29th International Cosmic Ray Conference Pune (2005) **00**, 101–106

Stereoscopic observations with the CANGAROO-III telescopes at the large zenith angles

T. Nakamori[a], Y. Adachi[b], A. Asahara[a], G.V. Bicknell[c], R.W. Clay[d], Y. Doi[e], P.G. Edwards[f], R. Enomoto[b], S. Gunji[e], S. Hara[b], T. Hara[g], T. Hattori[h], Sei. Hayashi[i], Y. Higashi[a], R. Inoue[h], C. Itoh[j], S. Kabuki[b], F. Kajino[i], H. Katagiri[a], A. Kawachi[h], S. Kawasaki[b], T. Kifune[k], R. Kiuchi[b], K. Konno[e], L.T. Ksenofontov[b], H. Kubo[a], J. Kushida[h] Y. Matsubara[l], Y. Mizumoto[o] M. Mori[b], H. Muraishi[p] Y. Muraki[l] T. Naito[g] D. Nishida[a], K. Nishijima[h], M. Ohishi[b], J.R. Patterson[d], R.J. Protheroe[d], Y. Sakamoto[h], M. Sato[e], S. Suzuki[q], T. Suzuki[q], D.L. Swaby[d], T. Tanimori[a], H. Tanimura[a], G. Thornton[d], K. Tsuchiya[b], S. Watanabe[a], T. Yamaoka[i], M. Yamazaki[i], S. Yanagita[q], T. Yoshida[q], T. Yoshikoshi[b], M. Yuasa[b], Y. Yukawa[b]

(a) Department of Physics, Graduate School of Science, Kyoto University, Sakyo-ku, Kyoto 606-8502, Japan
(b) Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba 237-8582, Japan
(c) Research School of Astronomy and Astrophysics, Australian National University, ACT 2611, Australia
(d) Department of Physics and Mathematical Physics, University of Adelaide, SA 5005, Australia
(e) Department of Physics, Yamagata University, Yamagata, Yamagata 990-8560, Japan
(f) Institute of Space and Astronautical Science, Sagamihara, Kanagawa 229-8510, Japan
(g) Faculty of Management Information, Yamanashi Gakuin University, Kofu, Yamanashi 400-8575, Japan
(h) Department of Physics, Tokai University, Hiratsuka, Kanagawa 259-1292, Japan
(k) Department of Physics, Konan University, Kobe, Hyogo 658-8501, Japan
(l) Ibaraki Prefectural University of Health Sciences, Ami, Ibaraki 300-0394, Japan
(m) Faculty of Engineering, Shinshu University, Nagano, Nagano 480-8553, Japan
(n) Solar-Terrestrial Environment Laboratory, Nagoya University, Nagoya, Aichi 464-8602, Japan
(o) National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan
(p) School of Allied Health Sciences, Kitasato University, Sagamihara, Kanagawa 228-8555, Japan
(q)Faculty of Science, Ibaraki University, Mito, Ibaraki 310-8512, Japan

Presenter: T.Nakamori (nakamori@cr.scphys.kyoto-u.ac.jp), jap-nakamori-T-abs1-og22-oral

CANGAROO-III is a stereoscopic observation system with four telescopes, which started full operation in March 2004. We have observed the Crab nebula in 2003 at zenith angles > 55 degrees because our telescopes are located in the southern hemisphere. The observations were made with an independent trigger mode using two telescopes. In the case of larger distances between showers and telescopes, events have a lower accuracy on the determination of intersection points, which degrades the theta-squared distributions. We are, therefore, trying to improve analysis methods. We report the current results of these observations and the performance of our system compared with Monte Carlo simulations.

1. Introduction

The Crab nebula (RA=5h24m32s, Declination=22°00'52", J2000) is the brightest known stable TeV gamma-ray point sources. So it is a very important target for calibration of the instruments and efficiency for gamma-ray detection. Emission of very high energy gamma-ray was confirmed by imaging air Cherenkov telescopes, Whipple[1], HEGRA[2] and CANGAROO-I[3], and the flux of the Crab nebula in the wide band for sub- to multi- TeV region has been reported. CANGAROO-II also measured the flux and the result was consistent within the systematic errors of Whipple and HEGRA[4]. Then we observed the Crab nebula to confirm the performance of the CANGAROO-III stereoscopic system.

