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# Search for pulsed multi-TeV gamma rays from the Crab pulsar using the Tibet-III air shower array

THE TIBET AS$\gamma$ COLLABORATION

**Abstract:** We searched for pulsed gamma-ray emissions from the Crab pulsar using data of the Tibet-III air shower array from November 1999 through November 2005. No evidence for the pulsed emissions was found in our analysis. Upper limits at different energies were calculated for a $3\sigma$ confidence level in the energy range of multi-TeV to several hundred TeV.

## Introduction

The Crab Nebula is one of the most studied objects and is the most energetic source at GeV - TeV energies. The energy source of that activity is known to be a pulsar in the nebula. The rotation period of the Crab pulsar is 33 ms, as inferred from radio, light, and X-ray observations. Pulsed emission with that rotation period has been detected by EGRET on board CGRO [1] at GeV energies, although several observers have reported no evidence of pulsed emissions of greater than 10 GeV energy [2, 3, 4, 5, 6].

The emission models of high-energy pulsed gamma rays are mostly the polar cap [7] and the outer gap [8] models. Their models predict a sharp cutoff of the energy spectrum because of the limitation of particle acceleration. The expected cutoff energy depends on many parameters of each model. Those parameters would be determined by observations. Herein, we present the results of a search for pulsed gamma rays from the Crab pulsar at energies of 2 TeV to 200 TeV using a Tibet-III air shower array.

## Experiment

The Tibet-III air shower array used in this experiment was constructed in 1999 at Yangbajing (4300 m a.s.l.) in Tibet. The array, corresponding to the inner part of the full-scale Tibet-III air shower array, consists of 533 scintillation counters covering 22 050 m$^2$ [9, 10]. The mode energy of detected events is about 3 TeV for proton-induced showers and the angular resolution is 0.9°. The systematic error of the energy determination of primary particles and systematic pointing error of the array were well calibrated by comparing the observed displacement of the moon shadow because of the geomagnetic field with the Monte Carlo simulation, as described in a previous paper [11].

We observed steady excess events from the Crab Nebula during November 1999 through November 2005. These events were selected by imposing the following conditions: 1) each shower must fire four or more counters recording 1.25 or more particles; 2) all fired counters or eight of nine fired counters which recorded the highest particle density must be inside the fiducial area; and 3) the zenith angle of the arrival direction must be less than $40°$. After these selections, the events were examined for further analyses.

## Data Analysis

The data analyzed here were chosen for events coming from a window around the direction of the Crab pulsar. The search window radius is expressed as $6.9/(\sum \rho_{FT})^{1/2}$ (degree), where $\sum \rho_{FT}$ is the sum of the number of particles m$^2$ for each scintillation counter with a fast-timing (FT)

PMT. The function was optimized to maximize the $S/\sqrt{N}$ ratio using MC simulation [9].

The arrival time of each event is recorded using a quartz clock synchronized with GPS, which has a precision of 1 $\mu$s. For the timing analysis, all arrival times are converted to the solar system barycenter frame using the JPL DE200 ephemeris [12].

The Crab pulsar ephemeris is calculated using the Jordrell Bank Crab Pulsar Monthly Ephemeris [13, 14]. The corrected arrival time of each event is calculated to a rotated phase of the Crab pulsar, which takes account of the derivative $\dot{P}$ of the period $P$ month by month.

## Results

Figure 1 shows the distribution of events for each phase in two rotational periods of the Crab pulsar. The distribution is compatible with a flat distribution ($\chi^2/d.o.f. = 0.95$). That is, no significantly pulsed signal was found in observations with mode energy of $\sim$ 3 TeV. The phase analysis is performed on seven intervals of $\sum \rho_{FT}$, as shown in Fig. 2 to examine the energy dependence. Table 1 shows the statistical results of the applied $Z_2^2$ test [15] and $H$ test [16], as well as the $\chi^2$ test.

Almost all statistical test results show that the phase distributions are uniform within a 3 $\sigma$ significance level. We have estimated the $3\sigma$ flux upper limit of the pulsed emission from the Crab pulsar using the $H$ test [16] as

$$\begin{aligned} x_{3\sigma} &= (1.5 + 10.7\delta)(0.174H)^{0.17+0.14\delta} \\ &\times \exp\{(0.08 + 0.14\delta) \\ &\times (\log_{10}(0.174H))^2\}, \end{aligned}$$

where $\delta$ is the duty cycle of the pulse component, assuming the $\delta$ for the Crab pulsar is 21%. Exposure from the Crab pulsar for the Tibet-III experiment is estimated using MC simulation. The upper limit is compared to previous results inferred from results of other experiments, as shown in Fig. 3.

