Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008

Vol. 2 (OG part 1), pages 671–674

30TH INTERNATIONAL COSMIC RAY CONFERENCE

On pulsed emission of TeV gamma rays from Crab Pulsar

B. S. ACHARYA[1], B. B. SINGH[1], D. BOSE[1], V. R. CHITNIS[1], P.R. VISHWANATH P.R.[2]
[1] *Tata Institute of Fundamental Research, Homi Bhabha Road, Colaba, Mumbai 400005*
[2]*Indian Institute of Astrophysics, Koramangala, Bangalore - 560 034*
acharya@tifr.res.in

Abstract: We have observed crab pulsar in the TeV energy band using the Pachmarhi Array of Cherenkov Telescopes (PACT) for about 90 hrs. Our observations span about 6 year period from 2000 to 2006. In the past we presented evidence of pulsed emission of TeV γ-rays from this source while few other groups did not see any evidence for pulsed emissions at these energies. We have re-analysed our data using new computer codes and the "Tempo" package. We have searched for evidence of pulsed emission of γ-rays from crab pulsar using the contemporaneous radio pulsar parameters. We do not see any evidence for the pulsed emission at a threshold energy of 825 GeV. We present our results on the light curve in the TeV energy band and set an upper limit on the time averaged flux of TeV γ-rays.

Introduction

The Crab pulsar is one of the most extensively studied object in all bands of electromagnetic spectrum. It was found to radiate at all wavelengths from radio to γ-rays with a period of 33.34 ms. It is the only known pulsar which has the same light curve at all energies. Pulsed γ-ray emissions from Crab pulsar has been detected up to 5 GeV by satellite-borne detectors [1]. The steep energy spectrum below 0.1 GeV is attributed to the tail end of the synchrotron radiation from the nebula. Beyond 0.1 GeV, the spectrum hardens and is dominated by pulsed emission. The phase-resolved spectrum indicate that the hardest emission come from the bridge region between the two γ-ray peaks [1].

Several groups have searched for the evidence of pulsed emission from Crab pulsar at TeV energies using the ground-based setups. Though, some earlier observations showed evidence [2, 3, 4] for transient or steady pulsed emissions, the recent observations [5, 6, 7, 8, 9] did not show any such evidence up to 80 TeV [10] but probably, an indication for the spectral cutoff below 60 GeV [11]. Thus, the details of origin of pulsed emission and the nature of energy spectrum of γ-rays from Crab pulsar at higher energy end are unknown. According to the models, *Polar Cap* [12] and *Outer Gap* [13] proposed for explaining the possible mechanism of pulsed emission at high energies, a sharp cutoff in the emission spectrum is expected at GeV - TeV energies. The detection of the cutoff energy is important to discriminate between models and understand the mechanism of high energy particle acceleration in pulsars.

We have re-analyzed our data using new analysis codes and TEMPO package for estimation of absolute phase. Here we present the results of periodic analysis of data on crab pulsar collected between 2000 and 2006.

PACT set up

Our observations were carried out using the Pachmarhi Array of Cherenkov Telescopes (PACT) [14] located at High Energy Gamma Ray Observatory, Pachmarhi ($78^d25^m10^s$E, $22^d27^m40^s$N and 1075 m above msl) in central India. It was setup to study VHE γ-rays from astronomical sources using the atmospheric Cherenkov technique and the wavefront sampling method. It consists of a 5×5 array of 25 non-imaging Cherenkov telescopes deployed over an area of $100\text{m}\times80\text{m}$. The total reflector area per telescope is 4.45 m^2. A fast Photo Multiplier Tube (PMT) of type EMI 9807B is mounted at the focus of each reflector behind a mask of diameter of 3 degree to limit the field of view.

The telescopes are independently steerable in both E-W and N-S directions up to to $\pm$40 degree. They are remotely controlled using an Automated computerized telescopes orientation system (ACTOS) [15]. The position angle of telescopes are monitored sequentially through out the observation, the cycle time is about 5 m. Corrections are applied in real time if any telescope is found to deviate from the desired position by more than $0^\circ.05$.

Individual PMT signals are brought to control room by low attenuation RG213 cables of length $40\ m$ and the information regarding pulse height, relative arrival time of shower front at the telescope, real time of the event, the triggered sector & telescopes etc. are recorded using a networked CAMAC based data acquisition systems. For each event, real time is recorded with a resolution of $1\ \mu s$ using 5 MHz Crystal oscillator which is synchronized with 1Hz GPS pulse. This 1 Hz GPS pulse is also used to reset the ms and μs counters. Using this array, the arrival time and density of Cherenkov photons at various telescopes are recorded.

Observations

The observations were carried out by pointing all telescopes in the same direction. Data on Crab pulsar were collected at a stretch, lasting for 1 to 3 hours, first either *ON-source* and followed by *OFF-source* region with equal exposure or vice versa during same night. The *OFF-source* region is chosen to have the same declination as that of *source* with an offset in Right Ascension such that same zenith angle range is covered for both *ON-source* and *OFF-source* runs. Only one set of observations (*ON-source* and *OFF-source*) were carried out on each clear moonless night most of the time. The total duration of Observations and the number of nights in which these observations were made for Crab are given in table 1. The night sky condition, rates of individual PMT's, the orientation of telescopes were monitored through out the observations.

