TeV gamma-ray observations of some extragalactic objects with CANGAROO-III

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***Abstract*. CANGAROO-III observations of several extragalactic objects have been made since its launch. Here we present the results for two BL Lac objects (H 2356−309 and PKS 2155−304) and one starburst galaxy (M 83). H 2356−309 was observed in July and August 2005. The quality selected data for a total live time of 26 hours are analyzed, and no excess events in the direction of H 2356−309 are found. The upper limit of the gamma-ray flux above 750 GeV is calculated. Observations of M 83 were done in Mar 2005 for 4 nights. No significant excess events was found, and the flux upper limit was obtained above 490 GeV. We have observed the well-known HBL, PKS 2155−304($z = 0.116$), for 19 nights from July to September 2008 with the CANGAROO-III telescopes including the multiwavelength campaign periods. No significant excess signal was detected, and the average integral flux upper limit was calculated above 720 GeV.**

***Keywords*: gamma rays, blazars, starburst galaxies**

I. INTRODUCTION

Active galactic nuclei are the only extragalactic source class of TeV gamma-ray emissions so far detected since the detection of Mrk 421 by the Whipple group [1]. Most of them are classified as blazars, which are characterized by rapid variability and high energy emission. Two peaks in the spectral energy distribution are observed. The lower energy component is believed to be synchrotron emission of relativistic electrons and the higher component is probably explained by the inverse Compton scattering of seed photons by the same population of electrons (see, *e.g.*, [2],[3],[4], [5]). However, hadronic models, where the emission is assumed to be produced via the interactions of relativistic protons with matter, still remain (*e.g.*, [6],[7],[8]). In each case, a supermassive black hole in the center of these objects is believed to play a major role in the high energy emission [9]. In addition, due to the absorption of TeV gamma rays via e^+e^- pair production with the photons of the extragalactic background light (EBL), the distorted spectrum provides strong constraints on the density of EBL.

H 2356−309 is one such high-frequency-peaked BL Lacertae object (HBL) located at a redshift of $z = 0.165$ [10]. It was first detected in X-rays by the Uhuru satellite [11]. This object was listed as a possible TeV source candidate by Costamante & Ghisellini [12] based on a simple one-zone SSC model. In 2004, the H.E.S.S. group discovered TeV gamma rays from H 2356−309 at the 2% Crab flux level above 200 GeV [13]. They reported indications of variability on an annual and monthly time scale, and qualified this object as an extreme synchrotron blazar. They also provided an upper limit on the EBL at near infrared wavelengths from the observed hard spectrum, and showed the EBL at these wavelengths is strongly dominated by the direct starlight from galaxies [14].

One of the potential class of extragalactic sources of TeV gamma-rays is a starburst galaxy. The star formation rate in a starburst galaxy is much higher than in a normal galaxy, and also a higher rate of supernovae is implied. Assuming supernova remnants accelerate cosmic rays, detectable TeV gamma rays may be expected via π^0 decay process. Theoretical calculations of TeV gamma-ray emission from these objects such as NGC 253 and M 82 are done by some authors (e.g., [15], [16], [17]), and the observational upper limits are reported in [18], [19], and [20].

M 83 is a nearby (4.5 Mpc [21]) starburst galaxy which can be observed in the southern hemisphere, although the FIR flux of M 83 is lower compared to NGC 253 by a factor of three or more (e.g., [22]) making it is a less promising candidate. This object was observed by H.E.S.S. in July 2006, and an upper limit on the integral flux of $2.21 \times 10^{-12}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ ($>$ 330 GeV at 99.9% C.L.), was reported [23].

CANGAROO-III observations of these objects were made in 2005. The results of these observations, which have not previously been reported, are presented here.

PKS 2155−304 is a well known HBL ($z = 0.116$ [24]) which has been detected with several IACTs [25][26][27] and many multiwavelength campaigns have been organized. The H.E.S.S. team has been monitoring PKS 2155−304 and found an extraordinary TeV flare in 2006 [28]. CANGAROO-III also observed PKS 2155−304 in 2006, and successfully detected TeV gamma-rays during active periods [27]. In 2008, a multiwavelength campaign of this object was performed. A part of the results were reported in Aharonian et al. [29]. CANGAROO-III observations have been made including the campaign period in 2008, and the results are also presented here.

II. CANGAROO-III Observations and analysis

The CANGAROO-III imaging atmospheric Cherenkov telescope system is operated near Woomera, South Australia (longitude 136°47′ E, latitude 31°06′ S, 160 m a.s.l.). The effective mirror area of each telescope is 57 m^2 and the field of view of each imaging camera is $\sim 4°$, made up of 470 pixels. The details of these system are described in [30], [31] and [32]. Three (T2, T3, and T4) out of the four telescopes were used in these observations in 2005 and newer two (T3 and T4) were used in 2008 due to a deterioration of the other telescopes. Furthermore, due to a problem of DAQ electronics of T2 in 2005, only the data from T3 and T4 were used in these analyses. These observations were made using so-called wobble mode, in which the pointing position of each telescope was shifted in declination by $\pm 0.5°$ from the target position alternatively every 20 minutes.

