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Detection of Multi-TeV Gamma Rays from the Crab Nebula with the Tibet Air Shower Array

The Tibet ASγ Collaboration

M. Amenomori[1], S. Ayabe[2], P.Y. Cao[3], Danzengluobu[4], L.K. Ding[5], Z.Y. Feng[6], Y. Fu[3], H.W. Guo[4], M. He[3], K. Hibino[7], N. Hotta[8], Q. Huang[6], A.X. Huo[5], K. Izu[9], H.Y. Jia[6], F. Kajino[10], K. Kasahara[11], Y. Katayose[9], Labaciren[4], J.Y. Li[3], H. Lu[5], S.L. Lu[5], G.X. Luo[5], X.R. Meng[4], K. Mizutani[2], J. Mu[12], H. Nanjo[1], M. Nishizawa[13], M. Ohnishi[9], I. Ohta[8], T. Ouchi[7], J.R. Ren[5], T. Saito[14], M. Sakata[10], T. Sasaki[10], Z.Z. Shi[5], M. Shibata[15], A. Shiomi[9], T. Shirai[7], H. Sugimoto[16], K. Taira[16], Y.H. Tan[5], N. Tateyama[7], S. Torii[7], T. Utsugi[2], C.R. Wang[3], H. Wang[4], H.Y. Wang[5], P.X. Wang[12], X.M. Xu[5], Y. Yamamoto[10], G.C. Yu[6], A.F. Yuan[4], T. Yuda[9], C.S. Zhang[5], H.M. Zhang[5], J.L. Zhang[5], N.J. Zhang[3], X.Y. Zhang[3], Zhaxisangzhu[4], Zhaxiciren[4] and W.D. Zhou[12]

[1] *Department of Physics, Hirosaki University, Hirosaki, Japan*
[2] *Department of Physics, Saitama University, Urawa, Japan*
[3] *Department of Physics, Shangdong University, Jinan, China*
[4] *Department of Mathematics and Physics, Tibet University, Lhasa, China*
[5] *Institute of High Energy Physics, Academia Sinica, Beijing, China*
[6] *Department of Physics, South West Jiaotong University, Chengdu, China*
[7] *Faculty of Engineering, Kanagawa University, Yokohama, Japan*
[8] *Faculty of Education, Utsunomiya University, Utsunomiya, Japan*
[9] *Institute for Cosmic Ray Research, University of Tokyo, Tanashi, Japan*
[10] *Department of Physics, Konan University, Kobe, Japan*
[11] *Faculty of Systems Engineering, Shibaura Institute of Technology, Omiya, Japan*
[12] *Department of Physics, Yunnan University, Kunming, China*
[13] *National Center for Science Information Systems, Tokyo, Japan*
[14] *Tokyo Metropolitan College of Aeronautical Engineering, Tokyo, Japan*
[15] *Faculty of Engineering, Yokohama National University, Yokohama, Japan*
[16] *Shonan Institute of Technology, Fujisawa, Japan*

ABSTRACT

Multi-TeV γ-rays from the Crab Nebula were detected at the 5.3 σ level with the high density air shower array operating at Yangbajing in Tibet since 1996. Using the data obtained from this array, we obtained the energy spectrum of gamma rays from the Crab Nebula between 3 TeV and 10 TeV. This is the first detection of γ-ray signals from point sources with ordinary air shower array.

