CANGAROO-III search for Galactic Sources

R. Enomoto*, **J. Kushida**†, **T. Nakamori**‡, **and T. Kifune***

* *Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba 277-8582, Japan*
† *Department of Physics, Tokai University, Hiratsuka, Kanagawa 259-1292, Japan*
‡ *Department of Basic Physics, Tokyo Institute of Technology, Meguro, Tokyo, 152-8551, Japan*

for CANGAROO-III collaboration¶ ‖ ** †† ‡‡ x xi xii xiii xiv xv xvi

§ *Research School of Astronomy and Astrophysics, Australian National University, ACT 2611, Australia*
¶ *School of Chemistry and Physics, University of Adelaide, SA 5005, Australia*
‖ *Narrabri Observatory of the Australia Telescope National Facility, CSIRO, Epping, NSW 2121, Australia*
** *Department of Physics, Yamagata University, Yamagata, Yamagata 990-8560, Japan*
†† *Ibaraki Prefectural University of Health Sciences, Ami, Ibaraki 300-0394, Japan*
‡‡ *Faculty of Management Information, Yamanashi Gakuin University, Kofu, Yamanashi 400-8575, Japan*
x *Department of Physics, Konan University, Kobe, Hyogo 658-8501, Japan*
xi *Department of Physics, Kyoto University, Sakyo-ku, Kyoto 606-8502, Japan*
xii *Faculty of Science, Ibaraki University, Mito, Ibaraki 310-8512, Japan*
xiii *Department of Physical Science, Hiroshima University, Higashi-Hiroshima, Hiroshima 739-8526, Japan*
xiv *Solar-Terrestrial Environment Laboratory, Nagoya University, Nagoya, Aichi 464-8602, Japan*
xv *National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan*
xvi *School of Allied Health Sciences, Kitasato University, Sagamihara, Kanagawa 228-8555, Japan*

***Abstract*. As one of the observations of "the CANGAROO-III search for Galactic Sources", the direction of the pulsar PSR B1706-44 and its neighborhood was surveyed, providing us with an evidence for extended emission of TeV gamma rays from the vicinity of the pulsar. Preliminary results are presented such as the morphological map of the extended emission and estimation of the gamma ray flux as a function of the angular extent of the emission.**

***Keywords*: Gamma ray, PSR B1706-44, Galactic plane.**

I. INTRODUCTION

The CANGAROO-I Project was commenced about 15 years ago in an attempt to search for Galactic TeV gamma ray sources along the Galactic plane, which are presumed to be more abundant at nearer region to the Galactic Center, by using an Imaging Atmospheric Cherenkov telescope (IACT) at Woomera, South Australia (31°S, 137°E) in the southern hemisphere. The CANGAROO-I observation, *i.e.* with a single IACT of 3.8m aperture, reported evidence of having detected TeV gamma rays consistent with point-like emission; at the position of PSR B1706−44 [1], from a vicinity of Vela pulsar ([2]) and from the north-east rim of supernova remnant SN1006 [3]. The stereoscopic observation with a system of multiple IACTs was, then, put into operation as "the second generation IACTs". However, observation by the H.E.S.S. did not confirm the point-like emission of CANGAROO-I detection from these objects [4] with its improved sensitivity and accuracy, having found a broad extended emission in the case of the Vela pulsar wind nebula [7], instead of a point-like emission. In addition, tens of Galactic sources of TeV gamma rays have been discovered through the scan survey of the Galactic disk by H.E.S.S. Group, [5], and the total number of TeV gamma ray sources, in 2007, amounted to more than 70 [6]. The number is steadily increasing, and very recently, H.E.S.S. reported emission from the north-east rim of SN1006 [8] with a flux considerably lower than the one as reported by the CANGAROO-I.

Series of observation of Galactic Sources have been conducted to examine extended and/or off-set emission which are possibly associated with the objects such as those which CANGAROO-I observed, by using CANGAROO-III system of IACTs. Each telescope of CANGAROO-III has a 10 m diameter of segmented reflector, consisting of 114 spherical mirrors made of Fiber Reinforced Plastic material each of 80 cm diameter, mounted on a parabolic frame with a focal length of 8 m. The total area for light collection is 57.3 m^2.