Year	Time (m)	(# Runs)
2000	1308.9	13
2001	725.4	8
2003	963.3	8
2004	763.7	7
2005	1366.9	12
2006	234.0	2
Total	5362.2	50

Table 1: Observation Log of Crab Pulsar

Analysis of data

The relative time of arrival of Cherenkov photons is fitted to plane shower front and the direction of arrival of shower is reproduced for each event. The space angle (ψ) between the direction of arrival of shower and the source direction, is obtained for each event. For further periodicity analysis, only those events for which space angle is $\leq 2^\circ.5$ were used. Cuts are applied on the number of telescopes (NDF) with valid 'timing' data as well as on the goodness of fit parameter (χ^2) of the timing fit. A minimum of 8 telescopes are demanded (NDF$\geq$8) in each event and those events with (χ^2) $\geq \chi^2\ +\ 1\sigma$ are rejected.

Periodicity analysis

TEMPO codes (developed by Princeton group) were used for periodic analysis. In this, first observed arrival times (t_{obs}) of recorded events from solitary pulsar were converted to barycentric position (t_{ssb}). The corrected barycentric time(t_{ssb}) were folded at pulsar rotational frequency relevant to epoch (T_0) to get phase ϕ as

$$\begin{aligned}\phi(T) \quad &= \quad \phi(T_0) + f_0(T - T_0) + \\ &\frac{1}{2}\dot{f}(T - T_0)^2 + \frac{1}{6}\ddot{f}(T - T_0)^3 \quad (1)\end{aligned}$$

where $\phi(T_0)$ is the phase at epoch T_0 and is taken as reference phase.

The radio position (J2000) of the Crab pulsar and the parameters are used for the timing analysis. The monthly ephemerids data are extracted from

Table 2: Details of Phase analysis of Crab pulsar as a function of space angle ψ of events

Parameters	$\psi \leq 2^\circ.5$	$\psi \leq 1^\circ$
Total Events	289922	81931
Duration(min.)	5362.1	5362.1
Main Pulse(P1)	28953	8366
Inter-region	86649	24504
Inter Pulse(P2)	28987	8311
Background	145333	40750
N_{ON}	57940	16677
N_{OFF}	58133.2	16300.0
P2/P1	1.00	0.99
Rate±(rms)	-0.036±0.053	0.070±0.028
Significance(σ)	-0.68	2.48

Jodrell Bank CRABTIME data base[1]. Absolute phase of each event was obtained using TEMPO codes in prediction mode corresponding to PACT site using contemporaneous pulsar elements. In prediction or 'tz' mode, TEMPO calculates pulsar ephemerids over short period of time (typically hours) in the form of a simple polynomial expansion. Reference phases are calculated over period of ± 3 hours centered with the transit time of the pulsar at Pachmarhi observatory in steps of 20 minute. By using these polynomial coefficients and reference phase(Φ_o), absolute phase of an event at arrival time T is obtained by interpolation within the 20 m interval.

Results & Discussions

The distribution of pulsar phases (phasogram)is formed for each observation data with 20 phase bins and then added episodically. The phasogram of added data of *on-source (Crab)* region for $NDF \geq 8$ and is shown in figure 1 (panel (a) for space angle (ψ) $\leq 2^\circ.5$ and panel (b) for $\psi \leq 1^\circ$). The details are given in table 4.2. Similar analysis of data were also carried out on *off-source* (Background) events.

Pulsed emission of radiation is expected at phases corresponding to First (P1) and Second (P2) pulse regions. The phasogram is divided into 4-regions, following EGRET group [1] as follows: 0.95 - 0.05 for First pulse (P1), 0.35 - 0.45 for the second pulse, 0.05 - 0.35 for Inter-pulse region and 0.45-0.95 for background.

The number of events with phases within the P1 and P2 intervals constitute the number of ON pulsed events (N_{ON}). The background events(N_{OFF}) is obtained by number of events in the background region and normalized by multiplying the ratio of phase ranges spanned by the pulse and non-pulse regions [5]. The statistical significance (σ) of the excess count is calculated using equation

$$\sigma = \frac{(N_{ON} - c * N_{OFF})}{\sqrt{(N_{ON} + c^2 * N_{OFF})}} \qquad (2)$$

where c is the normalization constant. The statistical significance (σ) for pulsed emission as function of space angle is shown in figure 2. The significance tend to increases when near axis events are selected.