1. Introduction

The Crab Nebula has been well studied with atmospheric Cherenkov telescopes (ACT) and been established as a standard source in the TeV astronomy, since the first detection of TeV γ-rays by the Whipple collaboration in 1989 [1]. The observed spectra so far reported [2] seem to extend up to at least several 10 TeV and to be consistent with a Synchrotron-Self Compton (SSI) model based on the pulsar wind model of plerions [3]. In this model, electrons are accelerated up to ultra-high energy (UHE), say 10^{15} - 10^{16} eV, in the pulsar wind shock, emitting soft photons by synchrotron process. Inverse-Compton (IC) scattering of these accelerated electrons with soft photons, including infrared radiation from dust and the 2.7K microwave background, would produce detectable fluxes in the multi-TeV energy region. It has been shown that the absolute fluxes of IC γ-rays appear to be very sensitive to the strength of the magnetic field in the nebula while its shape is rather stable to the basic parameters of the nebula. The IC gamma ray spectrum, however, will steepen at high energies, say higher than 10 TeV since UHE electrons rapidly dissipate their energy by the synchrotron radiation. So, the contribution of π^0-decay γ-rays will take up a subject for discussion at high energies [4]. If the protons are accelerated up to very high energies with a hard spectrum in the nebula, its contribution would become significant at multi-TeV, or even dominating in the energy region higher than several 10 TeV. Thus, the γ-ray spectrum from the Crab Nebula in the high energy region may provide vital information about the proton acceleration in SNRs being the most promising sources of cosmic rays in our galaxy.

Until now, using ACTs, several groups have succeeded to detect the Crab with very high significances in the TeV energy region, but the systematic uncertainties in the flux estimates remain large and then the spectrum, measured by several groups, differs in power-law slope as well as in absolute flux. A further observation of the spectrum up to high energy with a detector using well-established air-shower technique will be strongly required to clarify the production mechanism of high energy γ-rays in the Crab Nebula.

2. Experiment

The Tibet experiment, being successfully operating at Yangbajing in Tibet (4300 above sea level), now consists of two overlapping arrays (Tibet-II and HD) as described elsewhere [4]. The Tibet-II array consists of 221 scintillation counters of 0.5 m^2 each placed on a 15 square grid with an enclosed area of 36,900 m^2, and the HD (high density) array is operating inside the Tibet-II array to detect cosmic ray showers lower than 10 TeV (some of detectors are commonly used in both arrays). This HD array consists of 109 scintillation counters, each viewed by a fast timing phototube, placed on a 7.5 m square grid, covering an area of 5,175 m^2. The performance of the HD array is described elsewhere [5]. The threshold energy of showers induced by protons to be detected is about 8 TeV for the Tibet-II array and about 3 TeV for the HD array, respectively. In the following the results obtained from the HD array are mainly presented.

3. Analysis

The HD array has been operating since 1996 November at a rate of about 110 Hz under any 4-fold coincidence in the detectors. The data used in this search were collected between 1996 November and 1998 June. The event selection was done by imposing the following three conditions to the recorded data; 1) Each of any four FT detectors should record a signal more than 1.25 particles. 2) Among the four detectors recording the highest particles, two or more should be within the detector area [5]. 3) The zenith angle of the incident direction should be less than 45°. After data processing and quality cuts, the total number of events selected was 1.23×10^9, and the effective running time was 358.9 days.

The vast majority of events detected by the array are initiated by cosmic rays coming from the universe. Since the background cosmic rays are isotropic and gamma rays from a source are apparently centered on the source direction, a bin size for collecting on-source data should be determined based on the array's angular resolution so as to optimize the signal to noise ratio.

The angular resolution of the Tibet array can be well examined by observing the shadow that the Moon casts in the cosmic rays. Also, a high counting of cosmic ray events enables us to monitor the system operation by a monthly observation of the Moon's shadow. Using the HD array, the Moon's shadow was observed with the significance of 15σ at the maximum deficit position for all events. From this result, the angular resolution of the HD array is estimated to be 0.9° for all events. The resolution increases with increasing $\sum\rho$ as $0.8^\circ \times (\sum\rho/20)^{-0.3}$ $(15 < \sum\rho < 300)$. The systematic pointing error of the array is estimated to be smaller than 0.1°.

4. Results and Discussions

We use a circular search bin whose size is based on the estimated angular resolution of the experiment. The window size is chosen to maximize the ratio $N_s/N_B^{1/2}$, where N_S is the number of signals and N_B the number of background events, and to contain about 50% of the signals from source. The angular resolution of the array depends on the value of $\sum\rho$ in an event. We use the following search bin sizes, i.e. 0.8° radius for showers with $\sum\rho \geq 15$, 0.7° radius for showers with $\sum\rho \geq 50$ and 0.5° radius for showers with $\sum\rho \geq 100$. The signals were searched for by counting the number of events coming from the ON-source window. The background was obtained by averaging over events falling in the ten OFF-source windows adjacent to the source. The source window traverses a path in local coordinates (θ,ϕ) through the day, where θ is the zenith angle and ϕ the azimuthal angle. In order to avoid the strong zenith angle dependence on the background, the OFF-source windows were taken in the ϕ-directions for each θ.

