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Very High Energy gamma rays from Geminga Pulsar

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The analysis of data collected in 2000 on the Geminga pulsar by the atmospheric Cerenkov experiment at Pachmarhi (PACT) shows no excess events at any phase in the phasogram. However, there is a significant excess ($> 5\sigma$) in the phase interval 0.55-0.75 (the phase interval of GeV emission) when events are restricted to small values of space angle and large values of β, a parameter proportional to primary energy.

1. Introduction

Many groups using imaging technique have been able to establish good signals of Very High Energy (VHE) gamma rays from various sources including supernova remnants and active galactic nuclei [1, 2]. However, as for pulsars which were important target sources the earlier years, most groups have not seen any periodic signals [3, 4] in VHE gamma rays. The EGRET experiment [5] detected seven gamma ray pulsars. While the spectra show dominant power at energies of < 1 GeV there seems to be a falloff at higher energies indicating changes in characteristics at higher energies. Geminga, a very bright object in the COS-B catalog [6], remained a mystery for almost a decade till the discovery of $\sim$237 ms periodicity by ROSAT [7] and later by EGRET [8]. After the discovery by EGRET, two VHE gamma ray groups (Durham [9] and Ooty [10]) reanalyzed their archival data and found modest level pulsar signatures with Very High Energy (VHE) gamma ray peaks coinciding with the peaks in phasograms of COS-B data. It was looked at by the WHIPPLE [11] and the HEGRA [12]; Neither experiment saw any evidence for the emission of VHE gamma rays from the Geminga pulsar. The Crimean group [13] looked at their 1996-1997 data on Geminga and reported evidence for pulsed emission at level $> 4\sigma$. Also they have reported evidence for modulation of VHE emission with a periodicity of about 59 s [14]. During 1992-1994, the Tata group working at Pachmarhi with an interim array [15]) found that events in the phase interval at which GeV emission was found (around 0.6 for Geminga) displayed the same features as expected for pulsed emission of gamma rays. Thus there is no consensus on the emission of VHE gamma rays from the Geminga pulsar. A new atmospheric Cerenkov array to study cosmic sources of VHE Gamma rays was set up in Pachmarhi in central India in 1999 and fully commissioned in 2001. We report on the analysis of data taken in 2000 on Geminga pulsar with this experiment when half of the array (12 telescopes) was operational.

2. The PACT experiment and Analysis

The aim of the Pachmarhi Atmospheric Cerenkov Telescope (PACT) array was to use the temporal and spatial distribution of Cerenkov photons in distinguishing between proton and gamma ray showers for increase of sensitivity. The array consists of 25 telescopes, each having 7 parabolic mirrors, deployed in a field of 80 m $\times$ 100 m area [16]. The total physical area of the mirrors is $\sim$ 105 m^2. Each mirror is looked at by a fast PMT behind a 3 degree circular mask. To minimize the attenuation and distortions in the cables, the array is divided into 4 sectors, with each sector servicing a group of 6 nearby telescopes. The pulses from the 7 PMTs in a telescope were linearly added to form a Royal Sum pulse for each telescope. A four fold coincidence of these Royal Sum pulses generated the event trigger. Single sector event rate was about 3 to 4 Hz for most atmospheric conditions (the overall event rate of PACT for all the 4 sectors is about 9 Hz). Both the timing and pulse height information for each PMT were recorded. Monte Carlo estimates of the energy threshold for one sector is ∼800 GeV. The PACT experiment with pulse height and timing information from 175 mirrors is thus ideal for exploiting the various capabilities of the wavefront sampling technique.

A total of 10 hours (spread over 6 runs in Dec 2000) was taken on Geminga pulsar. While only two sectors (3 and 4) were operational, events triggering both sectors (3 and 4) were used for the analysis. For this purpose data from both the sectors were collated. Two parameters which could be obtained for each event were α, the space angle difference between the shower direction and the source direction and β, the total charge from all the telescope pulses. α was determined for each event using a 3 ns cut on the difference between expected and observed relative time of arrival of pulse and requiring at least 6 telescopes with valid timing information in which at least 2 telescopes have a large baseline. With this cut the usable rate of events was ∼1.3 Hz. The QDC count distribution for each PMT channel was first obtained and the mean QDC count for each channel was found for each run. Correction factors were applied to get the same mean QDC count for each channel. Adding the corrected ADC counts β parameter for the event was obtained.

