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Detection of 2006 TeV-outburst of PKS 2155-304 with the CANGAROO-III telescope

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Abstract: We present the detection of nearby BL Lacertae object PKS 2155-304 with the CANGAROO-III imaging atmospheric Cherenkov telescope system. This observation was triggered by the H.E.S.S. report in July 2006 that the outburst at TeV gamma-ray energy range occured on this object. Observations have been performed between 2006 July 28 and August 2. A signal from PKS 2155-304 was detected at $5.7\ \sigma$ level using the dataset of zenith angle $< 30^\circ$. The time averaged integral flux above 620 GeV and the differential energy spectrum are obtained.

Introduction

As is well known, the nearby blazar PKS 2155-304 is one of the brightest BL Lacertae objects in the X-ray and EUV bands.

The first detection of VHE gamma rays from PKS 2155-304 were reported at the $6.8\ \sigma$ level above 300 GeV by Durham group in 1997[1], which coincided with a period of a gamma-ray and X-ray outburst detected by EGRET[2], BeppoSAX[3] and RXTE[4].

CANGRAOO observations with the CANGAROO-I 3.8 m telescope was carried out in 1997. However, due to poor weather condition, overlaping with the Durham observation was not enough and no gamma-ray signal above 1.5 TeV was detected[5]. PKS 2155-304 further have been observed in 1999, 2000 and 2001 with the CANGAROO-II telescope, and was not detected above 420 GeV [6],[7],[8].

In 2005, H.E.S.S. group reported the detection of a clear signal from PKS 2155-304 with a significance of $45\ \sigma$ at enegies greater than 160 GeV. Then PKS 2155-304 was confirmed as an TeV gamma-ray source[9]. They also reported the flux variability on various time scales from months to hours and the steep power law shape energy spectrum with a photon index of 3.3.

In July 2006, the H.E.S.S. group sent out the alert that PKS 2155-304 was historically high active state at VHE gamma-rays($>\ 200$ GeV) up to $\sim\ 17$ Crab[10]. In respose to this alert, CANGAROO-III observations of PKS 2155-304 had been performed from 2006 July 28 to August 2 and August 17 to 25. Here we present the results obtained from observations between July 28 and August 2.

Obseravtions

The CANGAROO-III obseravtions of PKS 2155-304 was made for five moonless nights between July 28 to August 2 in 2006 just after the alert by the H.E.S.S. Unfortunately, there were no observations on August 1, and the July 29 observations were affected by cloud. Three (T2,T3,T4) of four telescopes are used in these observations. Details of the CANGAROO-III telescope system are described in [11],[12],[13]. Due to a mechanical tracking problem with T3 telescope during this period, stereoscopic observtions with three telescopes were done only after the culmination. Here we use only these data, although two-fold observations using T2-T4 were performed before culmination. The results using data before culminations will be presented in Nishijima[14].

A local trigger signal at each telescope is generated when the number of hit pixels exceeds four. Then the condition that any two trigger signals coincide for at least 10 nsec within a 650 nsec time window is required to obtain stereo events [15],[16]. Typical trigger rates were ~30 Hz. Obsevations were using the so-called wooble mode with $\pm 0.5^\circ$ offset. The daily observation time t_{obs}, average zenith angle z and trigger rate r_{tr} are summarized in Table 1.

Analysis

After the standard calibration of the relative gain and the timing for each pixel, five out of 427 pixels for T2 and two for T3 are removed from the analysis as bad pixels. Next image cleaning has been carried out by requiring each of at least five adjacent pixels has a signal larger than 5.0 p.e. within ± 30 nsec.

The moments of each shower image are then parametarized using Hillas parameters and the arrival direction is reconstructed with the intersection point of the major axes of the images. In order to reject numerous cosmic ray background events, we apply the Fisher discriminant method, which uses a linear combination of image parameters, The details of the application of this method to our analysis are described in [13],[17].

Since the energy threshold and the shape of image depends on the zenith angle z, we applied the Fisher discriminant method to the dataset taken at $z < 30^\circ$ and $z > 30^\circ$ separately. In this analysis we use only the data for $z < 30^\circ$. Average shower rate r_{sh} and the livetime t_{liv} for $z < 30^\circ$ are listed in Table 1 for the three-fold data.

