ICRC 2001

Multi-TeV gamma-ray emission from the Crab Nebula observed with the new Tibet-III air-shower array

The Tibet ASγ Collaboration

M. Amenomori[1], S. Ayabe[2], S.W. Cui[3], L.K. Ding[3], X.Y. Ding[4], C.F. Feng[5], Z.Y. Feng[6], Y. Fu[5], X.Y. Gao[7], Q.X. Geng[7], H.W. Guo[4], M. He[5], K. Hibino[8], N. Hotta[9], J. Huang[9], Q. Huang[6], A.X. Huo[3], K. Izu[10], H.Y. Jia[6], F. Kajino[11], K. Kasahara[12], Y. Katayose[13], K. Kawata[11], Labaciren[4], G.M. Le[14], J.Y. Li[5], H. Lu[3], S.L. Lu[3], G.X. Luo[3], X.R. Meng[4], K. Mizutani[2], J. Mu[7], H. Nanjo[1], M. Nishizawa[15], M. Ohnishi[10], I. Ohta[9], T. Ouchi[10], S. Ozawa[9], J.R. Ren[3], T. Saito[16], M. Sakata[11], T. Sasaki[8], M. Shibata[13], A. Shiomi[10], T. Shirai[8], H. Sugimoto[17], K. Taira[17], M. Takita[10], Y.H. Tan[3], N. Tateyama[8], S. Torii[8], H. Tsuchiya[10], S. Udo[2], T. Utsugi[2], C.R. Wang[5], H. Wang[3], X. Wang[5], X.W. Xu[3,10], L. Xue[5], X.C. Yang[7], Y. Yamamoto[11], Z.H. Ye[14], G.C. Yu[6], A.F. Yuan[4], T. Yuda[18], H.M. Zhang[3], J.L. Zhang[3], N.J. Zhang[5], X.Y. Zhang[5], Zhaxiciren[4], and Zhaxisangzhu[4]

[1]Department of Physics, Hirosaki University, Hirosaki, Japan
[2]Department of Physics, Saitama University, Saitama, Japan
[3]Laboratory of Cosmic Ray and High Energy Astrophysics, Institute of High Energy Physics, CAS, Beijing, China
[4]Department of Mathematics and Physics, Tibet University, Lhasa, China
[5]Department of Physics, Shangdong University, Jinan, China
[6]Institute of Modern Physics, South West Jiaotong University, Chengdu, China
[7]Department of Physics, Yunnan University, Kunming, China
[8]Faculty of Engineering, Kanagawa University, Yokohama, Japan
[9]Faculty of Education, Utsunomiya University, Utsunomiya, Japan
[10]Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Japan
[11]Department of Physics, Konan University, Kobe, Japan
[12]Faculty of Systems Engineering, Shibaura Institute of Technology, Saitama, Japan
[13]Department of Physics, Yokohama National University, Yokohama, Japan
[14]Center of Space Science and Application Research, CAS, Beijing, China
[15]National Institute for Informatics, Tokyo, Japan
[16]Tokyo Metropolitan College of Aeronautical Engineering, Tokyo, Japan
[17]Shonan Institute of Technology, Fujisawa, Japan
[18]Solar-Terrestrial Environment Laboratory, Nagoya University, Nagoya Japan

Abstract. Using a high density air-shower array (Tibet-HD array), we succeeded in detecting multi-TeV γ-ray signals from the Crab Nebula in 1999. In the late fall of 1999, the HD array was enlarged from 5175 m^2 up to 22000 m^2 (Tibet-III array). Using the 316 live-day data taken between 1999 November and 2001 May with this enlarged new array, we studied the emission of TeV γ-rays from the Crab Nebula. A preliminary analysis gives the excess γ-ray signal at the statistical significance of 4.8 σ. The energy spectrum of γ-rays observed is consistent with the previous observation. We report the result on the study of the Crab flux.

1 Introduction

The Crab Nebula has been well studied with atmospheric Čerenkov telescopes (ACTs) and has been established as a standard source in TeV γ-ray astronomy. The Crab was the first TeV source detected at high significance with the advent of imaging ACTs (Weekes et al., 1989). The observed spectra so far reported (Ong, 1998) seem to extend up to at least several 10 TeV and seem to be consistent with a synchrotron self inverse Compton model based on the pulsar wind acceleration model (de Jager & Hading, 1992). In this model, it is likely that electrons are accelerated to ultra-high energies extending up to 10^{15} eV in the pulsar wind shock (Gaisser, Harding and Stanev, 1989), emitting soft photons by a synchrotron process. The emission of TeV energies from the Crab Nebula can then be explained as the inverse Compton (IC) scattering of such relativistic electrons with soft photons, including infrared radiation from dust and 2.7 K microwave background. The IC γ-ray spectrum depends on a parameter, which is defined as the ratio of magnetic field to the particle energy density in the wind, and thus on the magnetic field distribution in the nebula.

