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On Pulsed emission of TeV γ-rays from Crab Pulsar

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We have observed crab pulsar in the TeV energy band using the Pachmarhi Array of Cherenkov Telescopes. Our Observations span about 5 year period from 2000 to 2005. In the past we presented evidence for pulsed emission of TeV γ-rays from this source while few other groups did not see any such evidence. We have re-analysed our data using new computer codes and the TEMPO package. We have searched for the evidence of pulsed emission of γ-rays from crab pulsar using the contemporaneous radio pulsar parameters.

1. Introduction

The crab pulsar is a source of 33 ms pulsed radiation in all bands of the electromagnetic spectrum. Several groups have searched for the evidence of pulsed emission at TeV energies. While a few observations have shown some evidence for steady or episodic pulsed emissions [1, 2, 3, 4], other observations did not show any evidence[5, 6, 7, 8]. Thus the question whether pulsed emission continue to higher energies is still to be resolved. With the detection of 7 γ-ray pulsars[9], including crab pulsar, by EGRET on board CGRO, the motivation for observation of pulsars in the higher energy band has renewed. The energy spectrum, as measured by EGRET [10], has two components. The steep spectrum below 0.1 GeV is attributed to the synchrotron radiation from the nebula. Beyond 0.1 GeV the spectrum hardens and is dominated by the pulsed emission. But most of the emission at TeV was found to originate from the nebula[11]. The details of origin of pulsed emission and the nature of energy spectrum of γ-rays from pulsar at higher energy end are unknown. Of the 2 models, Polar Cap[12, 13] and outer-gap[14, 15], constructed to explain the pulsed emission at GeV energies, the outer-gap model[16] could explain the emission at TeV energies if present. Thus detection of pulsed emission in GeV$-$TeV would discriminate between these models. The recent search has shown no evidence for pulsed emission upto 80 TeV[11] and probably a spectral cut off below 60 GeV[17]. In the previous ICRC, we presented a possible evidence[18] for pulsed emission at $>$1.6 TeV. We have re-analysed our data using new computer codes and the TEMPO package for analysing pulsar data. Here we present the results of periodic analysis of crab pulsar data observed between 2003 and 2005.

2. Pachmarhi Array of Cerenkov Telescopes (PACT)

Our data were collected with the PACT array[19] which consists of 25 Cherenkov telescopes arranged as 5$\times$5 matrix spread over an area of 80 m $\times$ 100 m. Each telescope consists of 7 parabolic F/1 mirrors of 90 cm diameter. Each mirror is viewed by a fast phototube (EMI 9807B) at its focus with 3° field of view aperture. The total reflector area of each telescope is 4.45 m^2. Each telescope is on an equatorial mount and is independently steerable ($\pm$45° in E-W and N-S directions) through remotely controlled by an automated telescope orientation system[20]. High voltages of individual phototubes are controlled through a computerized automated rate adjustment and monitoring system. The array is divided into 4 sectors of 6 telescopes each with independent data acquisition system for eah sector. The analog signals from 7 PMT's of a telescope are linearly added to form a telescope trigger pulse. A coincidence of any four telescope pulses initiate the data recording in each sector. A real time clock (RTC) synchronized with a GPS clock records the absolute arrival time (upto μs) of Cherenkov shower. Data regarding 'timing' and 'amplitude' (Charge) of PMT pulses are recorded for each event together with telescope information using a CAMAC based system operating under Gnu/Linux platform. Digital informations like the arrival time of photons at the telescopes, trigger status, event arrival times etc from all 4 stations are also recorded in the central control room.

3. Analysis

24 Telescopes were used for observations. The observations were usually carried out in a stretch first either ON-source and followed by OFF-source region or vice versa during same night. The OFF-source region is chosen to have the same declination as that of source but offset in RA such that same zenith angle range is covered for both ON-source and OFF-source runs. Typical run duration was about 1 to 3 hours. Data with all telescopes pointing zenith is used for calibration purposes. In the present analysis, only a part of data recorded in the central control room is used. Analysis of raw data was done to filter out data taken during bad nightsky conditions and instrument problems. After filtering, the data set reduced to total 24 runs corresponding to ON-source observation time of 50 hrs.

The radio position (J2000) of the Crab pulsar (RA=$05^h34^m31.972^s$ and DEC=$22^d00^m52.07^s$) was assumed for the timing analysis. For absolute phase calculation, reference phases and a 6 parameter polynomial fit to the phase are obtained using TEMPO codes (maintained by Princeton group) in prediction mode corresponding to HEGRO Pachmarhi site (Longitude=$78^d25^m10^s$East, Latitude=$22^d27^m40^s$North and Altitude=1075m) and using the contemporaneous pulsar elements. Reference phases are calculated over period of 3 hours centered with the transit time of the Crab pulsar at Pachmarhi observatory and for every 20 minute interval for every run. Using these data, the absolute phase of an event with arrival time T_i is obtained by interpolation as

$$\delta t = (T_i - T_o) * 1440 \tag{1}$$

$$\phi_i = \phi_o + \delta t * 60 * F0 + Coeff(1) + \delta t * Coeff(2) + \delta t^2 * Coeff(3) + ... \tag{2}$$

where ϕ_o is the reference phase at epoch T_o and F0 is the pulsar frequency.