Results

After the data reduction described in the previous section, the θ^2 distribution, where θ is an angular difference between the reconstructed arrival direction and the assumed source direction, is obtained by minimizing the sum of squared widths of the images seen from the assumed point with a constraint on the distance between images' center of gravity and assumed intersection point.

Obtained θ^2 distribution from the direction of PKS 2155-304 for the three-fold events is shown in Figure 1 together with the FD distribution in Figure 2. There is a clear excess from the direction of PKS 2155-304. The excess is 189 ± 33 events (5.7σ), which is calculated using a circular region of $\theta^2 < 0.06^\circ$ centered on the source position. Point Spread Function (PSF) of three-fold data is estimated to be 0.23° (FWHM) in this region. The hatched histogram in the Figure 1 represents the expected distribution normalized to the number of excess events in $\theta^2 < 0.06$. In Table 1, the number

Obs.Date	t_{obs}[hrs]	z[°]	r_{tr}[Hz]	r_{sh}[Hz]	t_{liv}[hrs]	N[events]	s[σ]
July 28	3.9	20.4	12.1	8.0	2.5	54 ± 16	3.4
July 29	2.0	12.1	6.2	4.1	0.9	28 ± 12	2.4
July 30	4.0	22.2	12.5	8.1	2.3	86 ± 17	5.0
July 31	3.9	21.7	11.6	7.6	2.4	35 ± 21	1.7
Aug. 2	3.9	21.5	11.9	7.7	2.3	1.6 ± 15	0.11
Sub total	17.6	20.4	11.4	7.3	10.5	189 ± 33	5.7
Aug. 17-25	19.1	20.9	10.9	7.4	11.6	75 ± 29	2.6

Table 1: Summary of observations for three-fold data

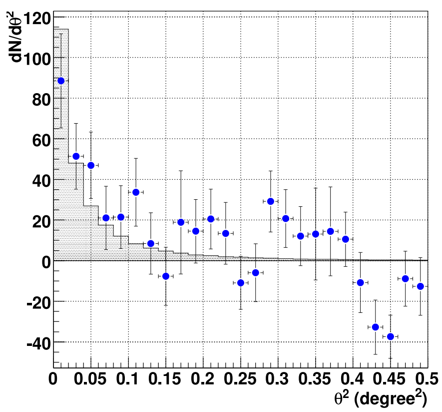

Figure 1: Distribution of squared angular distance θ^2 of the three-fold data in the outburst period, using the Fisher Discriminant method. The hatched histogram represents our point spread function normalized to the number of excess events in $\theta^2 < 0.06$

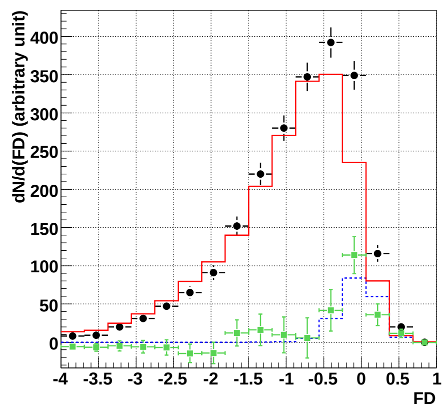

Figure 2: Fisher Discriminant distribution. The closed circles indicate on-source events. The solid and dotted histogram are the best-fit FD distributions for background events and for MC gamma-ray events, respectively. The closed squares show the background subtracted gamma-ray candidate events.

of nightly excess events N and their significance s are shown using the data only at $z < 30°$.

From these data, the time averaged integral flux above 620 GeV is calculated to be F ($>$ 620 GeV) $= (2.1 \pm 0.4_{stat}) \times 10^{-11}$ cm^{-2} sec^{-1}, which corresponds to $\sim 55\%$ of the flux observed from the Crab nebula. We further obtained the time-averaged differential energy spectrum which is shown in Figure 3. Here we add one more point which is obtained from the data taken at $z > 30°$. The best fit of a power law to those data yields a photon index $\Gamma = 3.5 \pm 0.5$ and a flux normalization N_0(1TeV)=$(1.6 \pm 0.3_{stat})^{-11}$cm^{-2}sec^{-1}TeV^{-1}. For the check of the reliability of the results, we analyze three combinations of two-fold data using the dataset taken with three telescopes (including three-fold data). The same analysis method as for the three-fold data are applied to the data except for rate cut for removing cloud effect. The average trigger rate r_{tr}, the shower rate r_{sh}, the live time t_{liv}, and the rate cut criteria for each combination are listed in Table 2.