Non-thermal radiation from the Crab Nebula is observed over the multi-wave lengths, i.e., radio waves, X-rays, GeV and TeV energy region γ-rays. A precise observation of γ-ray energy spectrum in TeV region will teach us some information of source distribution and source spectrum of rela-

Correspondence to: A.Shiomi (shiomi@icrr.u-tokyo.ac.jp)

tivistic electrons, global magnetic field distribution and seed photon distribution for the inverse Compton process in the nebula.

The Tibet experiment (Amenomori et al., 1992), at an altitude of 4300 m, is the lowest energy air shower array and is sensitive to γ-ray air showers at energies as low as 3 TeV (Amenomori et al., 1997). Thus, observations by the Tibet experiment using well-established air shower techniques partially overlap those of Čerenkov telescopes and will make a contribution to study the emission mechanism of high-energy γ-rays from the Crab.

With the HD air shower array operated at Yangbajing between 1996 and 1999, we observed multi-TeV γ-rays from the Crab Nebula and obtained the energy spectrum of γ-rays in the energy region above 3 TeV (Amenomori et al., 1999). This is the first clear observation of γ-ray signals from point sources using a conventional air shower array. The success of the air shower array in detecting a signal at the 5.5 σ level was achieved by the improvement of the array performance, which can be directly checked by observing the Moon shadow. We have shown that the HD array had the sensitivity to detect cosmic-ray showers at energies as low as $>$ 3 TeV, as well as to observe the Moon shadow with good statistics. A monthly observation of the Moon shadow had made it possible to monitor the angular resolution, pointing accuracy, and also the stable operation of the array over a long period.

The geometrical area of the HD array was extended by a factor of about 5 in the late fall of 1999. One of the most important improvements is that the MC simulation code is changed from GENAS to Cosmos (air-shower simulator) and Epics (detector response). We report a very preliminary result on the observation of multi-TeV γ-rays from the Crab with the new Tibet air shower array, Tibet-III, based on the newly developed a full simulation code.

2 Experiment

The 22000 m^2 Tibet-III array, consisting of 533 scintillation counters which are placed at a lattice with 7.5 m spacing, has been operating with energy range around 3 TeV since 1999 at Yangbajing in Tibet, China ($90.53°$E, $30.11°$N) at an altitude of 4,300 m above sea level, an atmospheric depth of 606 g/cm^2 (Amenomori et al., 2001a). Each counter has an area of 0.5 m^2, and a 3 cm thick plastic scintillator and a 2 inch-diameter PMTs are equipped.

The mode energy of triggered air showers by the Tibet-III array is about 3 TeV, covering the upper part of the energies by the atmospheric Čerenkov technique. The event rate is about 680 Hz, satisfying the triggering condition of any 4-fold coincidence of $>$ 0.8 particles within 300 ns gate width.

The long term stability of the detector angular resolution as well as of the cosmic-ray event rate ($< \pm 5\%$ instability without atmospheric pressure correction) is demonstrated elsewhere (Amenomori et al., 2001b).

3 Tibet-III performance for γ-ray from the Crab

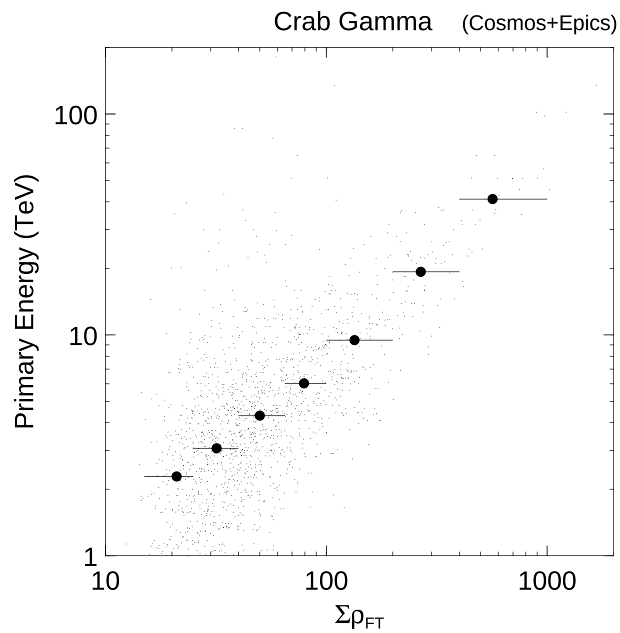

Fig. 1. Correlation between the air-shower size $\sum \rho_{\mathrm{FT}}$ and primary γ-ray energy. Primary γ-rays with a differential power index of -2.6 are thrown from the Crab orbit.

