Detection of VHE Gamma-Ray Flare From PKS 2155-304

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Abstract

We have observed the nearby blazar PKS 2155-304 with the CANGAROO-III atmospheric Cherenkov telescope between 2006 July 28 and August 2, just after the H.E.S.S. group reported the source was in a high TeV flux level. The excess events in VHE gamma rays above 630 GeV were detected at the 6.8\(\sigma\) level (preliminary) and the averaged integral flux is obtained to be \((2.3\pm0.4)\times10^{-11}\) cm\(^{-2}\) sec\(^{-1}\) (\(\sim\)60% Crab). Follow-up observations between August 17 and 25 indicate the source activity had decreased.

1. Introduction

PKS2155-304 is one of the brightest BL Lacs in the X-ray and EUV bands. It has been observed many times over a wide range of wavelengths. Gamma rays were first detected by EGRET with a hard spectrum at 0.03-10GeV (Vestrand et al. 1995), which suggested this object possibly emit gamma rays above 100 GeV. In fact, the Durham group reported the first detection of VHE gamma rays at the 6.8\(\sigma\) level above 300GeV in 1997 flare up state (Chadwick et al. 1999a). However they found no evidence for emission of VHE gamma rays in 1998 when X-ray flux level was low (Chadwick et al. 1999b).

The CANGAROO group has observed PKS2155-304 with the CANGAROO 3.8m telescope in 1997, which did not overlap with the Durham observations, and we did not detect any gamma-ray signals above 1.5TeV (Robert et al. 1999). In 1999, 2000 and 2001 we have observed PKS2155-304 with the CANGAROO-II telescope. In those observation periods, PKS2155-304 remained in a low state of X-ray activity and no gamma-ray signal was detected above our energy threshold of 420GeV (Nishijima 2002; Nakase 2003).

PKS2155-304 was confirmed as a TeV gamma-ray emitter by the H.E.S.S group in 2004 (Aharonian et al. 2005). They reported the detection of a clear signal with a significance level of 45\(\sigma\) at energies greater than 160GeV in July and October, 2002, and June-September, 2003, even though they include dark period. The flux variability on time scales of months, days, and hours were also reported. Energy spectrum is characterized by a steep power law spectrum with a time-averaged photon index of \(\Gamma\sim3.3\).

At the end of July 2006, the H.E.S.S. group reported PKS2155-304 had been a historically high active state at the TeV region (Giebels 2006a). The H.E.S.S report triggered multi-wavelength ToO observations, and we observed PKS2155-304 from 2006 July 28 with the CANGAROO-III telescope. Here we report the results of these observations.

2. Observations

The CANGAROO-III imaging atmospheric Cherenkov telescopes are operated in Woomera, South Australia (longitude 136°47'E, latitude 31°06'S, 160 m a.s.l.). Details of the total performance of the detector are described in Enomoto et al. (2006a). The CANGAROO-III observations of PKS2155-304 during this outburst period were made for five moonless nights between July 28 to August 2 in 2006, with three (T2, T3, T4) out of four telescopes using stereo trigger system. There were no observations on August 1, and the July 29 observations were affected by cloud. The typical trigger rate of three fold coincidences was \(~12\) Hz. These observations were done using the

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so-called Wobble mode. The mean zenith angle of the observations was 20.4° and the total observation time was 17.6 hours. Due to a mechanical tracking problem with the T3 telescope during this period, stereo observations with three telescopes were done only after culmination. Daily Observation time \( t_{\text{obs}} \), average zenith angle \( z \), trigger rate \( r_{\text{tr}} \), and other parameters are summarized in Table 1. Follow-up observations were made with the same system on six moonless nights between August 17 and 25. A summary of these observations is also given in the same table.

### Table 1. Summary of observations for PKS 2155-304 from 2006 July 28 to August 2 and the follow-up observations from August 17 to 25.

<table>
<thead>
<tr>
<th>Date</th>
<th>( t_{\text{obs}} ) [hr]</th>
<th>( z ) [°]</th>
<th>( r_{\text{tr}} ) [Hz]</th>
<th>( r_{\text{sh}} ) [Hz]</th>
<th>( t_{\text{liv}} ) [hr]</th>
<th>( N ) [events]</th>
<th>( s )</th>
</tr>
</thead>
<tbody>
<tr>
<td>July 28</td>
<td>3.9</td>
<td>20.4</td>
<td>12.1</td>
<td>8.0</td>
<td>3.6</td>
<td>62 ± 19</td>
<td>3.3</td>
</tr>
<tr>
<td>July 29</td>
<td>2.0</td>
<td>21.1</td>
<td>5.2</td>
<td>4.1</td>
<td>0.9</td>
<td>35 ± 12</td>
<td>2.8</td>
</tr>
<tr>
<td>July 30</td>
<td>4.0</td>
<td>22.2</td>
<td>12.5</td>
<td>8.1</td>
<td>3.5</td>
<td>122 ± 22</td>
<td>5.6</td>
</tr>
<tr>
<td>July 31</td>
<td>3.9</td>
<td>21.7</td>
<td>11.6</td>
<td>7.6</td>
<td>3.6</td>
<td>44 ± 18</td>
<td>2.4</td>
</tr>
<tr>
<td>Aug. 2</td>
<td>3.9</td>
<td>21.5</td>
<td>11.9</td>
<td>7.8</td>
<td>3.5</td>
<td>19 ± 10</td>
<td>1.0</td>
</tr>
<tr>
<td>Sub total</td>
<td>17.6</td>
<td>20.6</td>
<td>11.4</td>
<td>7.4</td>
<td>15.0</td>
<td>260 ± 41</td>
<td>6.8</td>
</tr>
<tr>
<td>Aug. 17-25</td>
<td>16.1</td>
<td>20.9</td>
<td>10.6</td>
<td>7.4</td>
<td>17.1</td>
<td>100 ± 39</td>
<td>2.7</td>
</tr>
</tbody>
</table>

### 3. Analysis

After the image cleaning to select shower events, average shower rate for three-fold coincidence, \( r_{\text{sh}} \), under good weather conditions is \( \sim 8 \) Hz at zenith. So we exclude data taken with shower rate lower than 5 Hz to keep the data quality. The effective total live time \( t_{\text{liv}} \) after taking into account the DAQ dead-time is 15.0 hours for the outburst period and 17.1 hours for the follow-up observations, respectively, which are also summarized in Table 1.