Presented in this paper is the case of PSR B1706−44, a young pulsar with a high spin-down luminosity as one of the gamma-ray pulsars detected by the EGRET instrument of the Compton Gamma Ray Observatory [9]. On PSR B1706−44, following the CANGAROO-I result [1], the Durham Mark 6 telescope reported detection of a flux of $\sim 4 \times 10^{-11}$ cm^{-2} s^{-1} at $E > 300$GeV [10]. Observations with the CANGAROO-II telescope preliminarily reported the detection of a gamma-ray signal, which appeared to be somewhat broader than the point-spread function, $\sim 0.2^o$ of the telescope [11]. However, the observation by H.E.S.S. Group could not confirm the point-like emission from the pulsar position of PSR B1706−44, setting an upper limit of 1.4×10^{-12} cm^{-2} s^{-1} for $E > 350$GeV [4] at the center of the field of view. CANGAROO-III also failed to detect the signal, and obtained a preliminary upper limit of 5×10^{-12} cm^{-2} s^{-1} for $E > 600$GeV on the point-like emission [12].

The emission which CANGAROO-I telescope observed was with a flux of $\sim 10^{-11}$ cm^{-2} s^{-1} for gamma-ray energy >1TeV [1], and not pulsed in modulation with the pulsar period. Thus, the detection, if valid, might suggest an emission from a compact pulsar wind nebula associated with PSR B1706−44, similar to the case of the Crab nebula. Pulsar wind nebulae (PWN) constitute the major class of the Galactic sources. Some of those which are considered as TeV emission from PWN are found as extended with its central position displaced from the position of the pulsar associated. Similarly, displaced and extended emission may be also the case for PSR B1706−44, encouraging and requesting further and deeper survey of the vicinity of the pulsar PSR B1706−44.

II. Observation of PSR B1706−44

The CANGAROO-III observed PSR B1706−44 during the period from Jul 11 to 19 in 2004 and between Apr 14 and Jun 15 in 2007. The observation in each night consists of two separate observations of ON- and OFF-source runs. During the ON-source runs in 2004, the center of the field of view of each telescope was set at right ascension α=257.4^o and declination $\delta = -44.5^o$ [J2000], *i.e.*, the position of PSR B1706−44. In 2007, the "wobble mode" [13] was adopted, *i.e.*, the pointing position of each telescope was displaced from PSR B1706−44 in declination by $\pm 0.5^o$, and was changed every 20 minutes to be set alternatively at $+0.5^o$ or at -0.5^o from $\delta = -44.5^o$.

Thus, the wobble method, which is usually used by the H.E.S.S. Group, *i.e.* the way of estimating the background event by using the data within the same field of view of the telescope but separated from the direction of interest as large as about 0.5^o, can be directly applied to the data in the 2007 year.

Each night was divided into two or three series of observation modes, such as "ON–OFF", "OFF–ON–OFF", or "OFF–ON" observations. The ON-source run was made to contain the meridian passage of the target, and the OFF-source run to have basically the same distribution of zenith angles with that of the ON-source observation. On the average, the OFF source region had an offset in the R.A. of more than 30° away from the target.

In the 2004 observation, the data of each telescope of T2, T3 and T4 were recorded with the clock signal from the satellite of the GPS (Global Positioning System), independently from the other telescope, when more than four photomultiplier (PMT) signals exceeded 7.6 p.e. (photo-electrons) in each telescope. In the stage of off-line analysis, the GPS time was used as a token to find coincidence events for the three telescopes. In the 2007 observation, a trigger circuit was employed into the electronics system [14] so that the events of more than two telescopes in coincidence were selected to be recorded.

The total efficiency of light collection, including the reflectivity of the segmented mirrors, the light guides, and the quantum efficiency of the photomultiplier tubes, was monitored by "muon-ring analysis" of the Cherenkov lights radiated by cosmic-ray muons [15], during the period of the observation. The deterioration ratios of the reflectivity relative to the initial value when the mirrors were made were measured to be 0.55, 0.60, and 0.75, for T2, T3, and T4, respectively, in 2004. The calibration data by the muon ring indicated that the reflectivity of T2 became too low in 2007, and we were obliged to use the two-fold coincidence data (i.e., T3 and T4) in the analysis of the 2007 year data.

Analysis was done for those events in which the images of the Cherenkov light consisted of at least five adjacent pixels exceeding the 10 p.e. threshold (called the "cluster events"). A cloud in the sky caused a low trigger rate when it blocked the direction of the telescope pointed, and events during the time of such a low-rate trigger were excluded from the analysis. The effective observation times for the 2004 and 2007 observations were 996 (998) and 2187 (2386) minutes, respectively, where the time for an OFF-source run is shown in parentheses. The mean of the zenith angle of the data used for the analysis was 19.8° and 18.6°, respectively.