The derived number of excess events and their significance are shown in Table 2 where applied θ^2 cut criteria were determined to keep 70% of gamma-ray events as for the three-fold data from the Monte Calro simulation. The obtained integral flux from two-fold coincidence data above 620GeV are listed in Table 2 in unit of 10^{-11}cm^{-2}sec^{-2}. We confirmed that fluxes derived from two-fold data are

telescope	$r_{tr}[Hz]$	$r_{sh}[Hz]$	$ratecut$[Hz]	$t_{liv}[hrs]$	$\theta^2 cut$	N[events]	$s[\sigma]$	$F(>620\ GeV)$
T2-T3	16.4	11.6	7.0	11.1	0.14	382 ± 80	4.9	2.3 ± 0.5
T3-T4	13.3	8.2	7.0	10.8	0.10	365 ± 51	7.1	2.0 ± 0.3
T2-T4	18.1	12.2	10.0	10.9	0.14	322 ± 79	4.1	2.0 ± 0.5

Table 2: Summary of observations for the two-fold coincidence data of $z < 30°$

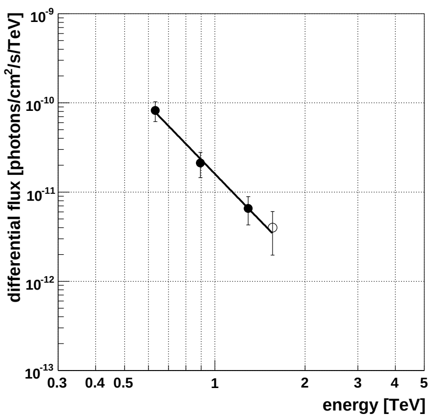

Figure 3: Time-Averaged differential energy spectrum of PKS 2155-304. The solid line represents the best fit to the data assuming power law spectrum. The data plotted by the closed circles and open the circle are obtained at smaller zenith angle $z < 30°$ and at larger $z < 30°$, respectively

all consistent with those for the three-fold data within errors.

Conclusion

We have observed PKS 2155-304 with the CANGAROO-III telescope during the active period in 2006. We obtained the time-averaged integral flux above 620 GeV of $F\ (>\ 620\ \mathrm{GeV}) = (2.1 \pm 0.4_{stat}) \times 10^{-11}$ cm^{-2} sec^{-1}, which corresponds to $\sim 55\%$ of the flux observed from the Crab nebula at small zenith angle. We confirmed that the flux derived from the two-fold coincidence data are consistent with that from three-fold data.

References

[1] C. P. et al., Astrophys. J. 513 (1999) 161–167.
[2] S. P., V. W.T., IAU Circular 6776.
[3] C. L. et al., Astrophys. J. 521 (1999) 552–560.
[4] V. W.T., S. P., Astropart. Phys. 11 (1999) 197–199.
[5] R. M. D. et al., Vol. 343, 1999, pp. 691–696.
[6] N. K. et al., in: Proceedings of the 27th International Cosmic Ray Conference, Humburg, Germany, 2001, pp. 2626–2629.
[7] N. K., Vol. 19, Publ.Astron.Soc.Australia, 2002, pp. 26–28.
[8] N. T., in: Proceedings of the 28th International Cosmic Ray Conference, Tsukuba, Japan, 2003, pp. 2587–2590.
[9] A. F. et al., Astron. & Astrophys. 430 (2005) 865–875.
[10] B. W. et al., Astronomer's Telegram #867.
[11] K. A. et al., Astropart. Phys. 14 (2001) 261–269.
[12] K. S. et al., Nucl. Instr. & Meth. (2003) 318–336.
[13] E. R. et al., Astrophys. J. 638 (2006) 397–408.
[14] N. K. et al., in: these proceedings (OG2.3).
[15] K. H. et al., in: Proceedings of the 27th International Cosmic Ray Conference, Humburg, Germany, 2001, pp. 2900–2903.
[16] N. K. et al., in: Proceedings of the 29th International Cosmic Ray Conference, Vol. 15, Pune, India, 2005, pp. 327–330.
[17] E. R. et al., Astrophys. J. 652 (2006) 1268–1276.