle in each of the four detectors, N, E, W, and S, placed at the corners of an approximate square of side 10 m near the center of the array; a further requirement was of at least three particles in any one of these four detectors (Tonwar, Gopalakrishnan, and Sreekantan 1985). The shower rate was about 0.13 s^{-1}. During the period 1984 June 27 (day 179 of the year) to 1986 November 12 (day 316), a total of 7.6×10^6 showers were recorded.

Data analysis of these showers involved two steps:

1. The first step was computation of the arrival direction cosines for all showers, using the relative arrival time information from all detectors which had a signal larger than about 0.3 of the signal expected from a through-going relativistic muon. Only showers with a signal >5 particles in at least one of the 4 triggering detectors (N, E, W, and S) were used in the analysis (Apte *et al.* 1988).

2. The second step was computation of the core position, shower size, and the lateral distribution parameter s (shower age) for each shower using the χ^2-minimization method (Sreekantan, Tonwar, and Viswanath 1983).

Since the determination of direction in individual showers suffers from unpredictable systematic effects in showers whose cores lie on the periphery of the array due to fluctuations in development, some minimum cuts were imposed on the data, to ensure accuracy in angle, shower size, and age determination. These cuts are as follows:

$$\text{shower size } N_e > 5 \times 10^4; \quad R_{\text{core}} < 30 \text{ m};$$
$$\text{zenith angle} < 40° .$$

The array has poor detection efficiency for showers of size less than 5×10^4 for core distances larger than 10 m with the hardware and software cuts discussed above. A zenith angle cut of 40° has been imposed to restrict atmospheric depth to less than about 1040 g cm^{-2}. The meridian zenith angle of Cygnus X-3 at Ooty is 29°.4, corresponding to an atmospheric depth of 920 g cm^{-2}. This range of 120 g cm^{-2} gives a variation of primary energy by a factor of about 2 for a recorded shower size since the attenuation length of showers of size 10^5 at Ooty altitude is about 150 g cm^{-2}.

With these selection criteria, 5.5×10^6 showers were available for search of discrete sources of energy $>10^{14}$ eV. For examining the Cygnus X-3 region, all showers with declination $\delta = 38°.9–42°.9$, were selected and grouped into 90 bins in right ascension (R.A.), each 4° wide, with the center of the 46th bin at R.A. of 307°.8. Thus all showers with R.A. and declination within $\pm 2°$ of Cygnus X-3 were binned into the 46th bin (Cygnus X-3 bin). Since data were taken on an almost continuous basis for nearly 2.5 years, the exposure was nearly equal for all the 90 R.A. bins. However, a low-level normalization for equal exposure was done using the total number of showers in different R.A. bins for all values of declination, as the index of exposure. The R.A. plot for bins 31–60 is shown in Figure 1*a* which shows an excess (1.8 σ) in the Cygnus X-3 bin. There are 884 events in this bin compared to the 90 bin average of (833 $\pm$ 3.0). This excess, while interesting, is not statistically significant by itself.

Showers with $N_e > 5 \times 10^4$ at Ooty have a broad age distribution (Apte *et al.* 1988) with a median value of 1.09. For reasons discussed later we put an age cut of 1.4 to enrich the data with old showers (Samorski and Stamm 1983), and Figure 1*b* shows the R.A. plot for these showers. Nearly one-third of the showers satisfy this condition. The statistical significance of the excess in the Cygnus X-3 bin increases to nearly 3.4 σ, with 300 events in this bin compared to the 90 bin average of (247 $\pm$ 1.6). Showers in Figure 1*b* were further subdivided into four differential shower size bins: $5 \times 10^4 < N_e < 10^5$ (A), $10^5 < N_e < 2 \times 10^5$ (B), $2 \times 10^5 < N_e < 5 \times 10^5$ (C), and $N_e > 5 \times 10^5$ (D). It is significant that Cygnus X-3 bins in these four independent data samples show excesses of 3.1, 0.8, 0.2, and 3.8 σ, respectively, relative to the background in each group. The R.A. distributions for subgroups A and D are

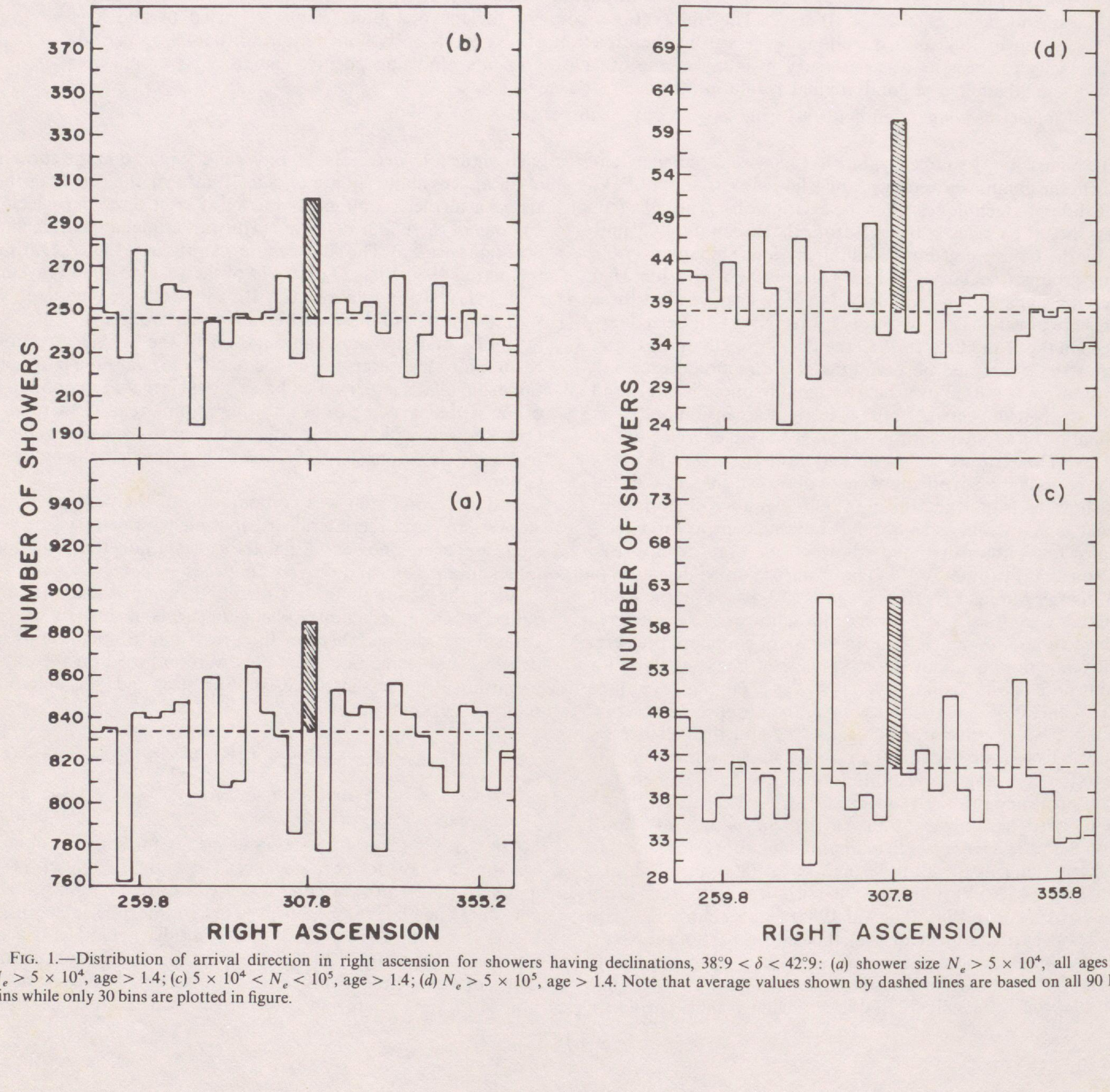

FIG. 1.—Distribution of arrival direction in right ascension for showers having declinations, $38°.9 < \delta < 42°.9$: (*a*) shower size $N_e > 5 \times 10^4$, all ages; (*b*) $N_e > 5 \times 10^4$, age > 1.4; (*c*) $5 \times 10^4 < N_e < 10^5$, age > 1.4; (*d*) $N_e > 5 \times 10^5$, age > 1.4. Note that average values shown by dashed lines are based on all 90 R.A. bins while only 30 bins are plotted in figure.

shown in Figures 1*c* and 1*d*, respectively. The probability that these excesses in the Cygnus X-3 bin could arise due to random fluctuations is less than 10^{-5}, when we took into account the four size groups and two age groupings (all ages and age >1.4) considered.