Using the information of a calibrated number of photoelectrons and an arrival timing for each pixel, and considering their hit pattern, the images were cleaned to eliminate night-sky background photons and shower images were selected. Then, the moments of each shower image are parameterized using Hillas parameters and the arrival directions are reconstructed using the intersection of image axes.

After event reconstruction, numerous cosmic-ray background events are rejected based on the Fisher discriminant (FD) method [33]. All results presented here are obtained using the standard FD cut of CANGAROO-III analysis. The FD cut criteria is determined from the Monte Carlo study assuming a power-law spectrum with the photon index Γ of the gamma rays. As a redundancy analysis, the FD fit method is also applied, and it is confirmed to give the same results within statistical errors. The background level was estimated using off-source data in the corresponding region in the other side of the field of view. For further details of the above data reduction, data cleaning, and background rejection, see Sakamoto et al. [27] and references therein. The primary gamma-ray energy is also estimated based on the same Monte Carlo simulation.

III. Observed extragalactic objects

A. *H 2356−309*

H 2356−309 was observed by CANGAROO-III for 15 nights in July and August 2005. The total live time used for analysis after good-quality data selection is 26.3 hours. We select the events with FD > -0.1 as candidate gamma-ray events based on the Monte Carlo simulation assuming a single power-law spectrum with $\Gamma = 3.1$ [13] of the gamma rays from H 2356−309.

Distributions of squared angular distribution of on-source and off-source events are shown in the left panel of Fig. 1, and the excess events of the on-source above the off-source level is shown in the right panel of the same figure. From these figures, we can find no significant TeV gamma-ray excess from the H 2356−309 region. The 2σ upper limit on the integral flux is $F(> 750\ \mathrm{GeV}) < 5.7\times10^{-12}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The upper limit is roughly an order of magnitude higher than the average flux in 2004 reported by the H.E.S.S. [13].

B. M 83

CANGAROO-III observed M 83 in March 2005 for only 4 nights because of the bad weather. After applying standard data selection criteria, the total live time used for analysis is only 8.3 hours. From the Monte Carlo simulation, assuming a single power-law spectrum with $\Gamma = 2.5$ of the gamma rays from M 83, the FD cut criteria is determined to be -0.2.

Fig. 2 left and right panels show the distributions of squared angular distribution of on-source and off-source events and the excess events of the on-source above the off-source level, respectively. No hint of gamma-ray excess from M 83 region is apparent in these figures. The resulting integral flux upper limit at 2σ level is $F(> 490\ \mathrm{GeV}) < 1.1\times10^{-11}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, which corresponds to $\sim 20\ \%$ Crab unit [34]. Following the discussions in [16], the upper limit of cosmic ray energy density is roughly estimated to be $\sim 100\ \mathrm{eV\ cm}^{-3}$. However, we need much deeper observations for limiting the TeV gamma-ray emission models and/or discussing the physics condition of starburst galaxies.

C. PKS 2155−304

We observed PKS 2155−304 from 2008 July 29 to September 27 with the CANGAROO-III imaging Cherenkov telescopes. After standard good-data selection, the total live time used for analysis is 47.3 hours out of the total observation time of 58.5 hours. Based on the Monte Carlo simulation assuming a single power-law spectrum with $\Gamma = 3.3$ [26], FD cut criteria is set to be -0.1.

After FD cut, the θ^2 distributions of on-source data and off-source data, and the distribution of excess events from the direction of PKS 2155−304 against θ^2, are shown in Fig. 3 left and right panels, respectively. No significant excess was found from these figures. During this period, the object was low state in TeV regime as reported by the H.E.S.S. [29] group. The preliminary 2σ flux upper limit above 720 GeV is calculated from Fig. 3, and is $F(> 720\ \mathrm{GeV}) < 2.7\times10^{-12}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. This limit is slightly above the averaged integral flux reported by the H.E.S.S. [29]. It is also reported in [29] that ~ 30 % variability above 100 GeV was seen and the flux in the late of August is a little bit higher. We analyzed the data taken for four nights in the late of August, but no significant gamma-ray signal was detected and the flux upper limit at 2σ level during this period is estimated to be $5.0\times10^{-12}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (> 720 GeV).

IV. SUMMARY

We have observed several extragalactic objects with the CANGAROO-III imaging atmospheric Cherenkov telescope system. The results of two HBLs, H 2356−309 and PKS 2155−304, and one starburst galaxy, M 83 are presented. No significant excess events are detected and the upper limits of the flux are obtained. For the discussion of physics processes, deeper observations are required.

