Detection of gamma-rays above 10 TeV from Markarian 421 in a high state with the CANGAROO-II telescope

K. Okumura[1*], R. Enomoto[1], A. Asahara[2], G.V. Bicknell[3], P.G. Edwards[4], S. Gunji[5], S. Hara[6], T. Hara[7], S. Hayashi[8], C. Itoh[9], S. Kabuki[1], F. Kajino[8], H. Katagiri[1], J. Kataoka[6], A. Kawachi[1], T. Kifune[10], H. Kubo[2], J. Kushida[6], S. Maeda[8], A. Maeshiro[8], Y. Matsubara[11], Y. Mizumoto[12], M. Mori[1], M. Moriya[6], H. Muraishi[13], Y. Muraki[11], T. Naito[7], T. Nakase[14], K. Nishijima[14], M. Ohishi[1], J.R. Patterson[15], K. Sakurazawa[6], R. Suzuki[1], D.L. Swaby[15], K. Takano[6], T. Takano[5], T. Tanimori[2], F. Tokanai[5], K. Tsuchiya[1], H. Tsunoo[1], K. Uruma[14], A. Watanabe[5], S. Yanagita[9], T. Yoshida[9], T. Yoshikoshi[16]

[1]Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, 277-8582 Chiba, Japan
[2]Department of Physics, Kyoto University, Sakyo-ku, Kyoto 606-8502, Japan
[3]MSSSO, Australian National University, ACT 2611, Australia
[4]Institute of Space and Astronautical Science, Sagamihara, Kanagawa 229 -8510, Japan
[5]Department of Physics, Yamagata University, Yamagata, Yamagata 990-8560, Japan
[6]Department of Physics, Tokyo Institute of Technology, Meguro-ku, Tokyo 152-8551, Japan
[7]Faculty of Management Information, Yamanashi Gakuin University, Kofu,Yamanashi 400-8575, Japan
[8]Department of Physics, Konan University, Kobe, Hyogo 658-8501, Japan
[9]Faculty of Science, Ibaraki University, Mito, Ibaraki 310-8512, Japan
[10]Faculty of Engineering, Shinshu University, Nagano, Nagano 380-8553, Japan
[11]STE Laboratory, Nagoya University, Nagoya, Aichi 464-8601, Japan
[12]National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan
[13]Ibaraki Prefectural University, Ami, Ibaraki 300-0394, Japan
[14]Department of Physics, Tokai University, Hiratsuka, Kanagawa 259-1292, Japan
[15]Department of Physics and Math. Physics, University of Adelaide, SA 5005, Australia
[16]Department of Physics, Osaka City University, Osaka, Osaka 558-8585, Japan
*Correspondence to : okumura@icrr.u-tokyo.ac.jp

Abstract

The observation result of Markarian 421 with CANGAROO-II 10 meter telescope is presented. CANGAROO-II telescope is a ground-based Čerenkov gamma-ray detector located at Woomera, Austrailia. We have observed Markarian 421 for ten nights during its high state in year 2001. The observation was carried out in a direction of very large zenith angle technique about 70 degree. The energy threshold is estimated to be around 10 TeV from the Monte Carlo simulation study. As a result, 250 $\pm$ 37 events (6.8σ) are detected for 14 hours livetime. The nightly count rate and energy spectral distribution are derived.