The occurrence time (UT) for each shower was known with an accuracy of 1 ms. For phase analysis, the observed times of showers in the Cygnus X-3 bin were converted to arrival times at the solar system barycenter. The phase histogram for showers in the Cygnus X-3 bin and size $>5 \times 10^4$, computed using the Cygnus X-3 ephemeris (van der Klis and Bonnet-Bidaud 1981 and van der Klis 1984; $P = 0^d.199968338$, $\dot{P} = 1.02 \times 10^{-9}$ days day^{-1}, and $T_0 = 2{,}440{,}949.8965$ JD), is shown in Figure 2*a*. Interestingly, the phase interval, 0.60–0.75, shows a somewhat significant excess (about 2 σ), compared to the expected background which is calculated by dividing the total number of showers by 20. The numbers actually plotted in the figure are normalized for exposure which was almost uniform for all 20 bins to within a few percent due to the rather long and almost continuous run of 868 days (179/1984–316/1986). It is to be noted that the phase region, 0.6–0.8, is a preferred region for emission, both at the TeV and PeV energies (Watson 1985; Protheroe 1987). The phase distribution for older (age >1.4) showers, shown in Figure 2*b*, shows similar features. Since the time-averaged signal seems to be strongest among larger size showers (Fig. 1*d*), it is of interest to see the phase plots for showers with size $>5 \times 10^5$, without and with age selection. These plots are shown in Figures 2*c* and 2*d*, respectively. The phase region, 0.6–0.8, shows an excess of nearly 3 σ in Figure 2*c*, while the excess is only about 2 σ in Figure 2*d*.

The background values shown in Figures 2*a*–2*d* by dashed lines are conservative estimates since these include contribution due to the source. There are two other ways of estimating background for these plots. One way is to subtract possible source contribution (for example, events in the phase region

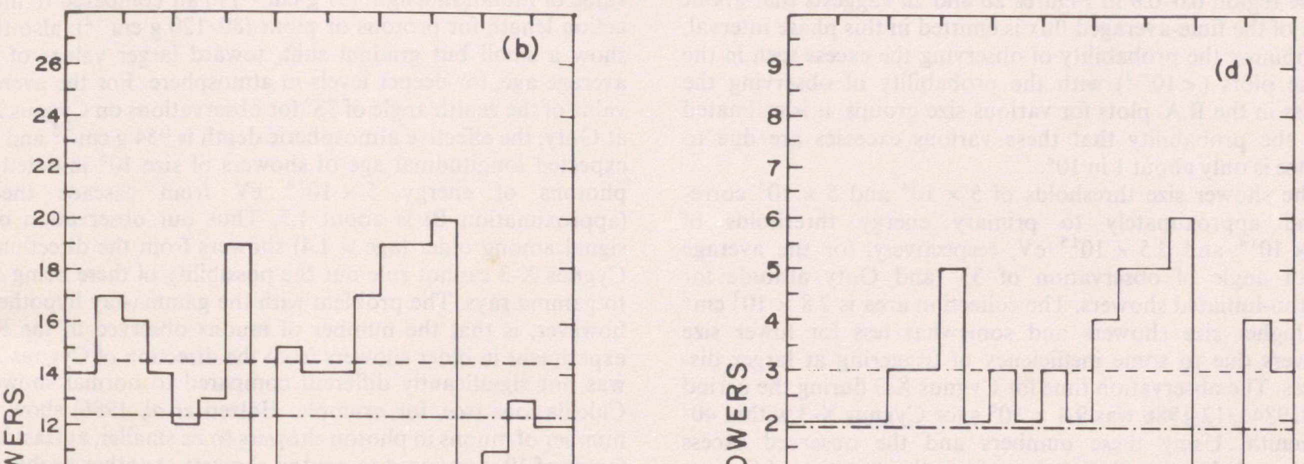

FIG. 2.—Phase histograms for 4.8 hr periodicity for showers in the Cygnus X-3 bin: (*a*) shower size $N_e > 5 \times 10^4$, all ages; (*b*) $N_e > 5 \times 10^4$, age > 1.4; (*c*) $N_e > 5 \times 10^5$, all ages; (*d*) $N_e > 5 \times 10^5$, age > 1.4. Dashed lines are averages based on the number of showers in the Cygnus X-3 bin, and the dash-dot lines are based on the average number of showers in all R.A. bins with same declination.

0.6–0.8) from the total number and then divide the remaining events by 16. This would increase the statistical significance of the excess seen in phase region 0.6–0.8 in plots 2*a*–2*d*, for example, the excess seen in Figure 2*c* increases from 3 σ to 4 σ above the background. A more realistic way of estimating background is to use the average number of showers expected in the Cygnus X-3 bin from data of other R.A. regions and divide it by 20. Using the average background values shown in Figures 1*a*–1*d*, new background values obtained for Figures 2*a*–2*d* are shown by dot-dash lines. This results in a dramatic increase in the statistical significance of the excess seen in phase region 0.6–0.8, for example, the excess in Figure 2*c* is now 4.7 σ. Also, now there seems to be some evidence for emission in the phase region 0.20–0.35 which is another region where excess has been observed in other experiments, both at TeV and PeV energies (Watson 1985). On the basis of present data alone it is difficult to make an accurate estimate of the fraction of flux that is pulsed with the 4.8 hr period, but a comparison of the excess seen in Figures 1*b* and 1*d* with the excess seen in phase region 0.6–0.8 in Figures 2*b* and 2*d* suggests that about 50% of the time-averaged flux is emitted in this phase interval. Combining the probability of observing the excess seen in the phase plots ($<10^{-3}$) with the probability of observing the excess in the R.A. plots for various size groups, it is estimated that the probability that these various excesses are due to chance is only about 1 in 10^8.

The shower size thresholds of 5×10^4 and 5×10^5 correspond approximately to primary energy thresholds of 2.5×10^{14} and 2.5×10^{15} eV, respectively, for the average zenith angle of observation of 33° and Ooty altitude for photon-initiated showers. The collection area is 2.8×10^7 cm^2 for higher size showers and somewhat less for lower size showers due to some inefficiency of triggering at larger distances. The observation time for Cygnus X-3 during the period 179/1984–312/1986 was 9.4×10^6 s for Cygnus X-3 within 40° of zenith. Using these numbers and the observed excess number of older ($s > 1.4$) showers from the direction of Cygnus X-3 and taking into account the average angle of observation and triggering inefficiencies, the integral time averaged flux of gamma rays from Cygnus X-3 are obtained as

$$F(E > 2.5 \times 10^{14}\ \mathrm{eV}) = (7.16 \pm 3.15) \times 10^{-13}\ \mathrm{cm^{-2}\ s^{-1}}\ ,$$

and

$$F(E > 2.5 \times 10^{15}\ \mathrm{eV}) = (1.04 \pm 0.44) \times 10^{-13}\ \mathrm{cm^{-2}\ s^{-1}}\ .$$

A comparison of flux values or upper limits given by different experiments (Protheroe 1987) is not very meaningful due to widely different values of angular resolution and effective aperture, leading to different signal to background ratios, particularly at PeV energies. A comparison is also difficult due to significant variation in the flux over periods of few months. Ooty observations, divided into five periods, each of approximately 6 months duration, show that the flux has varied by a factor of about 2–3 over this period. For example, the 3.8 σ excess seen in Figure 1*d* results from a combination of signals of 3.5, 0.6, 2.0, 2.0, and 1.1 σ over these five time periods. Though the signal is almost absent in the second period (345/1984–146/1985) in showers of size $> 5 \times 10^5$, the situation is different for showers of lower primary energies. Analysis of these data for short term variability and possible bursts (Baltrusaites *et al.* 1988) is in progress.

