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Search for pulsed emission of TeV gamma rays from Geminga Pulsar

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Abstract: Pulsed emission of γ-rays from Geminga pulsar were detected at the period of $\sim 237\ ms$ by satelliet-borne detectors. However, there are conflicting reports about emission of γ-rays from this pulsar at Very High Energies. We have observed this source for about 56 hours during the year 2000 to 2006 using the PACT setup at a threshold energy of $\sim 850\ GeV$. This pulsar was found by Jackson *et al.* to undergo a minor glitch in late 1996. We have analysed our data by using post glitch pulsar elements and using the "TEMPO" computer code for calculating the pulsar phase for each event. We do not see any significant evidence of pulsed emission of γ-rays from this object. In this paper we describe our data, analysis procedure and the results.

Introduction

Geminga was discovered [1] in 1972 as source of γ-rays. It is a very bright γ-ray object in the COS-B catalog [2]. It remained as a mysterious object for almost a decade till the discovery of $\sim\ 237\ ms$ periodicity by ROSAT [3] and later by EGRET [4], in its radiation. Prior to this discovery of 237 ms spin period, claims had been made for various periods in the range 59-60 s but no such periodicity is seen in the recent high quality X/γ-ray observations [5]. Geminga has been identified [6] as a weak X-ray source. It is also a weak source in optical and radio bands. Like Crab and Vela pulsars, the pulse profile of Geminga pulsar too showed double peaked profile. The phase-resolved spectra show [7] that the hardest emission corresponds to the second γ-ray peak

Geminga Pulsar as source of very high energy γ-rays was confirmed by ground observations of [8, 9, 10] using atmospheric Cherenkov technique. However, Observations of Geminga pulsar by Whipple group [11] during 1989-1991 and HEGRA group [12] during 1996 did not show any evidence for pulsed emission contrary to the positive detections by other groups earlier. The detection of TeV γ-rays from pulsars are important in understanding towards high energy phenomenon connected to acceleration mechanism. Nel & De Jager have suggested that pulsed emission is not expected beyond 6-20 GeV from isolated radio pulsars [13]. This pulsar was noticed to undergo a minor glitch in frequency of $\Delta f/f = 6.2 \times 10^{-10}$ in late 1996. A phase-connected, post-glitch ephemeris were presented [5, 14] spanning the period 22 April 1991 to 13 March 2004 using data from X/γ-ray satellite detectors. The possible evidence [15] of pulsed emisson at energy $> 1.6\ TeV$ were presented from PACT data which were analysed with pre-glitch ephemeris [16] as we did not know about the glitch in Geminga pulsar. We have re-analysed our earlier data as well as added new data and searched for the evidence of pulsed emission of γ-rays using the contemporaneous post-glitch pulsar parameters [14] and new analysis codes & TEMPO package for estimation of absoute phase. Here, we present our results on periodicity analysis of data from Geminga pulsar.

PACT

Our observations were carried out using the Pachmarhi Array of Cherenkov Telescopes (PACT) 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 is 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 Cherenkov telescopes deployed over an area of 100m×80m in the form of rectangular matrix. The inter telescope separation is about 20 - 25 m. Each telescope consists of seven back-coated parabolic glass mirrors (thichness 6mm, 0.9 m focal length, f/d $\approx$ 1), mounted paraxially on an equitorial mount. 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 average reflectivity of these mirrors in visible range is $\leq$70%. The total reflector area per telescope is 4.45 m^2. Each telescope is independently steerable in both E-W and N-S directions upto to ±40 degree from zenith.

All telescopes are remotely controlled using an Automated computerzied telecopes orientation system (ACTOS)[17]. The system can orient the telescopes to a known source direction in the sky from an arbitrary intial position with an accuracy of 0.003±0.25 degree. The source pointing is monitored at an accuracy of 0.05 degree and corrected in real time.

PACT array[18] is divided into four sectors with six telescopes in each. The sector can operate as an independent unit and has its own Data acquisition (Daq) system. PMT pulses are brought by 40 m long low attenuation RG213 cables. A real time clock (based on 5 MHz crystal oscillator), synchronized to a 1 Hz pulse from GPS clock, is used for recording absolute time with a resolution of 1 μs.

Pulses from individual PMTs' of a telescopes are lineraly added to from a Telescope pulse. The trigger for data acquisition is obtained from a coincidence of any 4 out of 6 telescopes pulses. For each trigger informations regarding pulse height and arrival time of pulses from all PMTs of a sector are recoreded. A master control room at the centre of the array recorded the trigger informations from all sectors and informations relevant to entire array, such as arrival time of shower front at individual telescopes, absolute arrival time of the event.

Year	# observations (Runs)	Time (m)
2000	8	837.3
2001	3	99.3
2003	5	542.1
2004	6	701.1
2005	5	687.3
2006	5	517.9
Total	32	3384.9

Table 1: Observation Log of GEMINGA pulsar

Observations

The alignment of mirrors within a telescope and orientation/tracking of telescopes were monitored and calibrated periodically using bright stars. Cosmic-ray Data were collected with all telescopes stationary and pointing to zenith and known directions. All sectors were used in our observations spanning 6 years during 2000 to 2006. The observations were carried out in 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 with an offset in Right Ascension such that same zenith angle range is conered for both ON-source and OFF-source runs. Observation durations (minutes) and number of observations (runs) are given in 1.