Distribution of pulsar phases (Phasogram) is formed for each observation data and then added episodically. Pulsed emission of radiation is expected at phases corresponding to radio main and inter pulse. At high energies emission of radiation is also expected to occur within the phase range of radio main and interpulses. The phasogram is divided into 4 regions, as defined by the EGRET group[10], viz, First pulse corresponds to phase interval of 0.94 - 0.04, Inter-region : 0.04 - 0.32, Second pulse : 0.32 - 0.43 and Background : 0.43 - 0.94. The number of events in each phase region, normalised to unit phase interval are obtained and are summarised in the second column of table 1.

The relative time of arrival of Cherenkov photons is fitted to a plane shower front and the direction of arrival of shower is obtained for each event. Space angle (SPA) between the direction of arrival of shower and the source direction is also obtained for each event. Cuts are applied on the number of telescopes (ge 8) with valid 'timing' data as well as on the goodness of fit parameter, χ^2. This reduced the data set to half and the summary of Phasogram for these events is shown in column 3 in table 1. The subsequent columns in this table corresponds to events with space angle $\leq 4°$, $\leq 3°$, $\leq 2°$ respectively.

4. Results

Figure1 shows the phasogram of events from the direction of Crab Pulsar in 50 phase bins. This data corresponds to those shown in 3^{rd} column of table1. No significant excess of events over the background is seen in

Table 1. Summary of results

Parameter	**All data**	**All SPA**	**SPA1**	**SPA2**	**SPA3**
	uncut data	with cuts	≤4°	≤3°	≤2°
Total Events	511466	257964	222877	192742	132242
Duration(min)	2699.1	1571.8	1571.7	1571.4	1570.4
Main Pulse(P1)	50608	25816	22353	19361	13304
Inter-region	142766	71867	62123	53828	37069
Inter Pulse(P2)	51431	25881	22283	19268	13246
Background	266661	134400	116118	100285	68624
N_{ON}	102039	51697	44636	38629	25550
N_{OFF}	102356	51566	44560	38528	26423
P1/P2	1.02	1.00	1.00	1.00	1.00
Rate/min	-0.12±0.17	0.08±0.20	0.05±0.19	0.06±0.18	0.08±0.15
Significance(σ)	-0.70	0.40	0.25	0.36	0.55

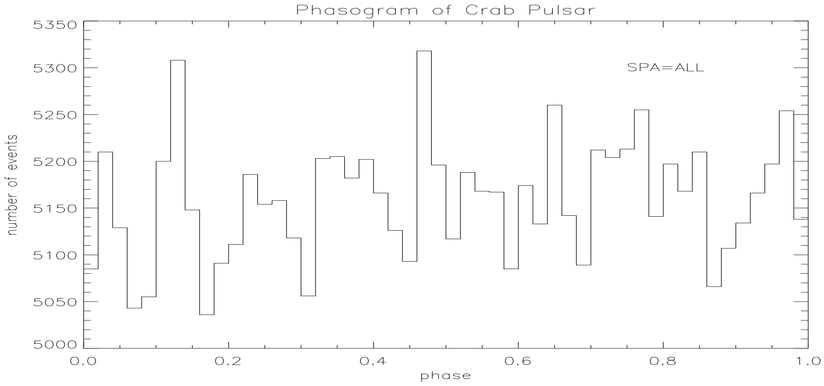

Figure 1. Phase plot for data shown in third column of Table 1

any phase bin. Events in the phase bins corresponding to first 3 phase regions (signal region, N_{ON}) is compared with those of the fourth phase region (Background, N_{OFF}) after normalisation of phase intervals and the significance (σ) of excess events over background is calculated. This significance is given in the last row of table1. Similarly, the significance of signal is calculated for each run and plotted in figure 2(a). A marginal improvement in the significance is seen for near axis events (events with short space angle). The ratio of main peak to inter peak (P1/P2) did not show any significant variation.

5. Conclusion

In our previous analysis[18] also we did not see any evidence for pulsed emission when all data was used. A 5.7 σ excess was seen only when events corresponding to primary energy of $>$ 1.6 TeV and with space angle $< 0^\circ.9$ were selected. In the present analysis, we did not see any significant evidence for pulsed emission from crab. Analysis of data with tighter cuts to select higher energy and near axis events are in progress. Also, analysis of 2000-2002 data and data recorded in individual sectors are going on.

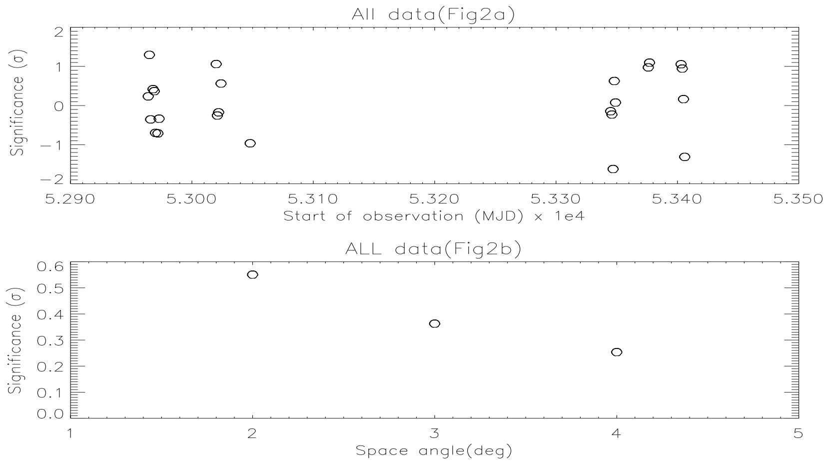

Figure 2. (a) Significance of 2003-2005 data and (b) significance vs maximum space angle

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