As in the Kiel experiment, the signal due to Cygnus X-3 in our experiment also is most prominent among older showers. Does this suggest photons as the primaries of these showers? There is some controversy (Watson 1985; Protheroe 1987) about photon showers having flatter lateral distribution relative to proton showers of same shower size. Some calculations (e.g., Hillas 1985; Fenyves 1985; Cheung and Mackeown 1987) have suggested that the expected age distributions for cosmic-ray (proton) and photon-initiated showers overlap considerably, thus eliminating age as a discriminating parameter. However, we would like to emphasize that none of these calculations reproduce the age distributions of normal showers observed experimentally. In fact, the expected average age for showers of size 10^5, according to these calculations, at mountain altitudes or sea level, is larger than 1.2, while the observed value is 1.0–1.1. This may be connected with large fluctuations in development of proton initiated showers coupled with the very steep primary energy spectrum for protons. Calculations by Cheung and Mackeown (1987) show that photon initiated showers have a narrower age distribution compared to showers initiated by protons, presumably due to the smaller value of radiation length (37 g cm^{-2}) in air compared to interaction length for protons or pions (80–120 g cm^{-2}); also they show a small but gradual shift, toward larger values of the average age, for deeper levels in atmosphere. For the average value of the zenith angle of 33° for observations on Cygnus X-3 at Ooty, the effective atmospheric depth is 954 g cm^{-2} and the expected longitudinal age of showers of size 10^5 initiated by photons of energy 5×10^{14} eV from cascade theory (approximation B) is about 1.5. Thus our observation of a signal among older (age > 1.4) showers from the direction of Cygnus X-3 cannot rule out the possibility of these being due to gamma rays. The problem with the gamma-ray hypothesis, however, is that the number of muons observed in the Kiel experiment in older showers from the direction of Cygnus X-3 was not significantly different compared to normal showers. Calculations (see, for example, Halzen *et al.* 1986) show the number of muons in photon showers to be smaller, at least by a factor of 10, compared to proton showers. Another problem is that photons of PeV energy suffer severe attenuation through pair production interaction with the optical and infrared photons near the sources (Appa Rao 1984) and microwave photons in the intervening space (Cawley and Weekes 1984). Thus the precise nature of the radiation responsible for the signal seen at TeV and PeV energies remains a puzzle.

Various scenarios have been proposed for understanding the high-energy emission from Cygnus X-3 and the shape of the observed light curve. Most of the models proposed (see Protheroe and Stanev 1987) assume the source to be a close binary involving a young neutron star/pulsar which is eclipsed periodically by a companion star. Particles accelerated in the vicinity of the neutron star are assumed to collide with the matter surrounding the companion and give rise to secondaries that under favorable viewing angles are seen by terrestrial detectors. Detailed information on the light curve for the source is very necessary for a good understanding of the emission region and the mechanism for particle acceleration near the source. However, many features of the observed light curve are still quite confusing and more observational data is needed, preferably through independent experiments with similar energy thresholds providing simultaneous data.

It is a pleasure to thank A. R. Apte, S. G. Bhargavi, C. Ravindran, T. Selvankumaran, and V. Uma for their scientific assistance in running the experiment and A. Pushpanathan and P. Sivaram for technical help.

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THE ASTROPHYSICAL JOURNAL, 342:489–492, 1989 July 1

A POSSIBLE VERY HIGH ENERGY GAMMA-RAY BURST FROM HERCULES X-1

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Received 1988 June 16; accepted 1988 November 11

ABSTRACT

We observed a large increase in the trigger rate in the direction of Hercules X-1 in our Atmospheric Cerenkov array at Pachmarhi, India. The burst lasted from 2147 UT to 2201 UT on 1986 April 11. The accidental coincidence rate did not show any increase during the burst. Barring any electronic noise or celestial or terrestrial optical phenomenon with time structure similar to that of atmospheric Cerenkov phenomenon, we ascribe the increase to TeV gamma rays from Her X-1. The number of gamma-ray events during the burst amounted to ~54% of the cosmic-ray flux, resulting in a 42 σ effect. This is the largest TeV gamma-ray signal seen from any source till now. The time-averaged flux for the burst period is 1.8×10^{-8} photons cm^{-2} s^{-1} above a threshold energy of 0.4 TeV, which results in a luminosity of 1.8×10^{37} ergs s^{-1}. The burst took place at the end of the "high on" state in the 35 day cycle of the Her X-1 binary system indicating accretion disk as the possible production site.

Subject headings: gamma rays: bursts — stars: individual (Her X-1) — X-rays: binaries

I. INTRODUCTION

Her X-1 was first discovered as a TeV gamma-ray source by the Durham group (Dowthwaite *et al.* 1984). A 3 minute outburst was seen in 1983 April in which there was a 33% excess in the rate. The events in the burst were found to be modulated at the 1.237 s pulsar period, approximately coincidental with the X-ray period. Later there were several detections of pulsed emission from this source by the Whipple group between 1984 and 1986 (Lamb *et al.* 1988; Gorham *et al.* 1986*a*; Gorham *et al.* 1986*b*). The Haleakla group also observed an outburst in 1986 at a pulsation frequency similar to that of the Whipple group (Resvanis *et al.* 1988). Thus, three independent groups have detected pulsations at TeV energies from Her X-1. At PeV energies, pulsed emission was seen in 1983 by the Fly's Eye group (Baltrusaitis *et al.* 1985) and in 1986 by the Los Alamos group (Protheroe 1987). The Los Alamos group detected also a rate increase. In this paper, we report on the results of our 1986 observations at Pachmarhi during which a 14 minute burst from Her X-1 was detected. During the burst, there was an increase of ~50% in the number of events.

II. OBSERVATIONS

The Atmospheric Cerenkov array, which was operated at Ootacamund until 1985 March, was shifted to Pachmarhi (longitude: 78°26′ E, latitude: 22°28′ N and altitude 1075 m above sea level) in 1986 March. The array, also described elsewhere (Bhat *et al.* 1987; Gupta *et al.* 1985), consists of 10 small (diameter 0.9 m) and eight large (diameter 1.5 m) parabolic mirrors. The mirrors were put close together and used in a compact rectangular array configuration with sides of 14.5 m × 7.2 m. Each mirror was mounted on independent drives capable of tracking the source. At the beginning of the run, the mirrors were manually aligned to a bright star near the source and then electronically moved to the source. During the runs, the scalers counting the pulses fed to the motors assured the tracking electronics was functioning well. Further, the mirrors were often brought back to the guiding bright star at the end of the run to check for any tracking errors. By tracking a bright star over a period of 5–6 hr, the tracking accuracy was found to be within ±0°.25.

A mask with an aperture corresponding to a cone of half-angle 2° was placed at the focal plane of each mirror. A fast PMT (RCA 8575) was mounted behind the mask on each mirror. The pulses from the PMTs were linearly added with fan-in units to form six banks. Banks I, II, III, and IV were formed from four sets of big mirrors, each set consisting of two mirrors. Banks V and VI had two sets of small mirrors, each set comprising five mirrors. Outputs from these banks were fed to a set of discriminators each of which generated a 20 ns logic pulse. The logic pulses from this set of discriminators were fed to another identical set of discriminators after being delayed by 0, 30, 60, 90, 120, and 150 ns, respectively. These discriminators also produced logic pulses of width 20 ns. The thresholds of both sets of discriminators were kept at 30 mV. While the inputs (amplitude = 800 mV) to the second set of discriminators got attenuated slightly because of the delay cables (the maximum attenuation was ~10%), the low bias assured that all the pulses triggering the first set would trigger the second set also. The outputs of both the sets of discriminators were fed to two identical multiplicity logic units (Lecroy 380 A). It was required that there should be pulses from at least four discriminators for both the multiplicity logic units to generate an output. The first multiplicity logic unit generated the master trigger pulse, whereas the second unit generated the chance coincidence pulse. The choice of the delay lines ensured that the second multiplicity logic would not give any output for a "genuine" trigger. The high voltages on the PMTs were adjusted to give a bank rate of ~250 kHz, which resulted in a chance rate amounting to 5%–10% of the trigger rate. The current from the PMTs had not been compensated for background light variations. Therefore, the atmospheric transparency would introduce some variation in the bank rates and thus in the trigger and chance rates. Both the trigger events and the chance events were counted on five digit scalers. The time of occurrence of each event was derived from an accurate (±30 μs with respect to UTC) clock. The high voltage was kept constant throughout the run. The following information was

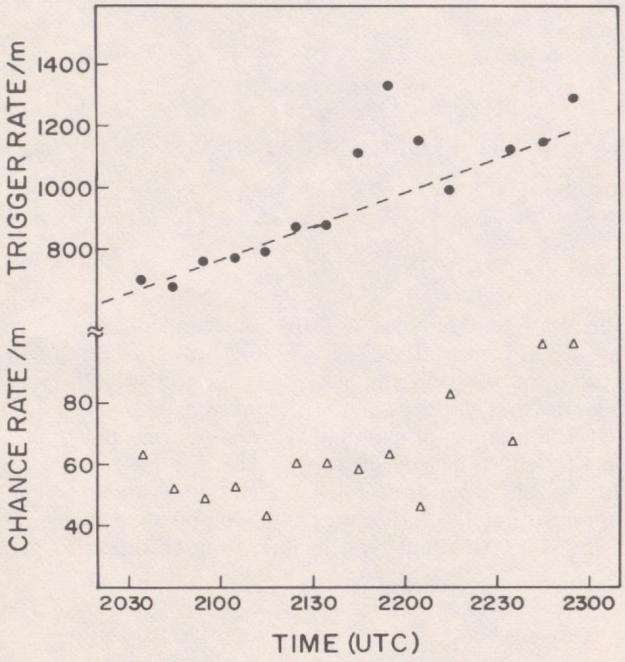

FIG. 1.—The increase in trigger rate with time on 1986 April 11. The rates were derived from the 10 minute on-line readings of the event counters. The dashed line is an eye fit to the gradual increase in rate which is compatible with the expected lowering of threshold energy with the decrease of the hour angle of the source. The source meridian transit is around 2230.

recorded on tape for each event: (1) the time to an accuracy of ± 0.5 ms and (2) the readings from the trigger counter and the chance counter. The trigger and the chance event counts were also monitored every 10 minutes and recorded in the run-log monitor. The average 1 minute rate for consecutive 10 minute intervals was derived from these readings. The run-log monitor was used to keep a check on the progress of the experiment. It also provided an independent and quick look at the data. The average trigger rate was 800 minutes^{-1}, which translated to a threshold of 400 GeV for gamma-ray primaries.