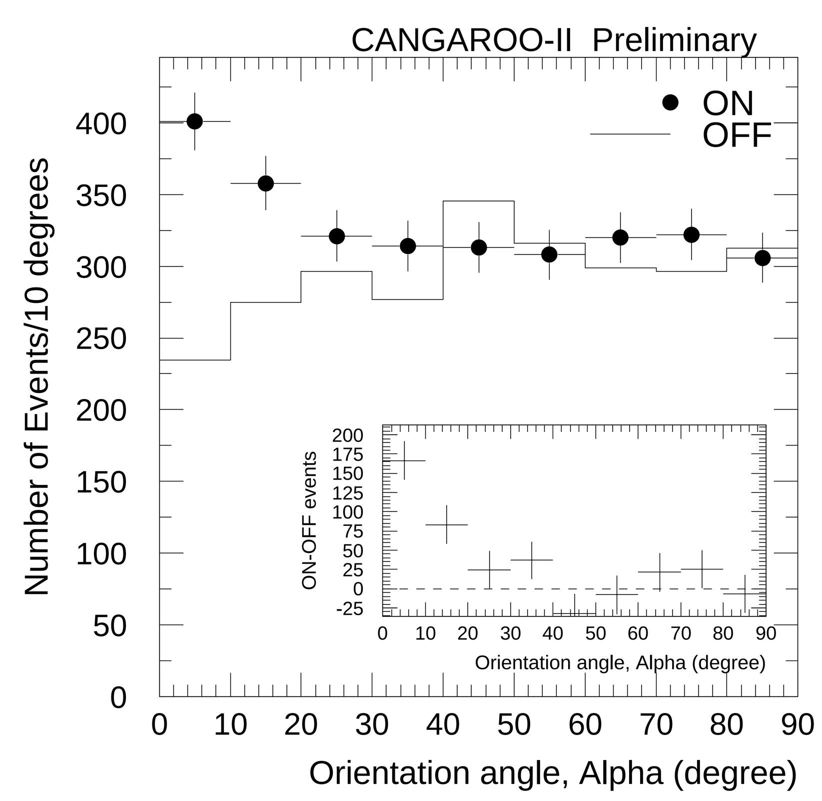

Figure 1: Image Orientation angle "Alpha" distribution of Markarian 421 observed by CANGAROO-II 10 meter telescope. Dots with error bars are ON source data and the solid line is for the OFF source data. 250 $\pm$ 37 execss events within 20 degree of Alpha is detected with 6.8 σ significance level.

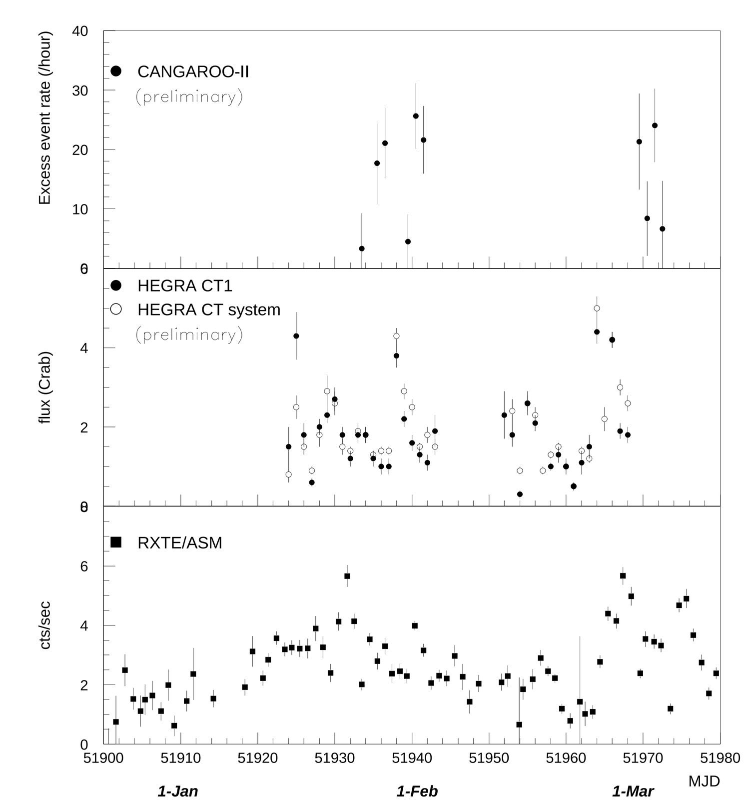

Figure 2: Nightly count rate of gamma-rays measured by CANGAROO-II telescope. Mkn 421 was observed for ten nights totally. Lightcurve measured by HEGRA [13] and RXTE/ASM [14] are shown for comparison.