The moments of the shower image are then parameterized using the so-called Hillas parameters (Hillas et al. 1985), and the arrival directions are reconstructed using intersection of three image axes. The intersection point is obtained by minimizing the sum of squared widths of the three images seen from the assumed point with a constraint on the distance between images’ center of gravity and assumed intersection point considering length/width ratio (IP-fit). After event reconstruction and excluding the truncated images, the Fisher discriminant (FD) method (Fisher 1936) was applied to the data in order to reject numerous cosmic ray background events (Enomoto et al. 2006b). The size-corrected width and length are used as parameters, where probability density function of gamma rays is determined by the Monte Carlo simulation generated assuming a single power-law spectrum, \( \frac{dF}{dE} \sim E^{-\Gamma} \), with an index of \( \Gamma = 3.3 \). The background level was estimated using events in a ring around the source position that is chosen so that \( \theta^2 \) is between 0.2 and 0.5, where \( \theta \) is an angular distance from the source position.

The energy of the gamma rays are estimated based on the same Monte Carlo simulation, and the detection energy threshold \( E_{\text{th}} \) is taken to be the energy of the peak of the distribution of triggered shower sizes.

### 4. Results

The data were divided by zenith angle \( z \) into two data sets, which hereafter we call smallz (\( z < 30^\circ \)) and largez (\( z > 30^\circ \)). FD values are calculated separately for each data set because a probability density function depends on zenith angle. Then the fitting is processed for the summed FD distribution. The result in the outburst period is shown in Fig. 1. We can find a clear excess signal from the direction of PKS 2155-304. The excess is 280±41 events (6.8\σ) within \( \theta^2 < 0.06 \). Using only the smallz dataset, the time-averaged integral flux above 630 GeV is calculated to be \( F (> 630 \text{ GeV}) = (2.3 \pm 0.4) \times 10^{-11} \text{ cm}^{-2} \text{s}^{-1} \) which corresponds to \( \sim 60\% \) Crab.

A night by night gamma-ray flux was also searched. A summary of number of excess events \( N \), the live time \( t_{\text{liv}} \) and significance \( s \) for each night are summarized in Table 1. The nightly averaged integral fluxes using the smallz data set are plotted in Fig. 2. This figure indicates there is a clear nightly time variation of the flux of VHE gamma rays from PKS 2155-304. In particular, the flux in
night of July 30 reached ~100% Crab.

The time-averaged differential fluxes are plotted in Fig. 3. The power-law fit to the data results in a photon index of $3.5 \pm 0.7$ with a flux normalization at 1 TeV of $(2.4 \pm 0.4) \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$. The systematic error in the flux is roughly estimated to be of the order of ~40 %, mainly of which arise from energy scale uncertainties (~15 %), ambiguities of the probability density function of images (~10 %), and the detector systematics (~10 %).

The results in the follow-up observations between August 17 and 25 are also summarized in Table 1. The time-averaged integral flux is obtained to be $F(>630 \text{ GeV}) = (8.9 \pm 3.0) \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ (~25% Crab). It is plotted by open circle in Fig. 2, which shows TeV gamma-ray activity had subsided compared to the outburst period.

5. Discussion

The flux we obtained on July 28 is about one fifth of the reported flux of July 27 reported by H.E.S.S. group (Giebel 2006b), taking into account the energy spectrum assuming a power law index of 3.3. This means that the flux varies at least by a factor five within a dozen hours.
Unfortunately, we cannot investigate shorter time variations due to insufficient statistics, though the H.E.S.S. group reported rapid time variation on timescales of as short as five minutes.

Foschini et al.(2007) reported the X-ray flux increased by a factor five in the 0.3-10 keV energy band without large spectral change and by a factor 1.5 at optical/UV wavelength. The average photon index we obtained in outburst period is also consistent with the value that H.E.S.S. group reported previously (Aharonian et al. 2005)

The difference in longitude between the H.E.S.S. and CANGAROO-III sites is ~120° which corresponds to an eight hour time difference. So the data obtained at each site are complementally and are important for the objects like PKS 2155-304 which show rapid and complex time variations of flux.

6. Conclusion

We observed PKS 2155-304 from July 26 to August 2 and from August 17 to 25 2006 with the CANGAROO-III imaging atmospheric Cherenkov telescopes. We detected statistically significant excess of events from PKS 2155-304 at the 6.8σ level in the effective live time of 15.0 hours in the first observation period. Time variation of the flux of VHE gamma-ray emission on the time scales of days was seen. The time averaged integral flux above 630 GeV is $F > 630 \text{ GeV} = (2.3 \pm 0.4) \times 10^{-11} \text{ cm}^{-2} \text{s}^{-1}$ corresponding to ~60% Crab. Follow-up observations two weeks later show the source activity had decreased to ~20% Crab level.

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