III. ANALYSIS

Ten runs on Her X-1 were taken between 1986 April 5 and 14. The run-log monitor was inspected for significant increases in trigger rate on 10 minute time scales. Only run 9, taken on 1986 April 11, showed a large increase. This had been noticed during the run itself. Figure 1 shows the variation of trigger rate (minutes^{-1}) and the chance rate from the beginning to the end of the run. The gradual increase in rate as the hour angle (hence zenith angle) of the source decreased is compatible with the expected lowering of the threshold energy. However, the trigger rate shot up after 2140 UT and stayed high for 30 minutes. During the period 2120 UT to 2220 UT, the mean trigger rates (minutes^{-1}) in the successive 10 minute intervals are 872, 880, 1107, 1332, 1150, and 995. The corresponding chance coincidence rates are 60, 60, 58, 64, 46, and 84. The tape had to be changed at 2224 UT and there was no further data-taking for the next 8 minutes (2224–2232 UT). The trigger rate for the next 10 minute interval (2232–2242 UT) was 1125 with a chance rate of 68. We terminated the run at 2300 UT due to the onset of dawn. Thus the average observed rate for the burst period was 1187 minutes^{-1} as against an expected rate (by interpolation) of 926 minutes^{-1}. Only three other runs had rates of 700 ± 50 at the beginning of the run (at $\sim 30°$ E) indicating sky conditions similar to that on April 11. All these runs showed rates of 850 ± 50 at $\sim 15°$ E and 1000 ± 50 around transit. Thus, the events on the night of the burst had the same zenith angle dependence as on other nights. Indeed, the zenith angle dependence of trigger rate during all the four runs were identical within statistics.

More detailed information on the burst time and event rates were obtained from the tape data. The increase in the rate was found to be essentially between 2147 UT and 2201 UT. Figure 2 shows the number of trigger and chance coincidence events in 2 minute time bins. The increase is for 14 minutes, with the largest rate being seen in the last 4 minutes of the increase. If we characterize the three time regions—2133–2147 UT, 2147–2201 UT, and 2201–2215 UT—as A, B, and C, respectively, the number of events from the tape in these three intervals were 13,254, 20,367, and 13,826, respectively. The number of chance events were 905, 873, and 790, respectively. The actual number of atmospheric Cerenkov events is obtained by substracting the chance events from the total number of events. The fractional increase in the actual event rate during the burst period is 53.6%. The expected number of events in interval B from a mean of those in intervals A and C is $12{,}692 \pm 89$ while 19,494 were seen. This results in a 42 σ effect. We note that this is the largest effect seen so far in very high energy gamma-ray astronomy. Figure 2 also shows the rate of excess events (as a percentage of the background rate) as a function of time.

It is important to note that the chance coincidence rate, as shown in Figure 2, did not increase during the burst when the total trigger rate went up. The chance rate showed a variation between 5% and 8% before the burst, between 3% and 8%

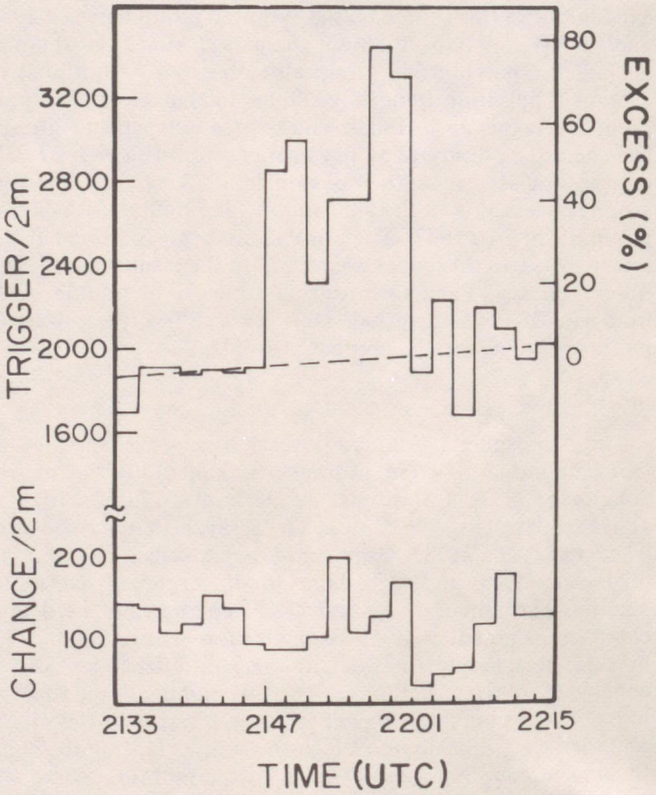

FIG. 2.—The trigger rate and the chance coincidence rate per 2 minutes from the data tape. The right-hand side shows the excess over the cosmic-ray background rate as a percentage of the background rate.

during the burst, and between 2% and 8% after the burst. The fraction of chance events during the burst was 4.3%, whereas outside the burst it was 6.2%. It is clear, then, that the excess trigger rate during the burst cannot be ascribed to any extraneous light source or electrical noise. We attribute the excess events during the period 2147–2201 UT to gamma rays from Her X-1 system.

The time-averaged flux for the entire burst period is estimated to be $1.80 \pm 0.04 \times 10^{-8}$ photons cm^{-2} s^{-1}. This gives a luminosity of $1.80 \pm 0.04 \times 10^{37}$ ergs s^{-1}, assuming a gamma-ray threshold energy of 400 GeV and a differential spectrum with an exponent of -3. The errors given here are statistical only. In addition, there can be systematic errors of a factor of 2, arising from uncertainties in the collection area and threshold energy. The burst-average flux seen here is a factor of 100 higher than the burst-average flux seen in earlier observations.

For a study of time structure of the events, millisecond accuracy is needed for the event arrival time. At this stage, it may be mentioned that because of recording problems, a stretch of 14 out of 41 events was lost in each data record. Missing bit problems resulted in further loss of events. Finally, 57% and 55% of the events could be recovered for the quiescent and active periods respectively. The number of recovered events in the three time intervals A, B, and C were 7398, 11,119, and 7963, respectively.

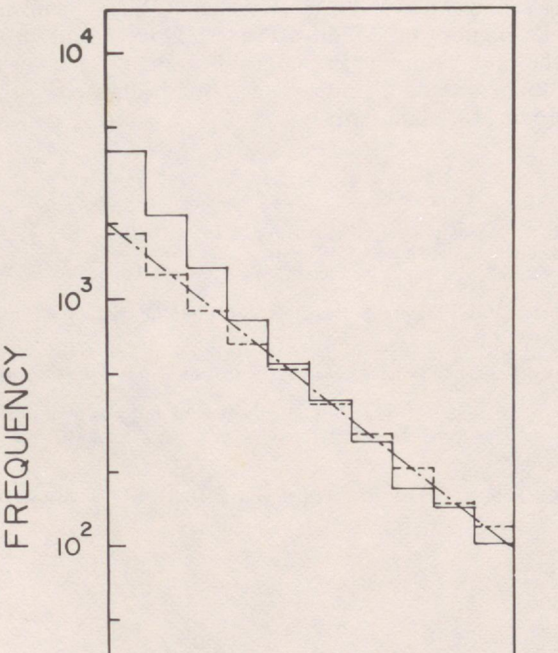

FIG. 3.—The frequency of time separation of events in the burst period (*solid histogram*) and the quiet period (*dashed histogram*). While the dot-dash line is the expectation for events on either side of the burst, there is no *a priori* expectation for events during the burst.