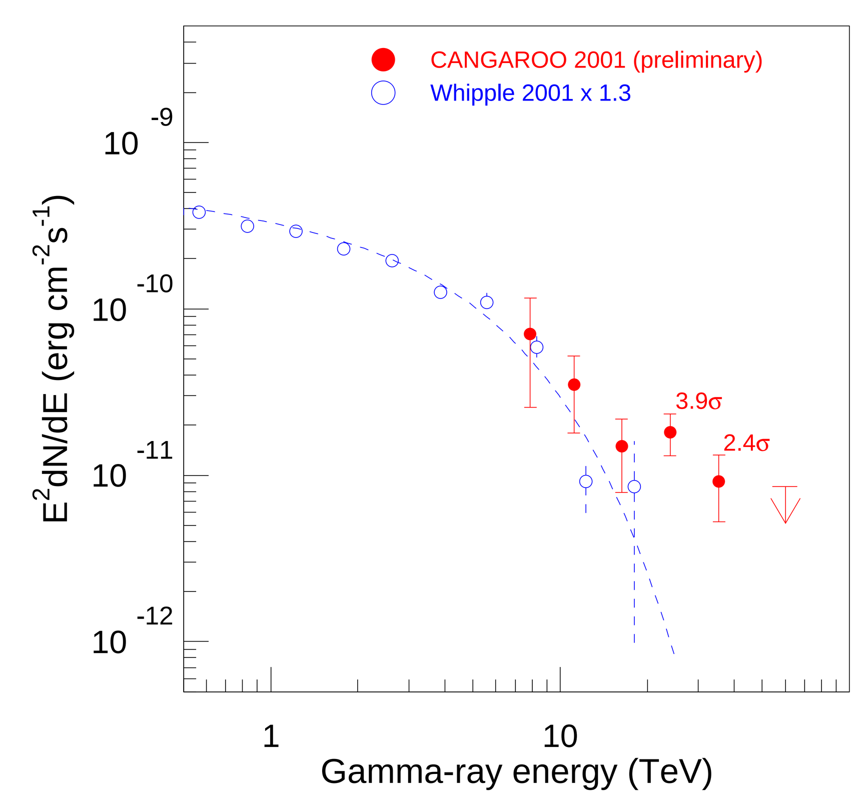

Figure 3: The spectral energy distribution of 2001 Mkn 421 observed by CANGAROO-II telescope. The confidence level of upperlimit is 2 σ. The cutoff energy spectrum measured by Whipple group [6], which absolute flux is increased by 30 % to compare our spectral shape.

1 Introduction

Markarian 421 (Mkn 421, z=0.031) was the first extra-galactic source from which TeV gamma-ray emission was detected [8]. Extensive measurements of the gamma-ray flux in the TeV energy region have been carried out by several groups using the ground-based imaging Cerenkov telescope[5, 1, 7]. The energy spectrum up to 10 TeV has been measured and is consistent with a power law of a spectral index of $-2.5\sim3.0$.

However, it is generally believed that TeV gamma-rays from extragalactic sources will suffer from the absorption due to photon-photon collisions with inter-galactic infrared radiation. At present, no apparent energy cutoff due to this absorption has been detected in the Mkn 421 spectrum. In order to determine meaningful constraints on this expected cutoff, it is important to measure the precise energy spectrum or extend measurements of the spectrum to energies above 10 TeV. We have aimed at detecting the highest energy spectrum of Mkn 421 around 10 TeV using large zenith angle technique.

2 Observation of Mkn 421 by CANGAROO-II telescope in 2001

- Observation period
  The observation was carried out using CANGAROO-II 10 meter telescope. Six nights from January 24th to February 1st, and four nights from March 1st to 4th in 2001. The observation date and period are summaried in Table 1. Totalling 14 hours for ON-source are used for this analysis.

- Source activity
  The observation was carried out during the period of high activity in TeV and X-ray energy region, as seen in Figure 2.

- Very large zenith angle (VLZA) Observation
  The elevation angle of Mkn 421 in culmination is very low at site of CANGAROO-II telescope (20.7 degrees), therefore observation was carried out in a direction of very large zenith angle (VLZA) around 70 degrees. For analysis, only data which elevation angle above 18.5 degrees is selected.

Date	MJD start	obs. time (hr.)
24-Jan-2001	51933.7041	1.1
26-Jan-2001	51935.7052	1.2
27-Jan-2001	51936.7050	1.6
30-Jan-2001	51939.6737	2.1
31-Jan-2001	51940.6737	2.1
1-Feb-2001	51941.6777	1.9
1-Mar-2001	51969.6381	0.9
2-Mar-2001	51970.6346	1.2
3-Mar-2001	51971.6144	1.6
4-Mar-2001	51972.6549	0.7

Tabel 1: Date, modified Julian day and effective observation hours for Markarian 421 observations.