2. Observation

The stereoscopic observation of the Crab nebula had been carried out in 2003 December with two telescopes, T2 and T3. These observations were made by so called wobble mode, changing the pointing directions +/- 0.5 degree in declination apart from the target every 20 minutes. Then we could obtain ”OFF-source” background events at the same time under the same environmental situation as those of ”ON-source”, and also be free from the ambiguity in the normalization between ON and OFF. Before 2004 December each telescope was triggered independently under the condition of more than 4 pixels hits where each pixel included at least 7.6 photoelectrons. There is a 3rd magnitude bright star in the field of view, in order to avoid the effect from the star, high voltage for camera PMTs within 0.2 degrees of the star were turned off automatically. GPS time stamp was recorded with each event at the same time and its accuracy is under 1 μsec. We selected coincident events if the difference of triggered time is less than 200 μsec. Trigger rate of each telescope is at most $<$ 80Hz, and after the stereo event selection the event rate is about 8 Hz. Analysis was done for only the data taken at the elevation angle greater than 30 degrees, rejecting the data taken in cloudy condition. The total used observation time is 890 minutes.

3. Analysis

According to Monte-Carlo simulations, there is some difficulty in stereoscopic observation at large zenith angles, such as the Crab nebula for CANGAROO-III. Orientation angles of gamma-rays are reconstructed by the intersection point of the two (or more) axes of the shower images. In the case of large zenith angles, the interval between telescopes looks smaller from the view of shower axes, which means more events have core distance far from telescopes than in the case of small zenith angles. Those events have a tendency to be overlapping each other on the camera plane and thus their intersection points are lose to images, which results in bad accuracy of intersection points and worse angular reslution (Fig.1 left). So we have to develop more effective analysis methods.

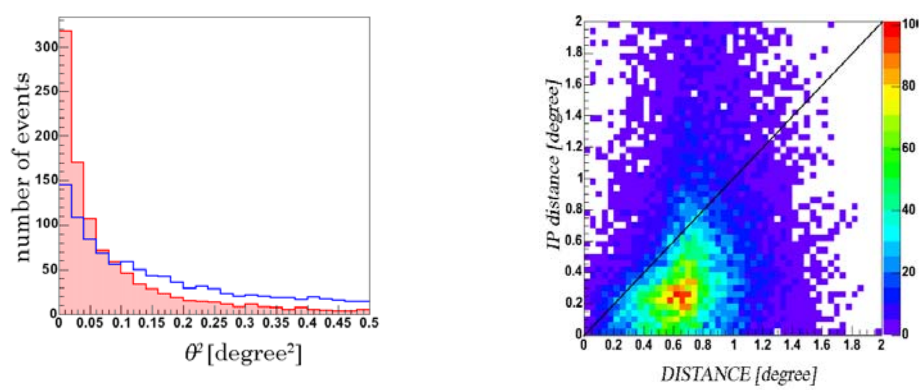

Figure 1. (left) θ^2 distributions. The hatched line and the blank line show θ^2 of Monte-Carlo simulations in the case of the small (0 degree) and large (55degree) zenith angle, respectively. (right) Correlation of DISTANCE and IP-distance (D_{IP}) at large zenith angles. The distribution should be along with the black line (DISTANCE $= D_{IP}$).

To avoid the increased uncertainty of the intersection points, we paid attention to the distance between the intersection point and centroid of images, "IP distance", or $D_{\rm IP}$. If the determination of the intersection point is accurate, $D_{\rm IP}$ should be approximately equal to the Hillas parameter DISTANCE (Fig1 right). Then we search the best intersection point with the χ^2 defined as

$$\chi^2 = \sum_{\rm telescopes} \Big[\frac{{\rm Width}(x,y)^2}{\sigma_w^2} + \frac{(D_{\rm IP} - \langle D \rangle)^2}{\sigma_{\rm D}^2} \Big],$$

where ${\rm Width}(x,y)$ is the width seen from the intersection point, $\langle D \rangle$ is the mean distance obtained by Monte-Carlo simulations for gamma-rays, and σ_D is its standard deviation. This constraint fitting resulted in improvement of θ^2 distribution. After that we first used the conventional square cuts method taking into account of the difference of the spot size between each telescopes. The cut parameters are *WIDTH*(T2)$<$0.20, *WIDTH*(T3)$<$0.15, *LENGTH*(T2)$<$0.30 and *LENGTH*(T3)$<$0.25. The significance for excess is 4.4 sigma. In the case of standard square cut method, there are four parameters on which cut can be made. Without precise simulations, some freedom is left in choosing exact cut parameters[5]. Then we applied two independent analyses aiming to reduce the degree of freedom in deciding cut parameters. One is the Likelihood method[6]. We produced probablity density functions from distributions of WIDTH and LENGTH for the both telescopes, and some other parameters such as opening angle of image axis and distance between each image's center of gravity. We used Monte-Carlo simulations for gamma-ray sampling, and real OFF data for background sampling. Then likelihood ratio is defined as