Figure 3 shows the distribution of time separation between consecutive events for the burst period (*solid histogram*) and the quiet period (*dotted histogram*). From the observed number of events before the recovery, the average time interval between events is expected to be 41 ms and 62 ms during the burst and the quiet periods, respectively. While the dot-dash line in Figure 3 shows a good exponential fit to the data during the quiet periods, there is no *a priori* basis to expect exponential or any other functional form for the interevent time distribution of the events during the burst. Experience with X-ray bursts which have been studied in great detail (see, for example, Tanaka 1984) shows that they have varying profiles—periodic, quasi-periodic, exponential, flat-topped trapezoidal, etc. Even during a single burst the profile changes with time. The only point we wish to make here is that the events in the burst did not all occur within a narrow bin of 20 ms. The burst events seen to be distributed over a broad range of time intervals with a mean of 41 ms.

A search for periodic emission during the burst was carried out around 0.8079 Hz, the known X-ray pulsation frequency (Ögelman *et al.* 1985; Lamb *et al.* 1988). Thirty-nine steps on either side of the X-ray period (step size = 0.000595 s) were used resulting in a search range from 0.8233 Hz to 0.7931 Hz for the frequency. For all test periods, an appropriate Doppler correction was applied on the basis of the binary elements given by Ögelman *et al.* (1985). The data showed peaks with Rayleigh power >10 at three frequencies corresponding to 0.8010 Hz, 0.8071 Hz, and 0.8197 Hz. The assess the probability of seeing such high values of Rayleigh power, a Monte Carlo simulation was done with the observed event separations (as in Fig. 3) as input. Further, the loss of events in the recovery of data was also simulated. The Rayleigh power analysis was done using the same range of periods as for the data. The probability of any one period showing Rayleigh power >10 in the Monte Carlo simulations was found to be as high as $\sim 5\%$. Therefore, the peaks in the Rayleigh power analysis of data could not be ruled out confidently as not due to the artefacts of the data. Thus, because of the loss of events, it is not possible to opine definitively on the nature of the periodic emission. We would like to emphasize, however, that this does not in any way affect our observation of the rate increase itself.

IV. DISCUSSION

At first, we discuss whether this observation could be due to a freak optical phenomenon. The response of our telescope to optical phenomena was tested out with stars of different magnitude. A drift scan with a bright star (α Andromeda: $m_v = 2.3$) showed that the normal trigger rate of 600 $minutes^{-1}$ doubled with the star at the center of the telescopes, while the chance rate of 80 $minutes^{-1}$ increased by a factor of 8 in the same time period. The variation in the optical light output from HZ Her the companion star, is known to be not large: during the entire orbital cycle, the visual magnitude changes from 13 to 11 (Middleditch and Nelson 1976). We have observed many times over the last 8 yr that lightning increases both the trigger rate and the chance rate in the system by 100–200 counts per minute. However, the difference between the trigger and chance coincidence rates was barely noticeable. For lightning or optical flashes from the source to mimic the phenomenon seen here, it has to have temporal characteristics similar to the atmospheric Cerenkov pulses (or it should last for less than 90 ns for the chance coincidence unit not to generate any output) and has to be sustained for 14 minutes. We also note that during the episode it was visually verified that there was no obvious indication of any extraneous source of light. We also consider here whether the increase seen here could be due to electronics problems. We first note that all the discriminators feeding the multiplicity logic units had the same width of 20 ns. Further, all pulses which trigger the first set of discriminators trigger the second set also. The two multiplicity logic units are identical for all purposes. The performance of these two units and the whole electronics was routinely tested by giving pulse generator pulses to the fan-in units. To mimic the observed burst, any electronic noise has to be present at the input of at least four discriminators with a time structure of less than 20 ns, and such noise has to be continuously present over 14 minutes, the duration of the burst. In this context, one should also state that a very similar system was operated at Ootacamund for at least 6 yr and at Pachmarhi for over 2 yr; and no phenomenon similar to this burst was ever seen either before or after the occurrence of the burst reported here. Thus, the conclusion is that the increase seen in this observation is genuinely due to gamma rays from Her X-1.

The burst occurred at an orbital phase ($\phi_{1.7d}$) of 0.19 and the 35 day phase (ϕ_{35d}) was 0.31. Among the detections from other groups, several detections are at the orbital phase of either 0.2 or 0.7. The Durham detection, as well as the 1986 Whipple detection (Lamb *et al.* 1988) showing the largest pulsed effect so far, are at the 35 day phase of ~ 0.0. The burst detected by us and the Whipple detection are separated by ~ 1.74 cycles of the 35 day period. It is significant that Eichler and Vestrand (Eichler and Vestrand 1984) predict very high energy gamma-ray emission at either the onset or the decline of the "high on" state in the 35 day period. According to them, the accretion disk presents the right amount of target thickness at these phases for the high-energy protons emitted from the neutron star. The burst seen by us coincides with the decline of the 35 day "high-on" state. It is possible that while the source has been detected at other phases, the onset and the decline of the "high-on" state provide the right amount of target material for copious production of gamma rays. We should however note that the 35 day period has not been completely understood. There are recent indications that the conventional understanding of this periodicity as due to the obscuration by the disk may not be correct (Trümper 1986).

In conclusion, we have observed a very large increase in the number of events from the direction of Her X-1 over a 14 minute interval (2147 UT to 2201 UT) on 1986 April 11. Barring unknown scenarios (such as electronic noise and celestial or terrestrial optical phenomena with time structure similar to that of atmospheric Cerenkov phenomenon which are highly unlikely in our experience), this increase can only be due to TeV gamma rays arriving from the direction of Her X-1. We note that this is the largest signal seen till now at these energies. Because of the gaps in our data we cannot opine on the pulsed nature of the emission.

We wish to thank Dr. K. Sivaprasad for fruitful discussions. We also wish to thank Mr. A. R. Apte for setting up the array, and Messrs. G. P. Satyanarayana and A. I. D'Souza for help with the observations. The help given by Professor T. S. Murthy of the Madhya Pradesh Council of Science and Technology and Messrs. N. R. Krishnan, Vinay Shankar, and Samar Singh of the Madhya Pradesh Government for setting up the observatory at Pachmarhi is gratefully acknowledged. We thank the anonymous referee for his/her comments for improving the manuscript.

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Nuclear Instruments and Methods in Physics Research A273 (1988) 403–409
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USE OF PLEXIGLAS SHEETS COATED WITH WAVELENGTH-SHIFTER DYES FOR DETECTION OF ATMOSPHERIC CHERENKOV RADIATION

A new technique for gamma ray astronomy at energies of $\sim 10^{13}-10^{14}$ eV

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Received 17 May 1988

A 900 cm^2 area plexiglas sheet coated with a thin film of a combination of wavelength shifter dyes is used for detection of atmospheric Cherenkov ultraviolet photons in extensive air showers at Cosmic Ray Laboratory, Ooty in southern India. The response of the coated sheet is compared with an otherwise identical but uncoated plexiglas sheet in showers of different primary energies and at different distances from the axes. It is shown that the coated sheet is an efficient detector of Cherenkov UV photons in showers of energies $>10^{14}$ eV. Based on these observations it is suggested that an array of detectors made from plexiglas sheets, coated with wavelength-shifter dyes, with interseparations of about 50 m can be effectively used as a large area detector for studies of cosmic sources of gamma rays of energies $>10^{13}$ eV. Using the relative timing technique such an array can provide a large collection area, good angular resolution and wide aperture. The advantages of this new technique, relative to conventional detectors such as large area reflectors for Cherenkov photons and arrays of particle detectors for air showers, are discussed.

1. Introduction

The atmospheric Cherenkov radiation (ACR) technique has been widely used for detection of cosmic sources of very high energy ($>10^{11}$ eV) gamma rays in ground based experiments. This technique has the advantage of a relatively large effective collection area due to the spread of Cherenkov photons typically over an area of radius 120 m around the axis of the shower initiated by a primary gamma ray photon or cosmic ray particle in the atmosphere. Arrays of parabolic/spherical reflectors, mounted on individual orientation and tracking platforms [1,2], are used to detect these showers. Since the opening angle of Cherenkov photons in air is about 1° and the imaging qualities of reflectors used in many experiments are poor, the angular resolution achieved in such studies has been 1° to 2°. Such systems are suitable for following suspected sources but not for a general sky survey. Also these detectors do not permit, in general, a good determination of background flux from nearby but well-separated off-source regions simultaneously with observations of a source region.