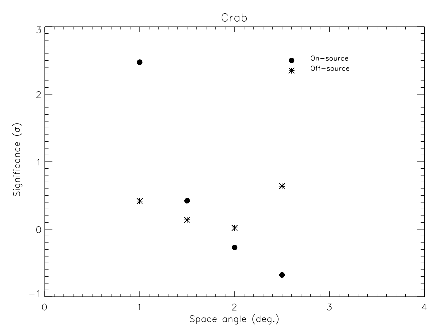

Figure 2: Significance as function of space angle

A χ^2 test for the possibility of the pulsar frequency modulation is conducted on the binned data. The χ^2 of each individual run data at different phase (20 bin) are calculated. These χ^2 are checked for main pulse(P1) and inter-pulse(P2) and compared with the background counts. The χ^2 per $doff$ at P1 and P2 phases are 1.22 and 1.06 respectively as compared to 0.92 at the 'background' phase region for $\psi \leq 1.0$. Similar test was done for crab background (*off-source*) data also. We observe that both distributions resemble uniform distribution with no phase bin showing significant deviations.

1. Andrew Lyne *et al.* at Jodrell Bank Observatory

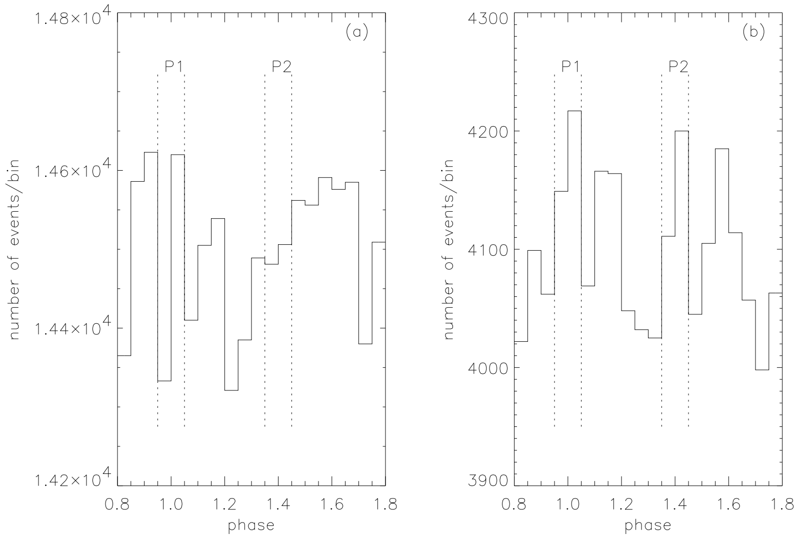

Figure 1: Phase histogram for Crab pulsar events (a) $\psi \leq 2^{\circ}.5$ and (b) $\psi \leq 1^{\circ}$

Conclusions

We have analyzed the Crab pulsar data collected using PACT. No significant evidence of pulsed emissions were seen in our data. We derive 3σ upper limits on integral flux. The flux limit has been calculated for the phase regions defined for P1 & P2 pulses. At very high energy, γ-ray excess flux observed from Crab pulsar is 2.48σ. We used collection area $1.45 \times 10^5 m^2$ for showers near zenith at $\sim\ 825\ GE$ threshold energy for estimation of integral flux at PACT threshold energy. The time averaged gamma ray flux upper limit (3σ UL) is obtained as $<\ 9.8 \times 10^{-13}\ \gamma cm^{-2}\ s$ which is consistent with other recent observations.

Acknowledgments

We thank to J.H.Taylor, R.N.Manchester, D.J.Nice, J.M.Weisberg, A.Irwin, N. Vex, A.G.Lyne and Yashwant Gupta for providing TEMPO code and clarification about pulsar data analysis. We are grateful to all members of High Energy gamma ray Observatory at Pachmarhi for their support in observation and maintenance of telescope system.

References

[1] J. M. Fierro, P. F. Michelson, P. L. Nolan, D. J. Thompson, , Ap J 494 (1998) 734.
[2] A. L. Gibson *et al.*, , Nature 296 (1982) 833.
[3] P. N. Bhat *et al.*, , Nature 319 (1986) 127.
[4] B. S. Acharya *et al.*, , A & A 258 (1992) 412.
[5] R. W. Lessard *et al.*, , Ap J. 531 (2000) 942.
[6] S. Oser *et al.*, , Ap J. 547 (2001) 949.
[7] J. Kildea *et al.*, , in: 29th ICRC, Vol. 4, 2005, p. 89.
[8] B. B. Singh *et al.*, , in: 29th ICRC, Vol. 4, 2005, p. 191.
[9] M. Lopez *et al.*, , in: 29th ICRC, Vol. 4, 2005, p. 243.
[10] F. Aharonian *et al.*, , Ap J 614 (2004) 897.
[11] M. d. Naurois *et al.*, , Ap J 566 (2002) 343.
[12] J. K. Daugherty, A. K. Harding, , Ap J 458 (1996) 278.
[13] K. Hirotani, S. Shibata, , Ap J 558 (2001) 216.
[14] P. N. Bhat, , in: High Energy Astronomy & Astrophysics, University Press (India) ltd., 1998, p. 370.
[15] K. S. Gothe *et al.*, , Indian Journal of Pure & Applied Physics 38 (2000) 269.