Figure 1 shows the excess events around the Crab direction for all events with $\sum \rho \geq 15$. The statistical significance of the excess is calculated to be 5.3 σ. Figures 2 show the opening angle distributions for the events of $\sum \rho \geq 15$, 30, 40 and 100, respectively. Here, the opening angle (ψ) is defined as a space angle between the source direction and the event direction. The ψ peak appearing around the origin in the source direction can be attributed to γ-rays from the Crab Nebula. The statistical significances of the excess events with $\sum \rho \geq 15$, 30, 40 and 100 are 5.3 σ, 4.9 σ, 2.8 σ and 2.2 σ, respectively.

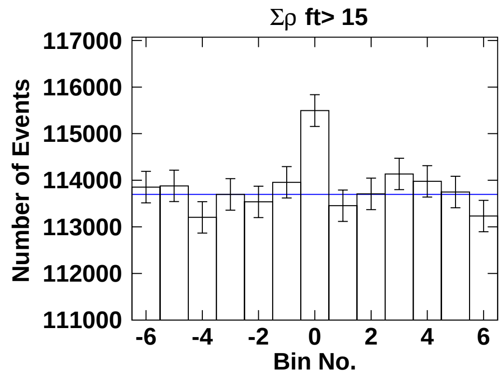

Fig. 1: Distribution of the events with $\sum \rho \geq 15$ around the Crab direction (center).

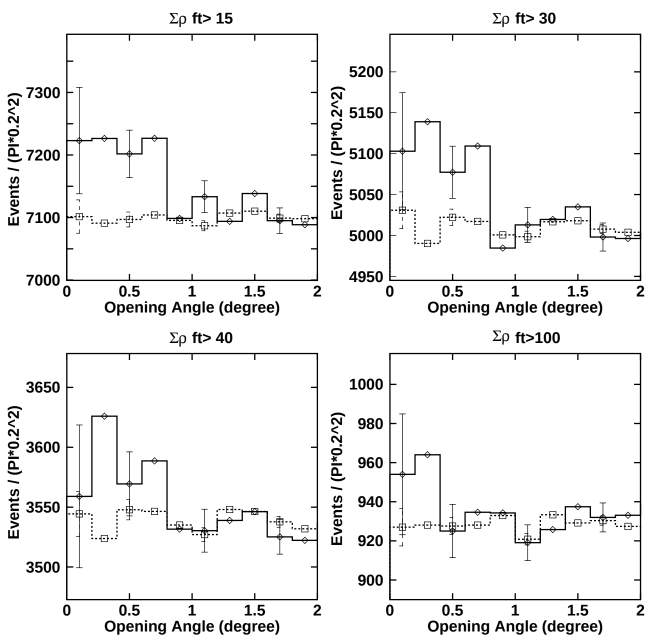

Fig. 2: Distributions of the opening angles relative to the Crab direction ψ, for the events with $\sum \rho \geq$ 15,30, 40 and 100, respectively. Solid and dashed lines show ON- and OFF-source data, respectively.

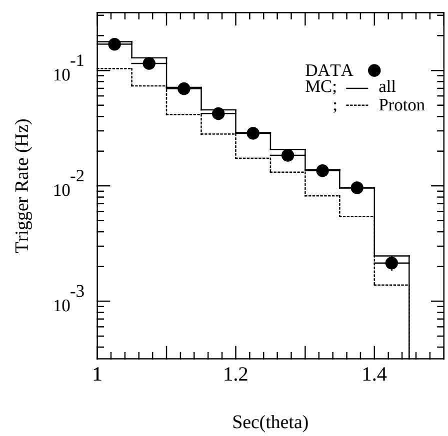

Fig. 3: Zenith angle dependence of the trigger rate under any four fold coincidence in the detectors. Each of any four detectors records a signal more than 1.25 particles. Simulation results are compared with the data. Solid and dashed lines show all primary particles and primary protons, respectively.