At higher energies ($\sim 10^{14}$ eV) the extensive air shower (EAS) technique, using arrays of charged particle detectors, has been widely used to study gamma ray sources [3–8]. The use of the relative timing technique with particle detectors yields an angular resolution [9] of about 1° at energies $>10^{14}$ eV but the resolution is expected to become poorer at energies $<10^{14}$ eV due to larger multiple scattering of lower energy electrons in the atmosphere. Also it is difficult to achieve an energy threshold of much lower than about 5×10^{13} eV with this technique, even at mountain altitudes (700–800 g cm^{-2}), due to a lower number of surviving charged particles and the dominance of fluctuations in shower development in the atmosphere. Generally the detection efficiency for showers is quite small for energies $<10^{14}$ eV, even with very compact arrays of particle detectors with interdetector separations of only 5–10 m. Apart from poorer angular resolution the other major problem with the EAS technique, particularly at lower energies $<10^{14}$ eV, is the smallness of the effective collection area with a given number of particle detectors. Since the expected density of particles at distances larger than about 20 m from the shower axis is smaller than 1 m^{-2} for showers initiated by gamma rays of energies $<10^{14}$ eV, interdetector separations have to be about 10 m or less to detect such showers efficiently. Therefore a large number of detectors are required to obtain a large collection area.

In view of these considerations, it was suggested by Tonwar [10] to combine some of the advantages of both the ACR and EAS techniques for detection of showers of energies $>10^{13}$ eV for studies on cosmic gamma ray sources. He suggested the use of plexiglas/acrylic sheets coated with wavelength-shifter (WS) dyes, coupled suitably to fast photomultipliers, for detection of Cherenkov photons. Showers could be selected by requiring a

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fast coincidence between signals from a number of such sheets placed near to each other. The use of the relative timing method with an array of such sheets spread over a large area can achieve an angular resolution better than 1° without unduly restricting the aperture of the system. Since the Cherenkov photon density decreases only slowly with the distance from the shower axis, the separation between groups of such sheets could be as large as 50 m without affecting the detection efficiency for showers of energies $> 10^{13}$ eV. Such an array will have the advantage of a large effective collection area, a characteristic of the ACR technique. It will also have a large aperture and good angular resolution, a characteristic of the EAS technique.

We report here the results of a preliminary experiment with a plexiglas sheet coated with a combination of WS dyes placed in different locations in the Ooty air shower array. The details regarding the WS coated sheet and the photon detection system are presented in the next section. The details of the EAS array and the experimental system are given in section 3. Experimental results on the efficiency of this sheet for detection of showers and distributions of observed photon density are discussed in section 4. In section 5 we present the conclusions drawn from these observations and a brief discussion on the advantages/disadvantages of an array of WS coated sheets for gamma ray astronomy at very high energies compared to the conventional detectors.

2. Plexiglas sheets coated with wavelength-shifter dyes

The use of wavelength-shifter dyes for coating plastic sheets for the detection of Cherenkov photons has been common in high energy physics experiments (e.g. see ref. [11]) for discriminating between particles of different masses. Such detectors have also been used for the detection of heavy nuclei in experiments studying the composition of primary cosmic rays at high energies. Viehmann and Frost [12] have made an extensive study of the sensitivity of thin films of acrylic/polyvinyltoluene heavily doped with various wavelength-shifter dyes having their absorption and emission spectra in different regions of the UV and optical wavebands. Using some specific type of acrylic resins dissolved in toluene and organic fluorescent dyes like PPO and Bis-MSB, they have shown that films with a thickness of a few microns, deposited by dipping or spraying on a substrate, have wide spectral response and essentially 100% photon conversion efficiencies for UV to blue. A plexiglas sheet of 1 cm thickness and 30×30 cm^2 area was dipped into the solution prepared in this manner at the Goddard Space Flight Center by R.E. Streitmatter and colleagues in September 1982. This sheet was coupled to a nearly triangular piece of plain plexiglas sheet

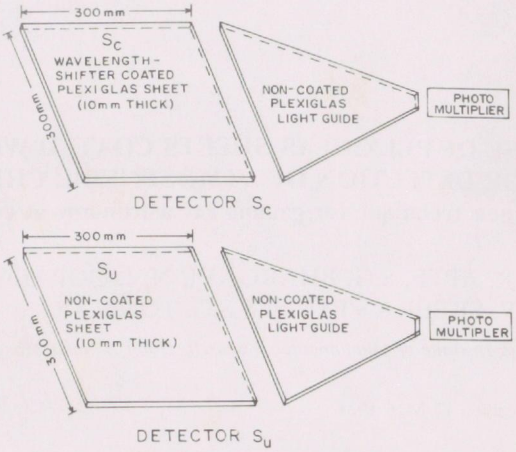

Fig. 1. A schematic sketch of the detector for atmospheric Cherenkov photons. A plexiglas sheet S_c of 30×30 cm^2 area, coated with a thin film of wavelength-shifter dyes, is viewed by a 5 cm diameter photomultiplier (RCA 8575) through a triangular shaped plexiglas light guide. Another sheet S_u of uncoated plexiglas, but otherwise identical to S_c, provides reference for measurements of the signal due to Cherenkov photons.

(fig. 1) which served as the light guide. A fast high gain photomultiplier (RCA 8575) was glued to the other end of this light guide, using an epoxy glue (Devcon). Except for the coated 900 cm^2 area of the plexiglas sheet all other parts were wrapped with black paper and cloth, to make this a detector (called S_c hereafter) for Cherenkov photons. A similar combination of a square plexiglas sheet (but without any special coating), a light guide and a photomultiplier was made to serve as a reference detector (S_u).

3. Experimental details

These two detectors S_c and S_u were installed first in the position marked "NEAR" in the 24 detector extensive air shower array [13] operating at Ooty, a mountain altitude (2200 m altitude and 11.4° N latitude) laboratory in southern India, as shown in fig. 2. After necessary observations at this position, as discussed in detail in the next section, these detectors were moved to the position marked "FAR" in fig. 2 and observations were repeated. These two positions NEAR and FAR are located at distances of 30 and 80 m, respectively, from the centre of the array. The observations were carried out during March 4–12, 1986.

Showers were selected using a loose trigger, called NEWS, requiring a single particle in each of the four detectors, N, E, W, and S, placed at the corners of an approximate square of side 10 m near the centre of the array; a further requirement was that at least 3 particles

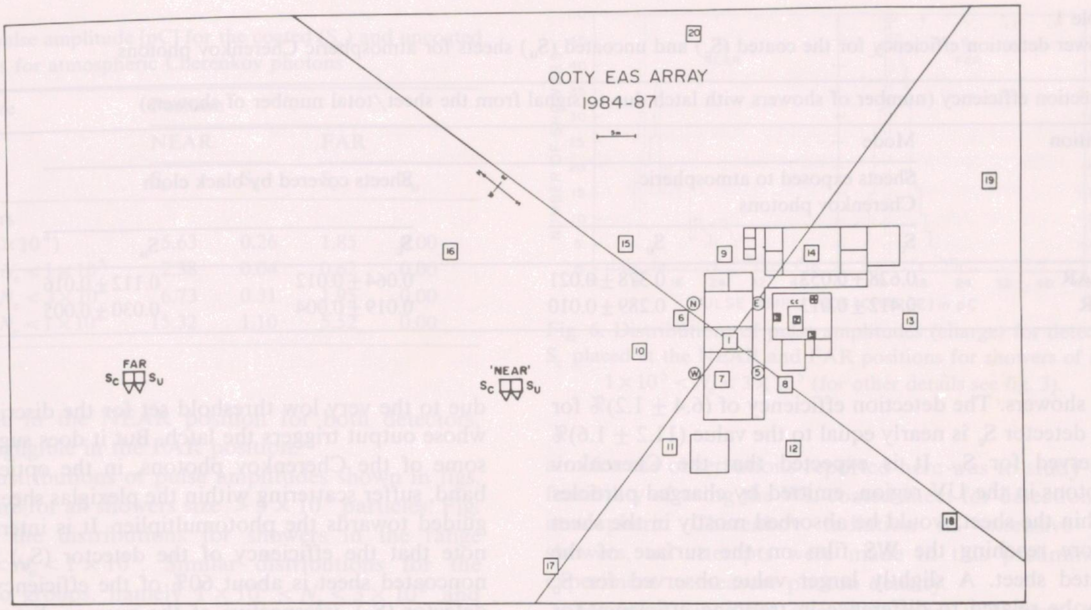

Fig. 2. A schematic sketch of the Ooty EAS array showing the positions NEAR and FAR of detectors S_c and S_u 30 and 80 m from the centre of the array, respectively.

should pass through any one of these 4 detectors [14]. The shower rate was about 0.13 s^{-1}. For each shower the amplitude of the pulse from each of the 24 density detectors and the relative arrival time of the signal were measured (LeCroy 2249A ADCs and 2228 TDCs) and recorded on magtape.

