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Observation of TeV Gamma-ray from the Active Radio Galaxy Centaurus A with CANGAROO-III

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We have observed the giant radio galaxy Centaurus A (Cen A) in the TeV energy region using the CANGAROO-III stereoscopic system. The system has been in operation since 2004 and is an array of four Imaging Atmospheric Cherenkov Telescopes (IACT) with about a 100 m spacing. The observations were carried out between March and April 2004. In total 20-hour data were obtained. No statistically significant gamma-ray signal has been found above 530 GeV and we obtain an integral flux upper limit of 3.2 $\times 10^{-12}$ cm^{-2} sec^{-1} (2-σ level). This upper limit is less than 7 % of the gamma-ray flux from the Crab nebula. Although some groups reported detections of Cen A in the past, we give upper limits more than one-order of magnitude lower for this object.

1. Introduction

Cen A is classified as a "misaligned" BL Lac type AGN at higher energies [1]. It is one of the best examples of a radio-loud AGN viewed in $\sim 60°$ from the jet axis [2, 3, 4] . The distance of Cen A is reported by many people around 2$\sim$8 Mpc. In this paper, we adopt a distance to Cen A of 3.5 Mpc [5]. It could be a good TeV gama-ray candidate with its high luminosity and its vicinity.

Although the first positive measurements of high energy gamma-rays from Cen A was reported in the 1970s, many later attempts have failed. First, the Narrabri Observatory reported a positive detection with a flux of $I(>0.3\,\mathrm{TeV}) \sim (4.4 \pm 1) \times 10^{-11}$ photon cm^{-2} sec^{-1} [6]. Buckland Park and the JANZOS Observatory also detected gamma-rays during burst states (Buckland Park : $I(>100\,\mathrm{TeV}) \sim (7.4 \pm 2.6) \times 10^{-12}$ photon cm^{-2} sec^{-1} [9], and JANZOS (burst) : $I(>150\,\mathrm{TeV}) \sim (5.5 \pm 1.5) \times 10^{-12}$ photon cm^{-2} sec^{-1} [7]. Thus, Centaurus A was one of promising extragalactic sources radiating VHE gamma-rays. However, CANGAROO-I [10], JANZOS (in steady states) [7], and Durham [8] observed the Cen A nucleus part and set moderate upper limits on the emission in the VHE range.

2. Analysis and Results

We took data on Cen A from 2004 Mar to Apr. The pointing position is $(\alpha, \delta) = (201°.365, 43°.019)$, the center of galaxy. The observation mode was again chosen to be the Wobble mode. The average zenith angle is 17 deg. The observation periods are summarized in Table 1.

Table 1. Summary of the Cen A observation periods.

Observation Date	Observation time (T2-T3)	Observation time (T2-T4)
15-Mar. – 28-Mar. 2004	643 min	452 min
15-Apr. – 28-Apr. 2004	554 min	468 min
Total	1197 min	920 min

The analysis method is described in Enomoto et al [11]. First, the cloud and elevation cuts were applied. we chose 7 Hz for the cloud cut and the elevation cut was chosen greater than the 60 degree. We applied a $Likelihood$ cut for the final selection The gamma-ray's PDFs (Probability Density Functions) can be obtained from the MC simulation and proton's can be obtained from the OFF data. Then we can define,

$$Likelihood\,ratio\;L = \frac{PDF(gamma-ray)}{PDF(gamma-ray)+PDF(proton)} \tag{1}$$

The Likelihood ratio cut of 0.9 was used.

The θ^2 distribution is shown in Fig 1. The points with statistical error bars show the θ^2 distributions of the ON-source data. The hatched area shows the OFF-source data. Six non-overlapping regions with the same radius as the target position were used as OFF-source in the same FOV observed regions in the Wobble mode. For this reason, the OFF-source data were normalized by the ratio of 1/6. We cannot see any statistically significant excess events in θ^2 <0.047 degree^2. 2-σ flux upper limits are shown in Fig 2. The arrows at 10^{12} eV region are the CANGAROO-III flux upper limits. The flux level is approximately 7 % Crab [12]. Here we include the systematic error.

3. Discussions

Our upper limits are approximately 1/10 compared with previous reports [6, 7, 8, 9, 10].