III. Analysis procedures

The procedures adopted in this work for analyzing the data are basically the same ones with those described in [16], with some more details to be found in [15] and [17]. As a measure of gamma-ray likeliness of each event, we used the Fisher Discriminant (hereafter called as FD) [18], [15], the details are described in [15].

The response function, f_γ, of FD for gamma-rays is estimated from a Monte-Carlo simulation, and the function f_b for background events is inferred from the distribution of the OFF-source data. The observed distribution, F_{on}, as a function of FD for ON-source data, can be expressed as a linear combination of f_γ and f_b, namely as $F_{on} = N_b f_b + N_\gamma f_\gamma = F_b + F_\gamma$, where the number of background and gamma-ray events contained in the ON-source data were designated as N_b and N_γ. By fitting the FD distribution of the ON-source data to $N_b f_b + N_\gamma f_\gamma$ under the condition of $N_{on} = N_b + N_\gamma$, we infer N_γ, the number of γ rays in the ON-source data, where N_{on} is the total number of events of the ON-source data.

The functions f_γ and f_b depend on the location in the field of view of the telescope, and thus a fitting for ON-source data was carried out for every arrival direction

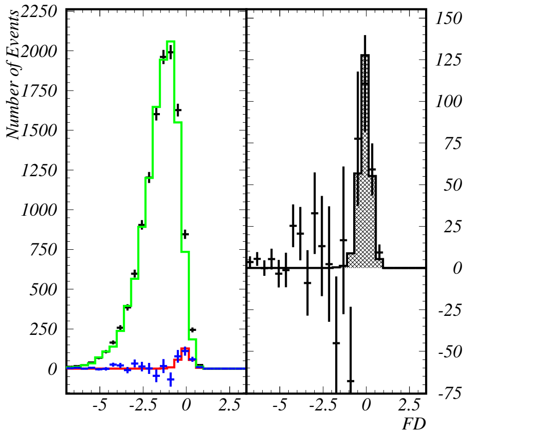

Fig. 1: FD distributions within 0.7^o from PSR B1706-44, obtained from 2004 data by using method (a) of ON- and OFF-source observations. In the left panel, the data points with error bars (statistical errors) are the ON-source run, *i.e.*,F_{on} by the black cross. The green histogram represents F_b, the OFF-source data, the crosses of blue color are the excess counts of $F_{on} - F_b$, and the histogram of red color shows F_γ, the response of gamma-rays (f_γ) inferred from a Monte-Carlo simulation multiplied by N_γ. The right panel shows a magnified view of the excess events.

investigated, within the field of view of the telescope.

The FD fit for the observed data in 2004 was made with the method (a), which will be explained later in the following section, and is shown in Fig. 1 for the region within a radius of 0.7^o from PSR B1706−44. The number of events of the ON-source data (the black cross) exceeds the distribution of the OFF-source events F_b (the green histogram) around $FD \sim 0$. The excess events, $(F_{on} - F_b)$, indicated by the blue cross concentrate in $FD = -0.5$ to 0.5, is consistent with the gamma-ray distribution, F_γ, inferred from the Monte-Carlo simulation and shown by the blue histogram. The right panel shows a magnified view of F_γ and $(F_{on} - F_b)$. The number of excess deduced is 255 $\pm$ 46.

A Monte Carlo simulation shows that gamma-ray events are likely to have FD larger than -0.5, which is consistent with the gamma-ray candidate events extracted from the observation data by using the method of estimating background events from the data of OFF-source run. Fig. 1 demonstrates that selection of the events of FD larger than -0.5 can enrich gamma-ray events, and in the case of the method (b), which is described in the following section.