In order to derive the gamma-ray spectrum from the Crab Nebula, the trigger efficiency, collecting area as a function of energy and threshold energy of the array were examined by using a Monte Carlo simulation [6]. First, we examined whether the background events are explained by cosmic rays coming from the universe or not. Adopting the primary cosmic ray spectrum obtained by the experiments [7], we calculated the trigger rate of background events by a Monte Carlo simulation, taking into account the detector response and observation conditions. Shown in Fig.3 is the zenith angle distribution of the trigger rate of the events with $\sum \rho \geq 15$. We used the events coming from the band of 2° width along the zenith angle changing from 0° to 45°. The experimental data show a good agreement with the calculation. The simulation also teaches us that the fraction of protons is about 60 %, while this fraction increases with increasing zenith angle when $\sum \rho$ is larger than 50.

We estimated the γ-ray spectrum as follows. The primary γ-rays were generated between E_{min} and E_{max} from the direction of the Crab, assuming a differential power-law spectrum of the form $E^{-(\beta+1)}$ starting at $E_{min} = 0.5$ TeV, which is below the lowest triggering energy. The values of β and E_{max} were examined between 1.4 and 1.7 and between 30 TeV and 50 TeV, respectively. These γ-rays, developed into cascade showers (air showers) in the atmosphere, were detected with the array under the same condition as the experiment. The simulated events were observed for respective $\sum \rho$ value to compare with the experimental results. The energy of gamma rays is defined as the energy of the maximum flux of simulated events for each $\sum \rho$ value. These steps were repeated until the simulation can well reproduce the experiment data. The resultant differential spectrum between 3 TeV and 10 TeV is shown in Fig.4 together with other experiments. In this analysis, we took into account the statistical errors only since the systematic errors are not completely estimated yet.

We also searched for γ-ray emission from the Crab Nebula in the energy region higher than 10 TeV with the Tibet-II array. No significant excess was found in this data set, while the improvement of angular resolution is still under way. Upper limit of the flux at the 2σ confidence level is plotted at 30 TeV in Fig. 4.

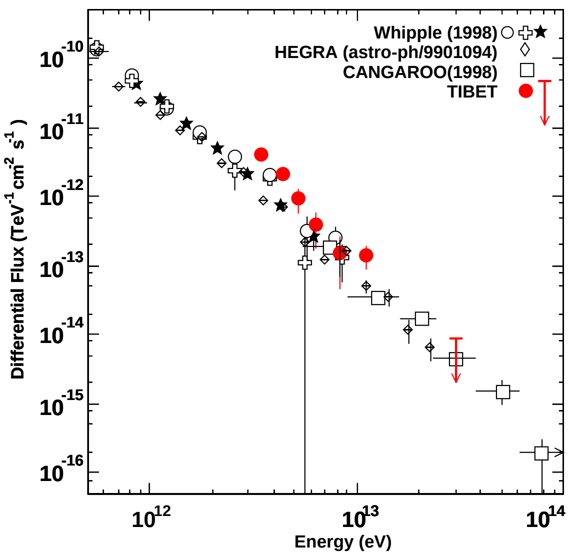

Fig. 4: Differential spectra of the present result in comparison with those of results from the CANGAROO [2] and Whipple [8]. Upper limits of the flux at greater than 10 TeV are at the 2σ confidence level.

5. Summary

With the high density (HD) air shower array, operating at Yangbajing since 1996, we succeeded to detect multi-TeV gamma rays from the Crab Nebula and obtained the energy spectrum of γ-rays between 3 TeV and 10 TeV. This is the first observation of gamma-ray signals from point source with ordinary air shower array. The area of the present HD array will be extended by a factor of about five, while its effective area will be increased by a factor of about seven. So, this array could cover the energy range from 3 TeV to several 10 TeV with sufficient statistics in the very near future.

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