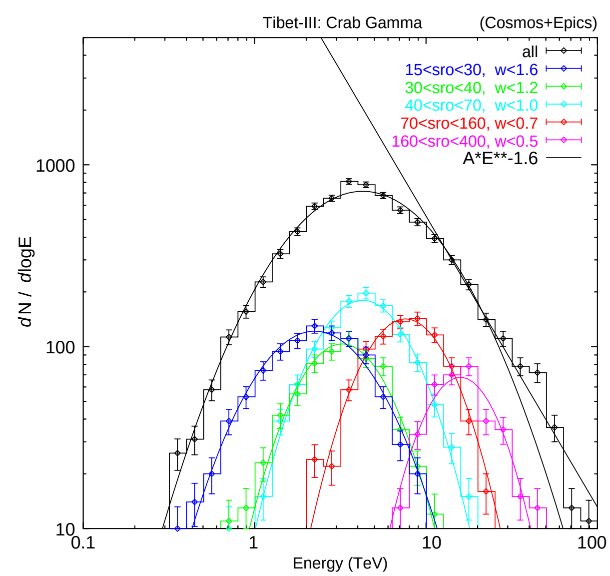

Fig. 2. Energy spectrum of γ-rays in each size interval of $\sum \rho_{\mathrm{FT}}$. Primary γ-rays are same as in Fig. 1 and the observation is assumed to be done with the Tibet-III array.

The vast majority of events detected by the array are initiated by primary cosmic rays rather than γ-rays, and therefore it is crucial to reject as much background as possible. The background cosmic rays are isotropic and γ-rays from a

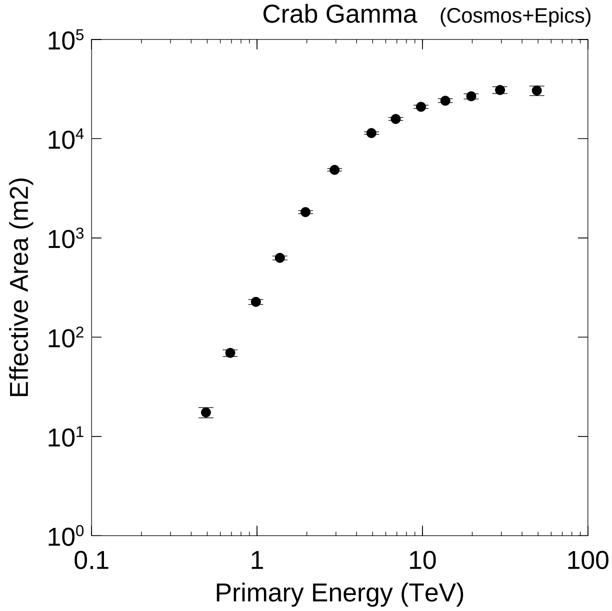

Fig. 3. Effective area of the Tibet-III array for detecting γ-rays from the Crab as a function of primary γ-ray energy, calculated by a Monte Carlo simulation. Primary γ-rays are same as in Fig. 1.

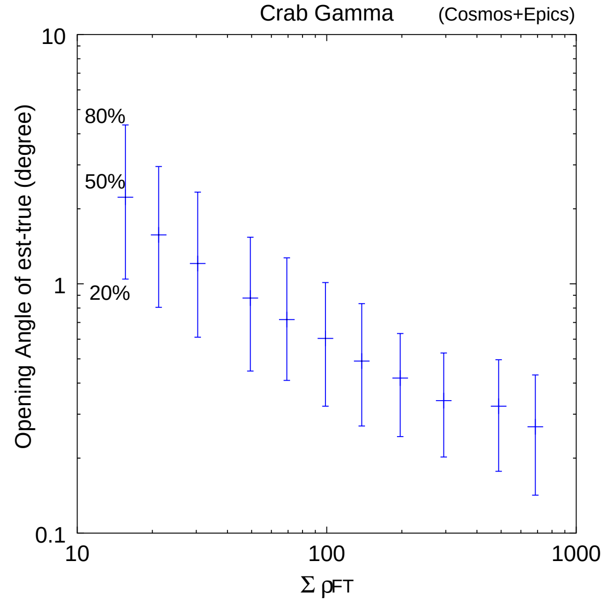

Fig. 4. Angular resolution of the Tibet-III array. Primary γ-rays are same as in Fig. 1.

source are apparently centered at the source direction, so that the reduction of hadronic showers must be accomplished via the good angular resolution of the array.