IV. Results and discussions

We utilizes two different methods for estimating the cosmic-ray background by (a) the "OFF-source observation", which is directed away from the Galactic plane,

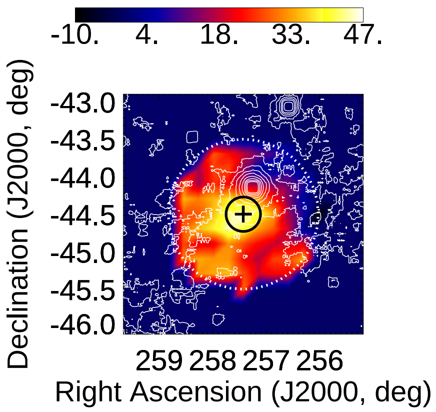

Fig. 2: Acceptance-corrected morphology map of excess events from 2004 and 2007 data combined. The number of excess events per 0.2^o $\times$ 0.2^o cell is plotted in the equatorial coordinate. The number of excess events was smoothed by taking the average of the 3 $\times$ 3 = 9 cells around each investigated direction.

and (b) the "wobble" method, in which we use those events which are in the directions along a ring-shaped region, displaced by an angular distance of $\sim 0.5^o$ from the observation target or the direction of interest, within the field of view of the ON-source run.

The arrival directions in the equatorial coordinate (J2000) of observed events were sorted into 19 $\times$ 19=361 cells with each having a 0.2^o $\times$ 0.2^o size. in a field of view of $\Omega_{FoV} = 3.8^o \times 3.8^o$. For each cell of the arrival direction, the FD distribution of ON- and OFF-source runs was made by applying the method (a) to the whole data of 2004 and 2007 years to infer N_γ, *i.e.* the number of gamma-ray events, and to construct the map of gamma-ray-like events, as plotted in Fig. 2. The black cross at the center of the map indicates the position of the pulsar PSR B1706−44, the radius of the black circle shows the point spread function (PSF) of $\delta\theta_0 = 0.24^o$, and the circle drawn with the white dotted line shows the region within 1^o distance from the pulsar (fiducial volume). The white contours are the ROSAT hard X-ray map taken from NASA Skyview [19].

The θ plot from the combined data of years 2004 and 2007 after the acceptance and solid angle correction is shown in Fig. 3, where θ is the angular distance from the position of the pulsar PSR B1706-44. The χ^2/d.o.f value (the chi-square value per degree of freedom) calculated for flat distribution, *i.e.* the case of constant excess counts against θ, is 16.8/7. When we fit the distribution by a test function $\propto$ 1-θ/a from the pulsar position, the best fit for the observed distribution was obtained when $a = 1.36^o \pm 0.21^o$ with χ^2/d.o.f. = 3.7/6. In the case of fitting by a Gaussian function $\propto exp(-\theta^2/(2\sigma^2))$, the χ^2/d.o.f value was 4.0/6, with $\sigma = 0.62^o \pm 0.10^o$. Fitting was also made for the case of "constant value plus Gaussian function", *i.e.* $\propto N_c + a \cdot exp(-\theta^2/(2\sigma^2))$, yielding results of $N_c = 19 \pm 6$, $a = 40 \pm 11$, and $\sigma = 0.34^o \pm 0.10^o$ with χ^2/d.o.f equal to $1.9/5$. The

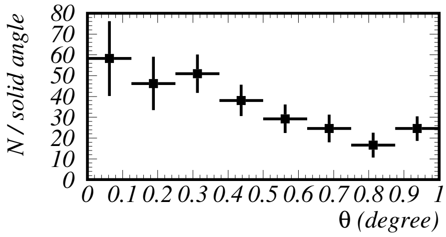

Fig. 3: Acceptance-corrected θ plot from the excess events per unit solid angle of 2004 and 2007 data combined.

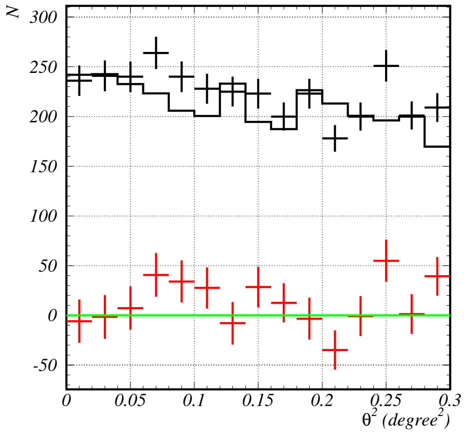

Fig. 4: θ^2 distributions of the 2007 data obtained by method (b), the wobble method.

study of systematic ambiguity in estimating the flux is now under way.