3 Simulation study for VLZA observation mode

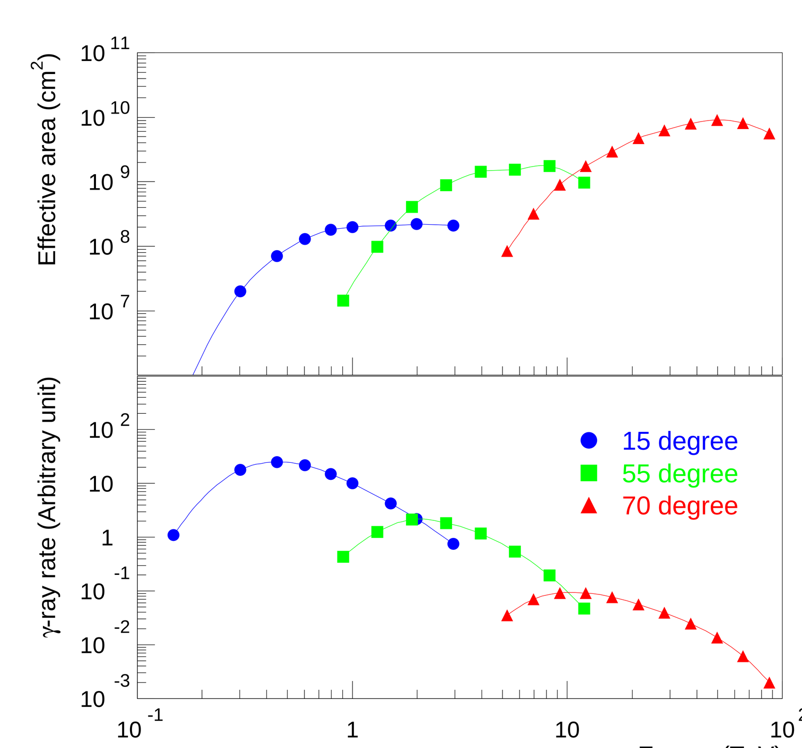

Figure 4: The effective area and relative event rate for different zenith angle observation, 15 degrees, 55 degrees and 70 degrees. Energy spectrum is assumed to be $E^{-2.5}$.

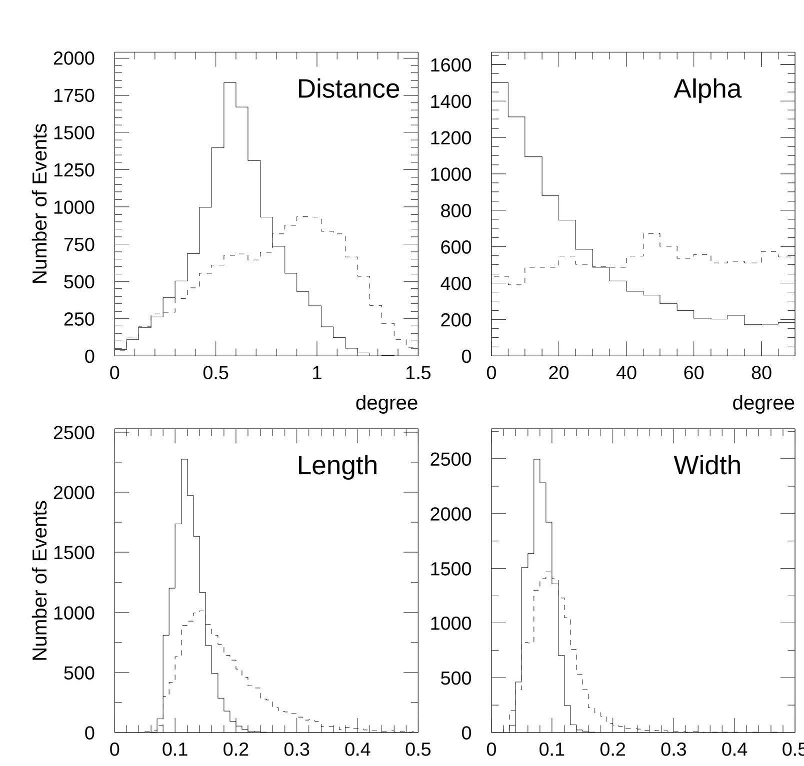

Figure 5: The Imaging parameter distributions obtained from gamma-ray simulations and OFF source events.