The anode pulses from each of detectors S_c and S_u are split into two pulses using passive fan-outs; one output is fed to a amplifier–discriminator module set at an effective threshold of about 5 mV; the other is connected to one of the channels of the charge-integrating ADC modules with appropriate delay. The ADC module is gated by the shower trigger described above. The discriminator outputs (100 ns width) for S_c and S_u are fed to independent latches gated by the shower trigger. The high voltage for the photomultipliers for both the detectors S_c and S_u were adjusted to give a rate of about 50 kHz at the discriminator output when viewing the night sky and atmospheric Cherenkov radiation. This rate reduced to about 100 Hz when the detectors were covered with black cloth.

4. Experimental results

Data were taken, both in the NEAR and FAR positions, in the following sequence. On each of the observational nights, after allowing for temperature stability of the system in the early part of the night, datataking was started at about 22.00 hours (local time) and continued till about 04.00 hours of the next morning. Showers were collected for about an hour with a black cloth covering the plexiglas sheets for both S_c and S_u detectors, followed by an hour of data with no cover, and this cycle was repeated. This sequence allowed a good monitoring of the sensitivity of the system for possible variations in atmospheric temperature and changes in night sky background. However, the data finally showed that these atmospheric factors are not of significance. Data taken with a black cloth cover on the plexiglas sheets give the contribution due to Cherenkov photons produced directed by charged particles traversing the sheets.

Table 1 gives the values of the efficiency for observing a signal in the detectors S_c and S_u as a fraction of the number of showers selected by the NEWS trigger described above. These efficiencies are obtained from the frequency of latched signals for the detectors S_c and S_u. The table gives the efficiency values for both configurations – the detectors covered with a black cloth as well as open to night sky and atmospheric Cherenkov radiation. The efficiencies for both positions, the NEAR and the FAR are given. The following observations can be made from the results listed in table 1:

(1) The charged particle contribution to the observed signal is small for both detectors. Analysis of showers [8] has shown that most of the showers selected with the NEWS trigger have their axes within about 30 m of the centre of the array and shower size $> 3 \times 10^4$ particles. The detectors S_c and S_u located at the NEAR position are therefore sampling the electron density at an average distance of only about 30 m from the axes of

Table 1
Shower detection efficiency for the coated (S_c) and uncoated (S_u) sheets for atmospheric Cherenkov photons

Detection efficiency (number of showers with latch due to signal from the sheet/total number of showers)				
Position	Mode			
	Sheets exposed to atmospheric Cherenkov photons		Sheets covered by black cloth	
	S_c	S_u	S_c	S_u
NEAR	0.628 ± 0.053	0.378 ± 0.021	0.064 ± 0.012	0.112 ± 0.016
FAR	0.412 ± 0.013	0.289 ± 0.010	0.019 ± 0.004	0.030 ± 0.005

the showers. The detection efficiency of (6.4 ± 1.2)% for the detector S_c is nearly equal to the value (11.2 ± 1.6)% observed for S_u. It is expected that the Cherenkov photons in the UV region, emitted by charged particles within the sheet, would be absorbed mostly in the sheet before reaching the WS film on the surface of the coated sheet. A slightly larger value observed for S_u may be related to difference in trapping efficiency for Cherenkov photons between coated and noncoated surfaces. The efficiency decreases significantly, in the covered mode, at the FAR position since showers have a much lower electron density at the average distance of about 80 m from their axes.

(2) The detection efficiency for the coated sheet (S_c) for Cherenkov photons is 62% at the NEAR position and 41% at the FAR position. This is a consequence of the slow decrease in the photon density from 30 to 80 m from the shower axis. The detector having the noncoated sheet (S_u) also shows larger values for the efficiency, 38% and 29% at the NEAR and FAR positions, respectively. However, the measurements on pulse amplitude, discussed later, show that these larger values for the efficiency for the noncoated sheet are mainly due to the very low threshold set for the discriminators whose output triggers the latch. But it does suggest that some of the Cherenkov photons, in the optical waveband, suffer scattering within the plexiglas sheet and are guided towards the photomultiplier. It is interesting to note that the efficiency of the detector (S_u) with the noncoated sheet is about 60% of the efficiency for the detector (S_c), irrespective of the average distance from the shower axis.

The amplitudes of the anode pulses were also measured in the experiment for both the detectors S_c and S_u through charge-integrating ADCs. The observed distributions of the pulse amplitude for the two detectors, in the NEAR position, are shown in fig. 3. Full lines show the distributions when the detectors were exposed to the night sky and the atmospheric Cherenkov photons, and the dotted lines represent the data obtained with detectors covered with black cloth. Similar distributions for the FAR position are shown in fig. 4. The average values of the pulse amplitudes from these distributions, expressed in pC, are given in table 2. Note the large difference in the average pulse amplitudes between S_c and S_u; the pulse from the WS coated detector has almost 15 times more charge compared to the uncoated detector in the NEAR and also the FAR positions. Table 2 also gives the average values of the pulse amplitudes for sheets covered with black cloth. These show that the charged particle contribution is barely

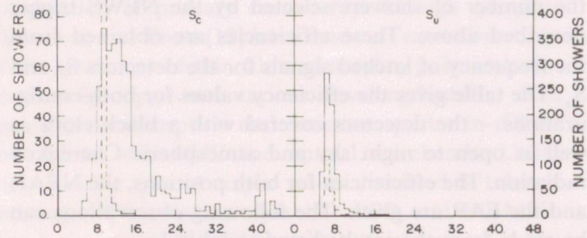

Fig. 3. Distributions of pulse amplitudes (charge) for detectors S_c and S_u placed at the NEAR position for all showers selected by the news trigger (see text). Full lines show the distributions for observations with sheets exposed to atmospheric Cherenkov photons and night sky. Dashed lines show the distributions for the detectors covered with black cloth. ADC pedestals are not subtracted and are given effectively by the positions of the peaks of the dashed line distributions.

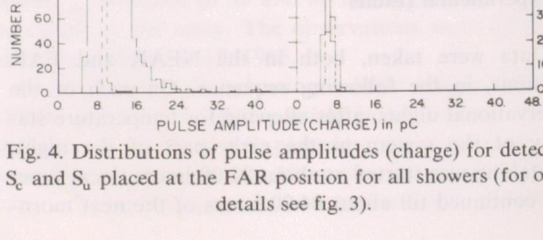

Fig. 4. Distributions of pulse amplitudes (charge) for detectors S_c and S_u placed at the FAR position for all showers (for other details see fig. 3).

Table 2
Average pulse amplitude [pC] for the coated (S_c) and uncoated (S_u) sheets for atmospheric Cherenkov photons

Shower size	NEAR S_c	NEAR S_u	FAR S_c	FAR S_u
All showers ($N_e > 3\times10^4$)	5.63	0.26	1.85	0.00
$3\times10^4 < N_e < 1\times10^5$	2.38	0.04	0.62	0.00
$1\times10^5 < N_e < 3\times10^5$	6.73	0.31	1.95	0.00
$3\times10^5 < N_e < 1\times10^6$	15.32	1.10	5.52	0.00

detectable in the NEAR position for both detectors, and is negligible in the FAR position.

The distributions of pulse amplitudes shown in figs. 3 and 4 are for all showers size $> 5\times10^4$ particles. Fig. 5 shows the distributions for showers in the range $3\times10^4 < N_e < 1\times10^5$. Similar distributions for the other two groups, namely $1\times10^5 < N_e < 3\times10^5$ and $3\times10^5 < N_e < 1\times10^6$ are shown in figs. 6 and 7, respectively. The average values for these distributions are also given in table 2. Note the increase in the signal from S_c with increasing shower size and the significant difference in the signal amplitude for the NEAR and FAR positions.

All the values given in table 2 for the average pulse amplitude of the two detectors for various configurations and also the distributions shown in figs. 3–7 refer to measurement of charge in the charge-integrating ADCs. The conversion of the detected charge to the number of photons has not been attempted here due to various complex factors involved, such as the spectrum of Cherenkov photons incident on the sheet, the spectral response of the sheet, the collection efficiency of optical photons in the sheet–light-guide–photomultiplier combination and the spectral response of the photomultiplier. However, it may be pointed out that the average value of the signal from S_c for throughgoing relativistic muons was less than 0.2 pC. Since the main

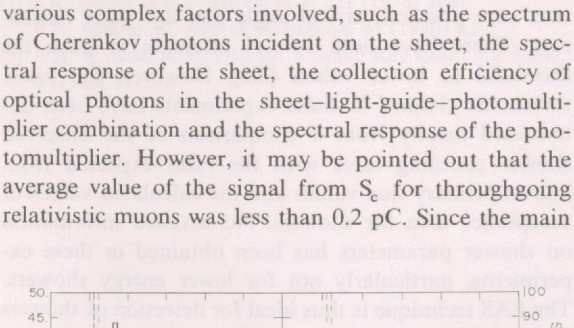

Fig. 5. Distributions of pulse amplitudes (charge) for detector S_c placed at the NEAR and FAR positions for showers of size $3\times10^4 < N_e < 1\times10^5$ (for other details see fig. 3).