$$LRatio = \frac{L(\gamma)}{L(\gamma) + L(BG)},$$

and we applied moderate cut value $LRatio > 0.5$, taking into account the uncertainty of Monte-Carlo simulation. The obtained excess is 5.2 sigma confident level. The other method is *Fisher Discriminant*[8][7]. Fisher Discriminant is a general analysis method in high energy physics experiments. Considering a linear combination of WIDTH and LENGTH (here, x_i) for each telescopes,

$$F = \sum \alpha_i x_i,$$

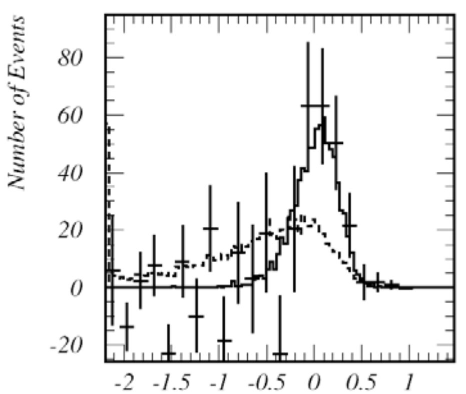

Figure 2. Distribution of *Fisher Discriminant* for the excess events (data points). Dashed and solid lines are derived from background data and Monte-Carlo simulations for γ-ray respectively.

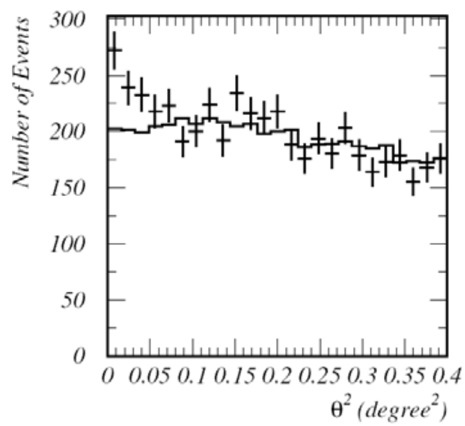

Figure 3. θ^2 distribution of the Crab nebula. Significance of the excess ($\theta^2 < 0.05$)is 5.8σ.

a kind of separation index is defined below.

$$S(\vec{\alpha}) = \frac{(\langle F_\gamma \rangle - \langle F_{BG} \rangle)^2}{\sigma_\gamma^2 + \sigma_{BG}^2}$$

Then we can mathematically determine coefficients α_i which maximize separation of $\langle F_\gamma \rangle$ and $\langle F_{BG} \rangle$, as a solution of $\partial S / \partial \vec{\alpha} = 0$. When x_i is redefined as $x_i - \langle x_i^\gamma \rangle$, where $\langle x_i^\gamma \rangle$ is mean value of x_i for gamma-ray obtained from simulations, mean value of F for gamma-rays is exactly zero. The distribution of F is shown in Fig.2, and we did selected $F > 0$ as a cut value. Fig.3 shows the θ^2 distribution of the result of Fisher Discriminant and significance of excess is 5.8 σ. We obtained integral flux as Fig.4 and error bars represent statistical error. We estimated energy of gamma-rays with simply the summation of SIZE of each telescopes and energy resolution is ~30%. Systematic error is approximately 15% for reflectivity of mirrors and transmission of cherenkov light. Our result is consistent with Whipple and HEGRA.

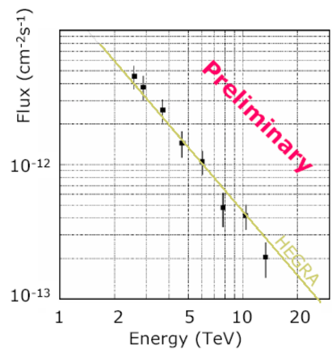

Figure 4. Integral flux of the Crab nebula.

4. Conclusions

CANGAROO-III has done stereoscopic observation on the Crab nebula and the obtained flux is consistent with other groups' results. We're developing the new analysis method for the object at the large zenith angles. We're now studying development of energy resolution using core parameters. Further analysis, using newest telescope for example, and tuning of simulation is now in progress.

References

[1] Hillas, A.M. et al., ApJ, 503, 744 (1998)
[2] Aharonian, F. et al., ApJ, 539, 317 (2000)
[3] Tanimori, T. et al., ApJ, 492L, 33 (1998)
[4] Itoh, C .et al., A&A. 402, 443 (2003)
[5] Dazeley,S.A., et al., Astropart. Phys., 15, 313 (2001)
[6] Enomoto, R. et al., Nature, 416, 823-826 (2002)
[7] Fisher, R. A., Annals of Eugenics, 7, 179 (1936)
[8] Enomoto, R. et al., submitted for publication (2005).