To the 2007 data, the "wobble" can be directly applied in a way similar to what has been usually used by the H.E.S.S. Group. Along the circle of $\theta_{r1} = 0.5^o$, six points that are successively at every 60^o of the opening angle around the center of the field of view were selected as the points for calculating the θ^2 distribution of Fig. 4, one of which is at the direction of PSR B1706−44, *i.e.*, the ON-source position with the other five points utilized as the off-source direction for background events. The events of having $FD > -0.5$ were selected as gamma-rays enriched events, and then the numbers of events from ON- and off-source directions were compared for estimating the flux of gamma-rays as a function of θ^2, where θ is the angular distance from PSR B1706−44. Fig. 4 shows the θ^2 distributions from the 2007 data. The black points with error bars, "ON-source events", are the number of events enriched by gamma-rays (by taking the events of $FD > -0.5$). The black histogram indicates the case for the background. The red ones with error bars are the subtracted data, *i.e.*, the number of "ON-source" minus "off-source" events, and the green line shows the level of the event number equal to zero. The 2004 data were analyzed with similar selection on the background region with acceptance corrections. When the cut $\theta^2 < 0.06$ degree^2 was applied to the observed θ^2 distribution, as matched to the point-spread function, the excess was consistent with the statistical fluctuation, giving the upper bound of the flux roughly lower than the level of 10% Crab at 1 TeV.

To summarize, the method (a) has yielded an evidence for TeV gamma-ray emission from an extended region around the pulsar PSR B1706−44, while the excess observed from method (b) is consistent with the statistical fluctuation failing to confirm the result by method (a).

The two differing results obtained through the two different methods, both of which were applied to the same ON-source data, can, however, be understood as not in contradiction with each other, if we take into consideration the fact that the region we used for subtracting the rate of background contains gamma ray events.

The result for the flux within an area of 1^o radius is as large as the intensity of the Crab nebula at 1 TeV. The flux, when integrated over solid angle of a $0.2^o \times 0.2^o = 3.8 \times 10^{-5}$sr, amounts to $10^{-13} \sim 10^{-12}$cm^{-2}s^{-1}TeV^{-1}, which is equivalent to $0.01 \sim 0.1$ of the flux from the Crab nebula. This intensity is of similar amount to the flux of the extended emission along the Galactic Ridge near Galactic Center[20].

ACKNOWLEDGMENTS

This work is supported by a Grant-in-Aid for Scientific Research by the Japan Ministry of Education, Culture, Sports, Science and Technology, the Australian Research Council, JSPS Research Fellowships, and Inter-University Researches Program by the Institute for Cosmic Ray Research. We thank the Defense Support Center Woomera and BAE Systems.

REFERENCES

[1] Kifune, T., et al., 1995, ApJ, 438, L91
[2] Yoshikoshi, T, et al. 1997, ApJ, 487, L65-L68
[3] Tanimori, T, et al. 1998, ApJ, 497, L25-L28
[4] Aharonian, F., et al., 2005a, A&A, 432, L9
[5] Aharonian, F., et al., 2005, Science, 307, 1938-1942
[6] Hinton, J, 2008, Rapporteur talk at the 30th International Cosmic Ray Conference, Merida, Mexico
[7] Aharonian, F, et al. 2006, A&A, 457, 899
[8] Naumann-Godo, M, et al. 2008, Proceedings of the 4th Heidelberg International Symposium on High Energy Gamma Ray Astronomy, 304
[9] Thompson, D. J., et al. 1992, Nature, 359, 615
[10] Chadwick, P.M., et al., 1998, Astropart. Phys. 9, 131
[11] Kushida, J., et al. 2003, Proc. 28th Int. Cosmic Ray Conf. (Tsukuba), OG2.2, 2493
[12] Tanimori, T., et al. 2005, Proc. 29th Int. Cosmic Ray Conf. (Pune), Vol 5, 215
[13] Daum, A., et al. 1997, Astropart. Phys., 8, 1
[14] Nishijima, K., et al. 2005, Proc. 29th Int. Cosmic Ray Conf. (Pune), OG2.7, 101
[15] Enomoto, R., Tsuchiya, K., Adachi, Y., Kabuki, S., Edwards, P. G., et al. 2006, ApJ, 638, 397
[16] Kabuki, S., Enomoto, R., et al. 2007, ApJ, 668, 968
[17] Enomoto, R., Watanabe, S., Tanimori, T., et al. 2006, ApJ, 652, 1268
[18] Fisher, R. A. 1936, Annals of Eugenics, 7, 179
[19] NASA, 2007, Skyview, http://skyview.gsfc.nasa.gov/
[20] Aharonian, F., et al., 2006, Nature, 439, 695