Performance of Tibet III Array is studied by a Monte Carlo simulation based on Cosmos uv5.65 (Kasahara, 1995).and Epics uv6.60 (Kasahara, 2001). Using this full MC simulation code, the detector performance for γ-rays from the Crab Nebula is studied.

We assume a differential power law spectrum with spectral index -2.6 for the γ-rays from the Crab above 0.3 TeV, taking into account the Crab orbit. The correlation between our energy scale $\sum \rho_{\rm FT}$ and primary γ-ray energy from the Crab is demonstrated in Fig. 1, which is projected on the primary energy axis in Fig. 2 to see the one-event energy resolution ($\sim$ 100 % at 3 TeV) for each $\sum \rho_{\rm FT}$ bin, where $\rho_{\rm FT}$ is the number of particles per m^2 observed in each detector and the summation is taken for all fired detectors. The primary γ-ray energy is estimated based on Fig. 2. Figure 3 and 4 show the effective area and the angular resolution, respectively, for the γ-rays from the Crab, where the effective area is defined to be the geometrical area efficiency. The MC simulation reproduced the absolute event rate by cosmic rays and the pointing accuracy and the energy dependent angular resolution measured by the Moon shadow in cosmic rays (Amenomori et al., 2001a).

4 Analysis

The data used in this search were collected between 1999 November and 2001 May. The event selection was done by imposing the following three conditions on the recorded data; 1) Each of any four FT detectors should record a signal more than 1.25 particles. 2) Estimated core location should be inside of the array. 3) The zenith angle of the incident direction should be less than 40°. After data processing and quality cuts, the total number of events selected was 3.9×10^9, and the effective running time was 316.3 days.

The vast majority of events detected by Tibet-III are initiated by cosmic rays. Since the background cosmic rays are isotropic and γ-rays from a source are apparently centered on the source direction, a proper angular window for extracting the γ-ray signal so as to optimize the signal to noise ratio data should be set, based on a MC study of the array's energy-dependent angular resolution.

The angular resolution of the Tibet-III depends on the value of $\sum \rho_{\rm FT}$ in an event. In this analysis, we use the following circular angular window; 1.6°, 1.2°, 1.0°, 0.7°, 0.5° for $15 < \sum \rho_{\rm FT} \le 30$, $30 < \sum \rho_{\rm FT} \le 40$, $40 < \sum \rho_{\rm FT} \le 70$, $70 < \sum \rho_{\rm FT} \le 160$, $160 < \sum \rho_{\rm FT} \le 400$, respectively. The angular windows contain approximately 50 % of γ-ray events form the Crab.

The background is estimated by number of events averaged over 6 to 12 off-source cells with the same angular radius as on-source, at the same zenith angle, recorded at the same time intervals as the on-source cell events.

5 Results and Discussions

The statistical significance of TeV γ-ray signal from the Crab is calculated using the excess events $(N_{\rm ON} - N_{\rm OFF})/\sqrt{N_{\rm OFF}}$, where $N_{\rm ON}$ and $N_{\rm OFF}$ are the number of events within the on-source cell and the average number events in the off-source

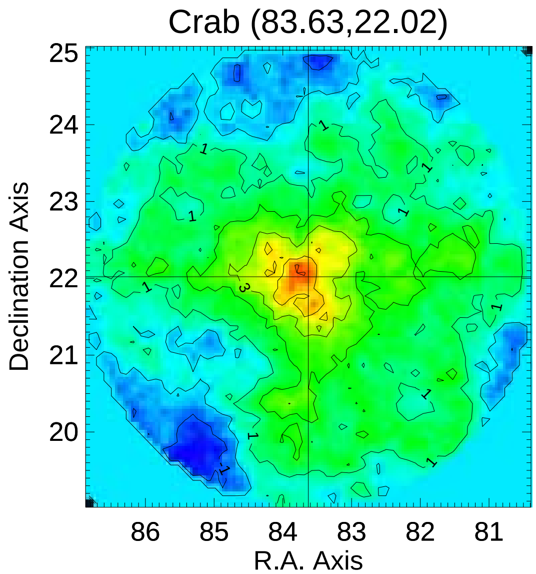

Fig. 5. Contour map of the weight of excess event densities around Crab Nebula. A clear peak is seen at the center, i.e., in the Crab direction.