Using the original ephemeris given by EGRET group, standard barycentric analysis was done to get the phase for each event. While the GeV emission was seen in the phase interval ∼ 0.56-0.70 and 0.06-0.20, the phasogram of events in the PACT data without any cuts does not show significant excess at any phase. If there are VHE gamma ray events one expects them to have characteristics different from the background cosmic ray events. Therefore, the α distribution and the β distribution in each phase interval was compared with the mean α and β distribution of other phase intervals. Table 1 shows the chi-square thus obtained as a function of phase.

Table 1. χ^2 for different Phase Intervals

Phase Interval	χ^2 (Space Angle)	χ^2 (β parameter)
0.15-0.35	0.9	2.7
0.35-0.55	1.5	1.5
0.55-0.75	4.2	5.9
0.75-0.95	2.4	1.5
0.95-1.15	2.5	1.4

It can be seen that the events in phase interval 0.55-0.75 have higher χ^2 for both the α and β distributions. Thus this phase interval is populated by events with different characteristics. When the reason for higher χ^2 in these distributions is explored further, it is found that the events in this phase interval are bunched at small space angles and in the large β region. The excess is restricted to within $1^\circ.25$ space angle and at $\beta > 300$. The fact that the excess events are from nearer the direction of the source shows that they could be due to VHE gamma rays.

When cuts on both β and space angle were made on the data, following were the number of events in phase intervals, .15-.35, .35-.55, .55-.75, .75-.95 and .95 - 1.15 : 2315,2274,2618,2280 and 2318. The phase interval .55 -.75 has 2618±52 events when the mean of the other 4 bins is 2297±23. This leads to 321±56 excess events (5.7σ) yielding a mean rate of 0.54±0.19 per minute. The rates of excess events in individual runs are as follows : 0.77±0.34, 0.48±0.33, 0.67±0.34, 0.21±0.26, 0.64±0.28 and 0.49±0.24 respectively for the 6 runs. Thus all the runs have similar excesses within errors. The basic energy threshold for the events triggering both sectors is ∼1100 GeV. However, the cut on the β removes lower energy events and the events after the cuts would correspond to an energy threshold of ∼2200 GeV.

3. Discussion

As noted earlier, the positive detection of pulsed emission of VHE γ-rays from Geminga in the earlier years were from the Tata group at Ooty [10] and the Durham group [9]. While the signal levels from the experiments were modest, the fact that the signals are seen at the same phases as the GeV emission increased the credibility of the results. The Tata group [15] working in the early 90s with an interim array in Pachmarhi found excess of events in the phase interval (P1) with two different types of analysis using lateral distribution parameters. However, no flux was quoted since the implication of the cuts were not completely studied.

It is interesting to see that the events in phase interval P1 had slightly higher energy compared to the events in the other phase bins [15]. The mean pulse height of events between, 0.53-0.73 was higher than the pulse height for the rest of the phases by a factor amounting to a 3σ effect. A similar excess is seen in the present analysis also. The mean QDC counts for the five bins are :355,354,372,353,350 with the highest in the phase interval 0.55-0.75.

The Crimean group [13] report a 4.4σ excess from the source direction when cuts on the Cerenkov images are applied to the data. When subjected to a periodicity analysis, they see periodic emission with probability of random phase distribution to be 0.3%. It is interesting to note that the signal is seen only after rejecting data with lower photon number in the detectors.

The fluence (in units of $10^{-11}\ cm^{-2}\ s^{-1}$) reported in the positive detections are (a) 2.1 $>$ 0.8 TeV [10] (b) $\sim$3 at $>$ 1 TeV [9] and (c) 2.4$\pm$ 0.8 at $>$ 1 TeV [13]. The present data show excess in the phase corresponding to P1 of EGRET for events with higher energy and a preliminary flux of $\sim 1\times 10^{-11}\ cm^{-2}\ s^{-1}$ at $>$ 2.2 TeV is obtained. The upper limit for pulsed emission by HEGRA experiment [12] is about a factor 10 less at $>$1.5 TeV. While it is possible that the source is time variable, the reasons for the disagreement between various experiments have to be explored further.

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