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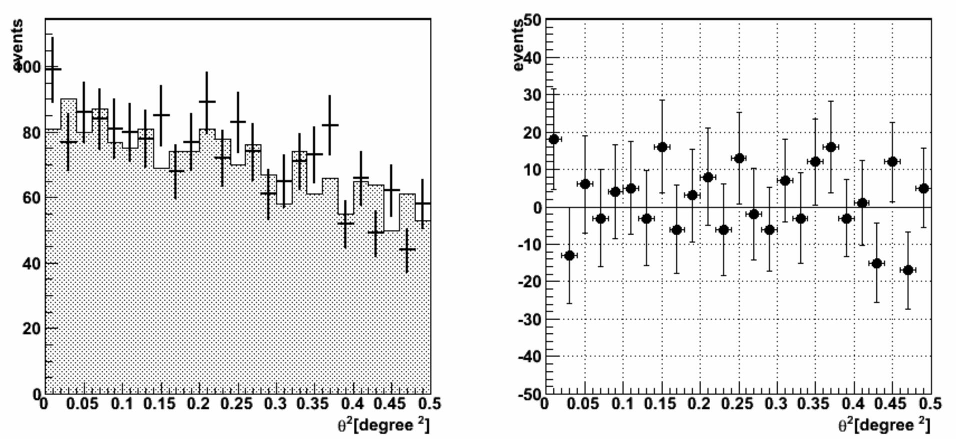

Fig. 1. Left panel: Squared angular distance, θ^2, distribution of on-source ($errorbars$) and off-source ($histogram$) events of the CANGAROO-III observations of H 2356−309. Right panel: Excess events of the on-source above the off-source level.

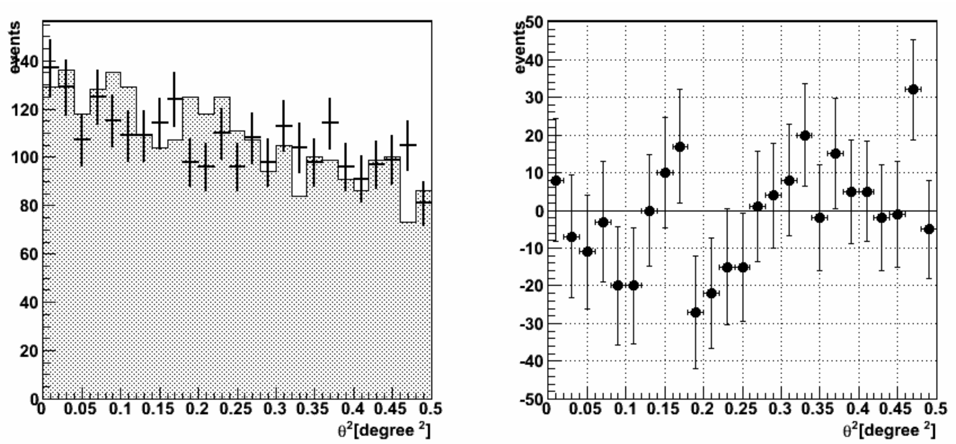

Fig. 2. Left panel: θ^2 distribution of on-source ($errorbars$) and off-source ($histogram$) events for M 83. Right panel: Excess events of the on-source after the off-source subtraction.

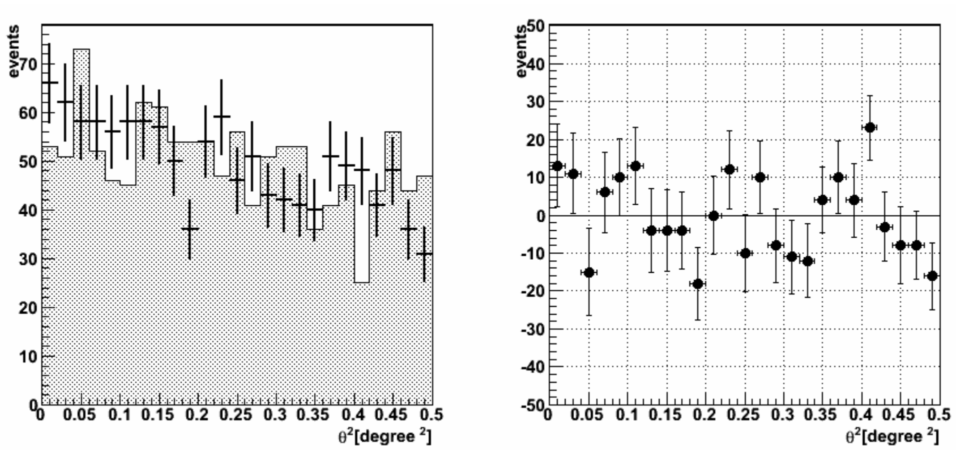

Fig. 3. Left panel: θ^2 distribution of on-source ($errorbars$) and off-source ($histogram$) events for PKS 2155−304. Right panel: Excess events of the on-source after the off-source subtraction.