The performance of VLZA observation is verified by Monte Carlo simulation. The gamma-ray events are generated in the energy range of $3\sim100$ TeV with the assumed spectrum of $E^{-3.0}$. The elevation angle of each event is adjusted according to the distribution of selected data. The energy threshold is defined where the event rate becomes maximal and estimated to be around 10 TeV. The averaged effective area above this energy threshold is calculated to be 5×10^9 cm^2. It increases to 10^{10} cm^2 as the gamma-ray energy increases. From these figure, the VLZA observation is effective to measure the energies above 10 TeV. The resolution of the pointing angle, "Alpha", decreases due to the shrinkage of the shower image.

4 Analysis procedure

- Image cleaning
  Pixels which exceeds more than 3.3 photoelectron and lies within 30 nanoseconds are selected. Additionaly those which neighbor pixels are more than 3 hits are required.

- Likelihood analysis
  The selection of the gamma-ray events is based on the standard imaging analysis parameters; "Width", "Length", "Distance" and "Alpha" [4]. The Likelihood method [2] is adopted for the selection of gamma-ray events, instead of the conventional parameterization method. The discrimination of gamma-ray events is based on the probability ratio R_{prob}, expressed as follows :

$$R_{prob} = \frac{Prob(\gamma)}{Prob(\gamma) + Prob(B.G.)}$$

  where $Prob(\gamma)$ and $Prob(B.G.)$ are calculated probabilities of image shape parameters for gamma-ray and background events, respectively. These are the products of individual probabilities for "Width", "Length" and "Distance". Energy dependence is taken into account in these probability functions. We adopted a cut of 0.56, as the signal-to-noise (S/N) ratio was maximized at this value from the simulation study.

- Energy determination
  The energy of gamma-ray event is calculated based on the sum of discriminated ADC value after image cleaning precedure, correted by the observed elevation angle and "distance" parameter. As a result, $25\sim30$ % of energy resolution is obtained in the measured energy range.

5 Result and discussion

Figure 1 shows the "Alpha" distribution of selected events. The events less than 20 degrees in "Alpha" are taken as the gamma-ray signal and the excess events after subtraction of the background is 250 $\pm$ 37 events (6.8 σ). The broader alpha acceptance is due to the shrinkage of the shower images as predicted from gamma-ray simulations in VLZA observation mode.

Figure 2 shows the nightly count rate of the gamma-rays. We have observed Mkn 421 for ten night. The count rate is extensively variable night by night. This figure shows that the observation period is during the high activity of the source.

Figure 3 shows the energy spectral distribution. Data points more than 2 σ confidence level are shown and the energy spectrum ranged to 35 TeV is obtained. Recently, whipple group reported a significant cutoff feature of the energy spectrum [6]. The cutoff spectrum is also shown in this figure for comparison. Our observed spectrum agrees with the cutoff spectrum below 20 TeV, but still extends further. Fitted with the reported cutoff spectrum, $E^{-2.14}\exp(-E/4.3\ TeV)$, gives a large χ^2 (6.1/d.o.f.). The significance of data point at 24 TeV and 35 TeV is 3.9σ and 2.4σ, respectively and the total excess events over 20 TeV amount to 83$\pm$18 events, corresponding to 4.5σ. If the cutoff spectrum is confirmed, this is an evidence for the discrepancy from the cutoff spectrum in the energy region over 20 TeV.

6 Summary

We have observed Markarian 421 with the CANGAROO-II 10 m telescope for 14 hours (ON source data) while the source was in a high state at both X-ray and TeV energies around the end of January and the beginning of March, 2001. The observations were carried out at very large zenith angles, around 70 degrees. The viability of gamma-ray observations are verified with Monte Carlo simulations and the energy threshold is estimated to be around 10 TeV. An excess of 250 $\pm$ 37 events was detected using Likelihood method. in the significance level of 6.8 σ. The nightly count rate shows the intense valiability in this energy range. The energy spectrum extented up to 35 TeV is observed.

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