Periodicity analysis

The relative time of arrival of Cherenkov photons is fitted to plane shower front and the direction of arrival of shower is obtained 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 events with space angle $\leq\ 2^{\circ}.5$ are used. Cuts are applied on the number of telescope (NDF) with valid 'timing' data as well as on the goodness of fit for the arrival direction parameter(χ^2).

The TEMPO code (developed by Princeton group) is used for periodicity analysis. The proceedure is similar to the one explained in [19]. Monthly pulsar ephemerides were extracted from Princeton GRO/Radio Timing Data base.

Table 2: Parameters of Geminga Pulsar

PSR	0633+1746
RA (2000)	$06^h33^m54^s.153$
DEC (2000)	$17^d46^m12^s.91$
PMRA (μ_α)	138 ± 4 mas/yr
PMDEC (μ_δ)	97 ± 4 mas/yr
PX	6.3694 mas/yr
Distance	157 pc

Absolute phase of each event was obtained using TEMPO codes in "prediction mode" corresponding to PACT site using the pulsar parameters shown in table 2. In prediction or 'tz' mode, reference phases are calculated over period of 3 hours centered with the transit time of Geminga pulsar at Pachmarhi observatory in steps of 20 minute interval for each night data. By using TEMPO polynomial coeifficents and reference phase(Φ_o), absolute phase of an event at arrivial time T is obtained by interpolations.

The Geminga pulsar was observed for a total of 56.4 hours between December 2000 and 2006 Feburary. The J2000 co-ordinates of Geminga pulsar and other parameters shown in table 2 were used for the timing analysis.

The post glitch ephmeries [14] were used and the Phasograms for each night's data were constructed with 20 phase bins. The light curve of Geminga pulsar and summary of phasogram data are shown in figure 1 and table 3 respectively.

Parametrs	$\psi \leq 2^\circ.5$	$\psi \leq 1^\circ$
Total Events	264057	82738
Duration(min.)	3384.9	3384.9
Main Pulse(P1)	52775	16820
Inter-region	79013	25049
Inter Pulse(P2)	53085	16440
Background	79184	24429
N_{ON}	105860	33260
N_{OFF}	105578.7	32572.0
P2/P1	1.01	0.98
Rate±(rms)	0.083±0.147	0.203±0.082
Significance(σ)	0.57	2.48

Table 3: Details of Phase analysis of Geminga

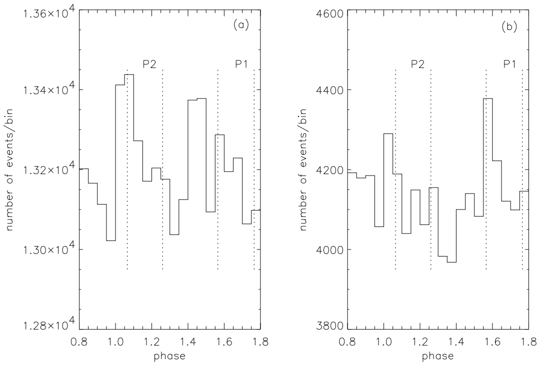

Figure 1: Phase histogram of Geminga pulsar events for **(a)** Space angle $\leq 2^\circ.5$ and **(b)** Space angle $\leq 1^\circ$

Results and Discussion

Pulsed emission of radiation is expected at phases 0.55 - 0.75 and 0.05 - 0.25 corresponding to First (P1) and Second (P2) pulse regions. The Inter-pulse region is defined as 0.75 - 0.05. The phase region 0.25 - 0.55 is expected not contain any signal and hence used as *background* region. 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* phase region and normalized by multiplying the ratio of ranges spanned by the pulse and non-pulse phase regions [20]. The statistical significance (σ) of the excess count is calculated using equation

$$\sigma = \frac{(N_{ON} - c * N_{OFF})}{\sqrt{(N_{ON} + c^2 * N_{OFF})}} \tag{1}$$

where c is the normalization constant. The significance (σ) as function of space angle is shown in 2. The significance increases when near axis events are selected.

A statistical analysis of the light curve is carried out for the possibility of rotational frequecy modulation. In every run and for each of 20 phase bin, χ^2 is calculated for the deviation of observed num-

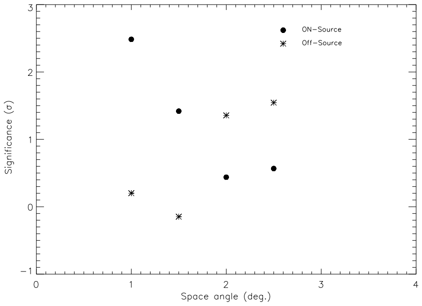

Figure 2: Siginificance as function of space angle for Geminga pulsar

ber of events in that phase bin from the expected number of events as obtained from the background phase region. The χ^2 corresponding to the same phase bins of all runs are added. The reduced χ^2 for phase bins corresponding to P1, P2 and *background* regions are 1.44, 0.63, 1.04 for source and 0.65, 0.44, 0.57 for off-source data (for $\psi \leq 1^\circ$).

Conclusions

We have re-analysed the data on Geminga pulsar collected using PACT. No significant evidence for pulsed emission was found in our data. The 3σ upper limits on integral flux have been derived. The upper limits have been calculated for the phase regions defined according to EGRET peak regions. At very high energy, excess flux of pulsed γ-rays observed from Geminga pulsar is at a low significance level of 2.48σ. Using $1.45 \times 10^5 m^2$ for collection area we estimate the time averaged upper limit (3σ C.L.) for pulsed flux of γ-rays at a threshold energy of $825\ GeV$ as $< 28.3 \times 10^{-13} photon/cm^2/sec$.

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