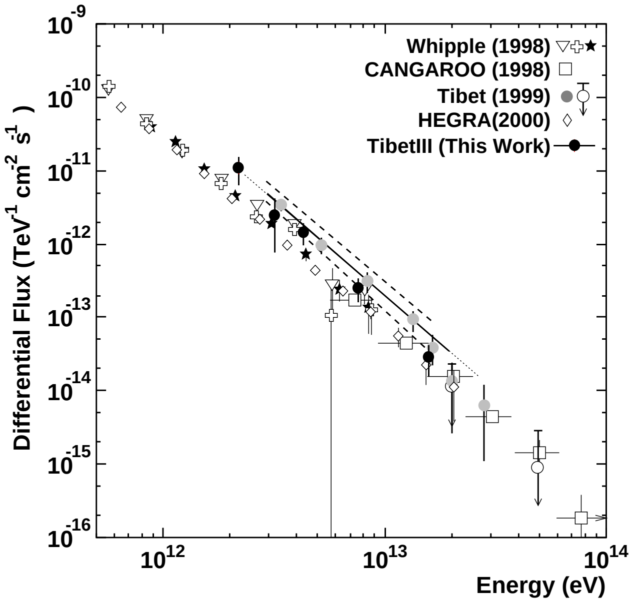

Fig. 6. Differential γ-ray flux from the Crab Nebula with Tibet-III (316 days) and HD (Amenomori et al., 1999), together with other experiments; Whipple (Hillas et.al., 1998), CANGAROO (Tanimori et al., 1998), and HEGRA (Aharonian et al., 2000)

cells, respectively.

The excess events for 316.3 live day are plotted on the equatorial coordinates as shown in Fig. 5, to demonstrate that a clear peak is observed in the the Crab direction. Using the number of excess events of each $\sum \rho_{\mathrm{FT}}$ bin from the Crab, detector live-time, calculated effective area, and correlation (Fig. 2) between $\sum \rho_{\mathrm{FT}}$ and primary γ-ray energy, the differential γ-ray flux is calculated as shown in Fig. 6.

While the present analysis is still preliminary, the observed spectrum is consistent with the Tibet-HD result. Various systematic errors in the Tibet-III array is now under extensive study.

6 Summary

With the Tibet-III air shower array, operating at Yangbajing since 1999, we succeeded to detect multi-TeV γ-rays from the Crab. We analysed the data set obtained for 316.3 observation days during the period from 1999 through 2001, and observed the excess events coming from the Crab direction. The statistical significance of the excess events is calculated to be 4.8 σ and the observed energy spectrum between 3 TeV and 10 TeV is consistent with the previous observation. This detector sensitivity will be more increased by a fine turning of the array.

The Tibet-III array is still in the middle of its construction, and the effective area of high density part becomes 36900 m^2 in the fall of 2002. Further observations of the Crab with the Tibet-III array could well establish the energy spectrum of γ-rays up to $\sim$ 100 TeV.

Acknowledgements. This work is supported in part by Grants-in-Aid for Scientific Research and also for International Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology in Japan and the Committee of the Natural Science Foundation and the Academy of Sciences in China.

References

Aharonian, F. A., et al. 2000, *Astrophys. J.*, **539**, 317
Amenomori, M., et. al. 1992, *Phys. Rev. Lett.*, **69**, 2468
Amenomori, M., et. al. 1997, *25th ICRC*, **5**, 245
Amenomori, M., et. al. 1999, *Astrophys. J.*, **525**, L93
Amenomori, M., et al. 2001a, Talk given by M. Ohnishi at ICRC 2001, will be published in the proceedings.
Amenomori, M., et al. 2001b, Talk given by K. Kawata at ICRC 2001, will be published in the proceedings.
de Jager, O. C., Harding A. K. 1992, *Astrophys. J.*, **396**, 161
Gaisser, T. K., Harding, A. K. and Stanev, T. 1989, *Astrophys. J.*, **345**, 423
Hillas, A. M., et. al. 1998, *Astrophys. J.*, **503**, 744
Kasahara, K. 1995, *24th ICRC*, **1**, 339 http://eweb.b6.kanagawa-u.ac.jp/ ˜kasahara/ResearchHome/cosmosHome/index.html
Kasahara, K. 2001, http://eweb.b6.kanagawa-u.ac.jp/ ˜kasahara/ResearchHome/EPICSHome/index.html
Ong, R. A. 1998, *Phys. Rep.*, **305**, 93
Tanimori, T., et al. 1998, *Astrophys. J.*, **492**, L33
Weeks, T. C., et al. 1989, *Astrophys. J.*, **342**, 379