Here we consider the possibility on HBL (high-frequency-peaked BL Lac object) assumption. If we assume the peak frequency of the synchrotron radiation is located at 100 MeV, we can regard the data of radio and COMPTEL measurements as due to synchrotron radiation (Fig 2). The blue line is plotted after the theoretical calculation assuming that electron power-law index is -2.5. This value is adopted from radio observations. Here E^e_{max} is assumed to be 100 TeV and B to be 0.01 G which are typical in AGN models. In this case, the

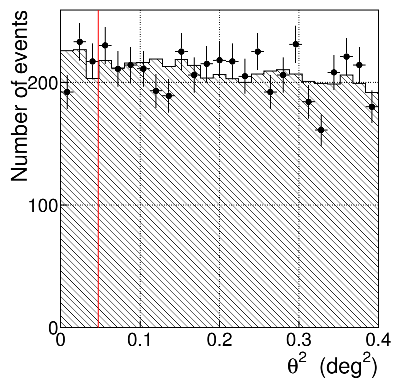

Figure 1. θ^2 distribution. The points with statistical errors show the θ^2 distributions of the ON-source data. The hatched area shows the Off-source data. The OFF-source data were normalized by the ratio of number of background points, i.e., 6 regions. The red line is the θ^2 cut $(0.°217)^2$.

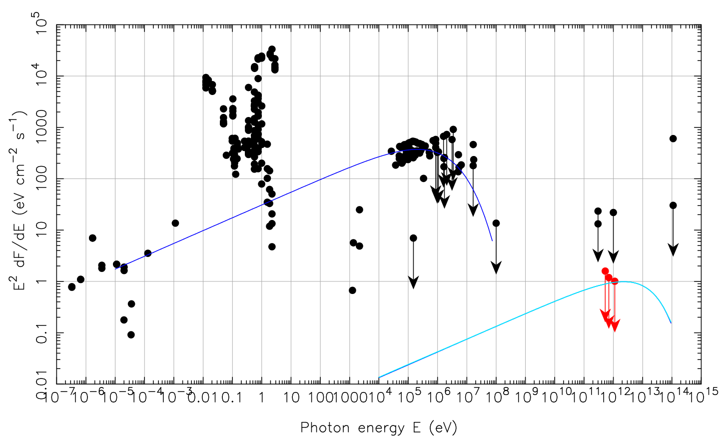

Figure 2. SED of HBL model. The blue line is synchrotron radiation and the higher-energy light-blue is IC emission line. The radio observations are plotted around $10^{-7} \sim 10^{-4}$ (eV). The infrared and optical observations are plotted around $10^{-2} \sim 10^{1}$ (eV). The X-ray observations which are plotted around $10^3 \sim 10^4$ (eV) are ROSAT [13] and EINSTEIN [14]. The MeV gamma observations which are plotted around $10^4 \sim 10^8$ (eV) are OSSE, EGRET, COMPTEL and BATSE [15, 16]. The red arrows are CANGAROO-III flux upper limit.

maximum energy of TeV gamma-rays which are emitted by the inverse Compton (IC) scattering is affected by the Klein-Nishina suppression and $\nu_{ssc}/\nu_{sync} \sim 10^7 < 10^8$, (light blue line in Fig 2). The IC line is scaled so that it does not exceed our upper limit (~1 eV cm^{-2} sec^{-1} at 1 TeV). Then, we find the upper limit, $L_{ssc}/L_{sync} < \frac{1}{400} \ll 1$. This value is small compared with "typical" blazars which show $L_{ssc}/L_{sync} \sim 1$. The result leads to the conclusion that it is not a "typical" HBL, although having jets and flares. Considering that our angular resolution is larger than the size of jets observed in the radio, we can consider the size of the emission region, R, as a free parameter. Then we obtain

$$B > 210\mu\text{G} \times (R/12\,\text{kpc})^{-1}.$$

In the cases of Mkn 421 and 501, the TeV emission regions are considered to be $10^{16} \sim 10^{17}$ cm. Even in the rest frame of the relativistic jets, it is $10^{17} \sim 10^{18}$ cm which is far less than 1 pc. The above formula gives $B >$ a few Gauss which is high even compared with the geomagnetic field of the earth, and high compared with typical estimations of several mG. A field energy of this magnitude within such a large volume is extemely large. This would give more stringent lower limit than the above result.

4. Conclusions

In this paper, we show the result of the first stereoscopic observation of Cen A with CANGAROO-III telescopes. The observation period was from Mar. 16 to Apr. 19 2004 and the total observation time was 1197 min. We could not detect any TeV gamma-ray signal and the 2-σ upper limit was obtained to be $3.2 \times 10^{-12}\,\text{cm}^{-2}\,\text{sec}^{-1}$ at energies greater than 530 GeV. This 2-σ upper limit corresponds to be approximately 7 %-Crab flux. This is an order of magnitude lower than past data. We derived physical parameters for an HBL model using our upper limits and multi-wavelength spectra. Assuming a volume of the emission region to be that defined by our angular resolution, $B > 210\,\mu\text{G}\,(R/12\,\text{kpc})^{-1}$, was finally obtained. Even using a size of an order of a light year, it exceeds one Gauss, a situation which can be hardly understood. We conclude that Cen A is not classified as a normal HBL.

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