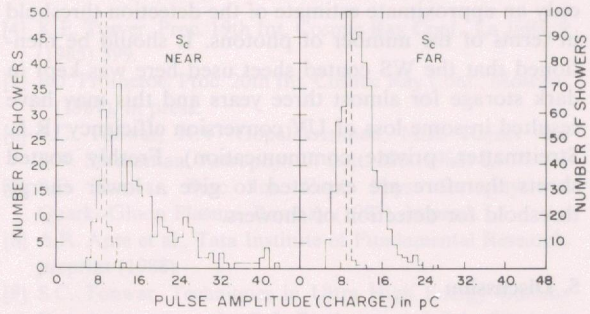

Fig. 6. Distributions of pulse amplitudes (charge) for detector S_c placed at the NEAR and FAR positions for showers of size $1\times10^5 < N_e < 3\times10^5$ (for other details see fig. 3).

aim for the observations reported here was to study the feasibility of using the WL coated sheet for detection of atmospheric Cherenkov radiation in extensive air showers, no attempts were made in this preliminary experiment to measure photon density.

However, since the size of showers is known from the EAS array, it is possible to obtain an estimate of photon density from simulations [15]. The expected photon densities for showers of size 3×10^4–1×10^5 at 30 and 80 m from the shower core are about 1000 and 650 m^{-2}, respectively. Since the area of S_c is only 0.09 m^2 the expected number of photons over S_c is 90 and 55, at the NEAR and FAR positions respectively. (It may be noted, for comparison, that the charged particle densities expected at these two positions are about 1 and 0.01 m^{-2}, respectively.) However, these numbers refer to photons over the full waveband, from near UV to the middle of the optical region. On the other hand, the efficiency of the WS coated sheet is high for near UV region and poor for longer wavelengths. The effective number of photons incident on the sheets may therefore be only about 45 and 25, at the NEAR and FAR positions respectively for showers of size $> 3\times10^4$ particles or energies $> 2\times10^{14}$ eV. Since there are large fluctuations in individual showers, these numbers give

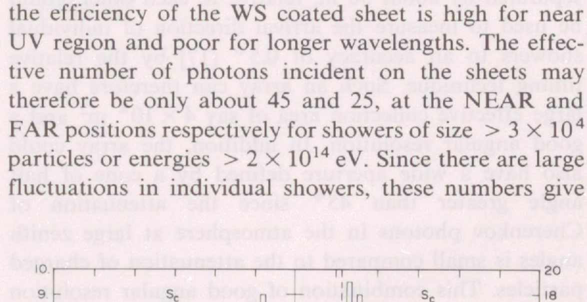

Fig. 7. Distributions of pulse amplitudes (charge) for detector S_c placed at the NEAR and FAR positions for showers of size $3\times10^5 < N_e < 1\times10^6$ (for other details see fig. 3).

only an approximate estimate of the detection threshold in terms of the number of photons. It should be mentioned that the WS coated sheet used here was kept in dark storage for almost three years and this may have resulted in some loss of UV conversion efficiency (R.E. Streitmatter, private communication). Freshly coated sheets therefore are expected to give a lower energy threshold for detection of showers.

5. Discussion

The experimental results discussed above have unambiguously shown the wavelength-shifter coated plexiglas sheet to be an efficient detector for atmospheric Cherenkov photons for showers of energies $> 2 \times 10^{14}$ eV. With the observed detection efficiency of about 50% with a small area (0.09 m^2) sheet, we may expect that a freshly WS coated sheet of 1 m^2 area would have almost 100% efficiency for the detection of showers of energies $> 4 \times 10^{13}$ eV. Since showers initiated by primary gamma rays are expected to have about double the number of Cherenkov photons [16] compared to showers initiated by primary cosmic rays of the same energy, it seems feasible to achieve a threshold energy of 2×10^{13} eV for the detection of showers due to primary gamma rays.

An array of 1 m^2 area WS coated sheets spread over a large area can offer substantial advantages over the conventional detectors for very and ultra high energy gamma ray astronomy. A fast coincidence between three to four of such sheets kept near each other as a cluster could select showers of energies $> 2 \times 10^{13}$ eV, incident over a large area around. An array of such clusters separated by about 50 m, relative to each other, could be used to measure the arrival direction of individual showers to an accuracy of 0.5° [17] by the relative timing technique. Such an array can therefore have a large effective collection area of say 4×10^4 m^2 and a good angular resolution. In addition, the array could also have a wide aperture defined by a cone of half angle greater than 45° since the attenuation of Cherenkov photons in the atmosphere at large zenith angles is small compared to the attenuation of charged particles. This combination of good angular resolution and wide aperture makes this technique very appealing.

The conventional methods that have so far been employed are:

(a) A large area parabolic/spherical reflector mounted on a single orientation platform with a single or a cluster of photomultipliers at the focus [1];

(b) A large array of many smaller area (~ 1 m^2) reflectors mounted on individual platforms with interreflector separations of few meters [2];

(c) A large array of many smaller area (~ 1 m^2) reflectors mounted on individual platforms with interreflector separations of tens of meters [17];

(d) A small array of few clusters of reflectors [18]; and

(e) A small array of few open photomultipliers facing the night sky [19].

In the focussing reflector technique, the opening angle has to be a few degrees necessarily to allow for the angle of emission of Cherenkov photons in air and the poor quality of imaging by the reflectors generally used. The use of a cluster of photomultipliers at the focus of a large spherical reflector and measurement of amplitudes of pulses from these photomultipliers individually, thus imaging the Cherenkov spot, has helped the Whipple group [1] to some extent in achieving better angular resolution and reducing the background. Similarly the use of the relative timing technique with an array of widely spaced reflectors has helped the Tata group [17] in reducing the background by making possible the rejection of offsource showers. The open photomultiplier system has tremendous background problems and the detection threshold cannot be much lower than 10^{15} eV. One of the serious disadvantages of these methods is that there are no simultaneous observations on nearby but well-separated offsource regions.

The EAS method employing a large array of charged particle detectors combined with relative timing technique has definite advantages over the ACR technique. However the detection energy threshold is much higher even at mountain altitudes of 700–800 g cm^{-2}. Even with compact arrays with interdetector separations of 5–10 m the detection efficiency is quite small for showers of primary energy less than 10^{14} eV. The number of particles is too little and the fluctuations are large, making the determination of shower parameters like size, core position, arrival angle and age quite inaccurate. There have been several attempts to push the threshold to lower values [3,5]. However, the lower thresholds claimed in these experiments have been determined mostly from a comparison of the observed shower counting rates with the rates expected from known primary flux values and the calculated values of acceptance area for showers. No detailed information on shower parameters has been obtained in these experiments, particularly not for lower energy showers. The EAS technique is thus ideal for detection of showers induced by gamma rays or other neutral radiation at PeV energies.

The method suggested here, using an array of WS coated sheets, combines the advantages of both the ACR and EAS techniques and our preliminary studies suggest that it should be possible to achieve a threshold close to few times 10^{13} eV for primary gamma rays using this method at mountain altitudes. However, it is essential that a study be made for the following parameters for evaluating the usefulness of this method for practical use in gamma ray astronomy experiments at very high energies:

(a) wavelength response of coated sheets for Cherenkov photons as well as night sky and moon light,

(b) variation of the efficiency with time, and reproducibility of results with different sheets, and

(c) weathering effects on sheets exposed to night sky to determine the required frequency for recoating sheets.

Some of these studies are in progress in Ooty laboratory. It should be emphasized here that the cost of plexiglas sheets required in this technique, including the cost of coating them with the WS dyes, is a small fraction of the cost of other type of detectors, such as a plastic scintillator or a parabolic reflector, of equivalent area. Therefore, the technique retains its advantages even if the weathering effects make recoating of sheets necessary every few weeks.

Acknowledgements

We are grateful to V.K. Balasubrahmanyan and R.E. Streitmatter for providing the facility for coating the test sheet with wavelength-shifter dyes at GSFC. We are also thankful to them and to G.B. Yodh for many fruitful discussions. Thanks are also due to C. Ravindran, A. Pushpanathan, P. Sivaram and other technical staff members of Cosmic Ray Laboratory, Ooty for their valuable help during observations.

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