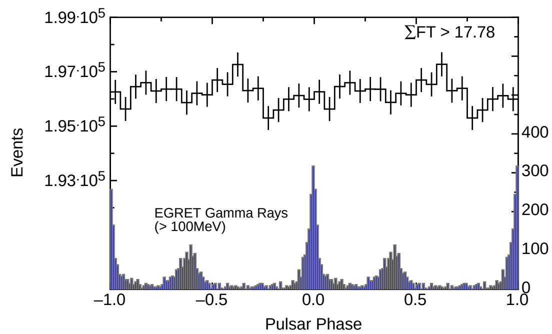


Figure 1: Distribution of the event phase of the Crab pulsar. Phase 0 is defined using the timing solution derived from the main pulse of the radio observations. The upper plot shows our result for $\sum \rho_{FT} > 17.78$. The lower plot shows the $\gamma$-ray phase histogram above 100 MeV, as measured using EGRET [1].

## Conclusions

During the period from November 1999 to November 2005, we searched for pulsed gamma-ray emissions synchronized with the rotational period provided from the radio observation of the Crab pulsar. No evidence for the pulsed emission was obtained through our analyses. The upper limits at different energies were calculated for a $3\sigma$ confidence level. These results are inconclusive in relation to the polar cap and outer gap model. We will report additional detailed analyses and discussion in the near future.

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Table 1: Results of statistical tests for pulsed emission. $\chi^2$-, $Z_2^2$- and $H$-test (probabilities) are calculated for a flat phase distribution.

| $\sum \rho_{FT}$ | Energy (TeV) | $\chi^2/d.o.f.$ | $Z_2^2$ | $H$ |
|---|---|---|---|---|
| 17.78 – 31.62 | 2.1 | 0.97 (0.49) | 9.62 (0.047) | 9.62 (0.021) |
| 31.62 – 56.23 | 3.6 | 1.21 (0.24) | 7.64 (0.11) | 7.64 (0.047) |
| 56.23 – 100.00 | 5.7 | 0.81(0.70) | 2.54 (0.64) | 4.49 (0.17) |
| 100.00 – 215.44 | 9.3 | 0.35 (0.96) | 2.30 (0.68) | 6.14 (0.086) |
| 215.44 – 464.16 | 20.4 | 1.41 (0.11) | 9.68 (0.046) | 14.56 (0.0030) |
| 464.16 – 1000.0 | 51.7 | 0.80 (0.71) | 3.67 (0.45) | 6.09 (0.088) |
| $>$ 1000.0 | 122.7 | 0.60 (0.91) | 1.11 (0.89) | 4.48 (0.17) |
| $>$ 17.78 | $>$ 2.1 | 0.95 (0.52) | 8.41 (0.078) | 8.87 (0.029) |

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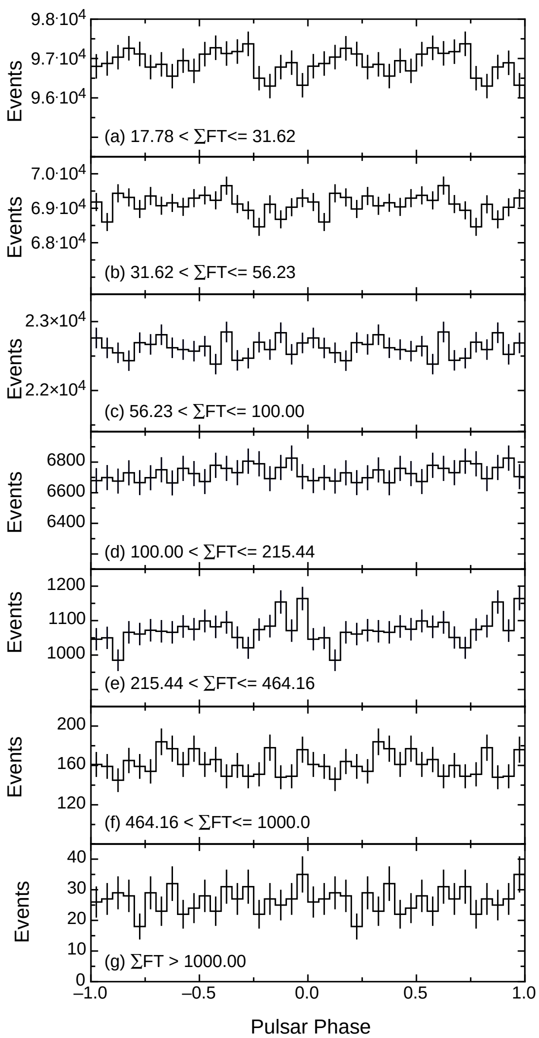


Figure 2: Distributions of the event phase of the Crab pulsar. Each plot shows a histogram for every $\sum \rho_{FT}$ range, which is the equivalent of the energy region, as shown in Table 1.

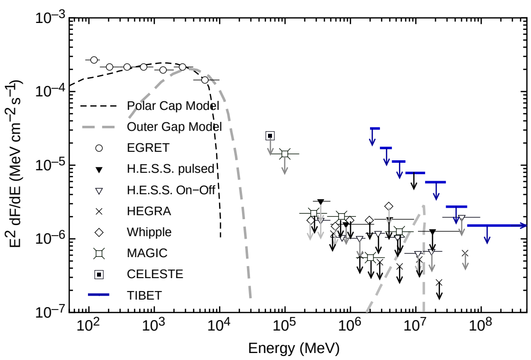


Figure 3: Upper limits on the pulsed gamma ray flux from the Crab pulsar.