Recent CANGAROO observations of extra-galactic objects

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Abstract

This report outlines recent notable extra-galactic source observations by the CANGAROO-II 10-m telescope. Flux upper limits above ∼400 GeV were obtained from observations of the BL Lacertae object, PKS 2155−304, in 2000 and 2001. Diffuse gamma-ray emission from the starburst galaxy NGC 253 was also detected at a high confidence level, and E>10 TeV gamma-rays were observed with 5.7 σ significance from Markarian 421 by very large zenith angle observations.

1. Introduction

Since the diameter of the mirror was extended to 10 m in March 2000 [16], the CANGAROO-II telescope has been used extensively to observe several can-

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didate extra-galactic TeV gamma-ray emitters. Although active galactic nuclei (AGNs) are known sources of TeV gamma-ray emission, the present observations were targeted at other extra-galactic sources in order to explore cosmic-ray phenomena in the universe. This proceeding presents selected results of recent extra-galactic source observations using the CANGAROO-II 10 m telescope.

2. CANGAROO extra-galactic source observations

2.1. Search for TeV AGN in the southern hemisphere

The search for TeV AGNs in the southern hemisphere is an important part of the CANGAROO-II project. In the northern hemisphere, apart from the two well-documented AGNs, Markarian 421 (Mrk 421) and Markarian 501 (Mrk 501), a number of TeV gamma-ray AGN source have been reported, including 1ES 2344+51 (z=0.044) [6], 1ES 1959+650 (z=0.048) [9] [19], and H 1426+428 (z=0.129) [2] [11]. Among southern AGNs, PKS 2005−489, PKS 0548−322, and PKS 2155−304, are considered to be promising TeV gamma-ray candidates, as they belong to the group of high-frequency BL Lacertae objects (HBL). These AGNs have been investigated using several small-diameter telescopes [7] [8] [22]. A larger aperture telescope, with an energy threshold of ∼400 GeV, was expected to be able to detect gamma-rays from these AGNs because sub-TeV gamma-rays from extra-galactic sources are less affected by interaction with the cosmic infrared photon background compared to those at TeV energies. Observations of these AGNs were made in 2000 and 2001, as listed in Table 1.. In this paper, only a brief summary of the observation of PKS 2155−304 is presented.

Despite approximately 65 h of ON-source data and extensive analysis and processing [17], no significant TeV gamma-ray signals were detected for PKS 2155−304. The upper limit for integral flux was derived using Monte Carlo simulations of the telescope response, as shown in Fig 1.. Based on a confidence level of 2 σ, the integral flux limits are $F(> 420\ \mathrm{GeV}) < 1.0 \times 10^{-11}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ and $F(> 420\ \mathrm{GeV}) < 1.2 \times 10^{-11}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for the 2000 and 2001 observations, respectively. A search on a night-by-night timescale for transient flares was also performed, and the results are presented in another paper in these proceedings [17].

2.2. Evidence for TeV gamma-rays from NGC 253

NGC 253 is a nearby (∼2.5 Mpc) starburst galaxy [24] with a high supernova rate (0.05 yr^{-1}), as estimated from observations of high far-infrared luminosities inside the galaxy. The galaxy is also expected to have high cosmic-ray

BL Lac	Type	Redshift	Exposure (h)	
			2000	2001
PKS 2005−489	HBL	0.031	17	-
PKS 0548−322	HBL	0.069	3	-
PKS 2155−304	HBL	0.116	18	20

Table 1. Observation summary of southern AGNs using the CANGAROO-II telescope in 2000 and 2001

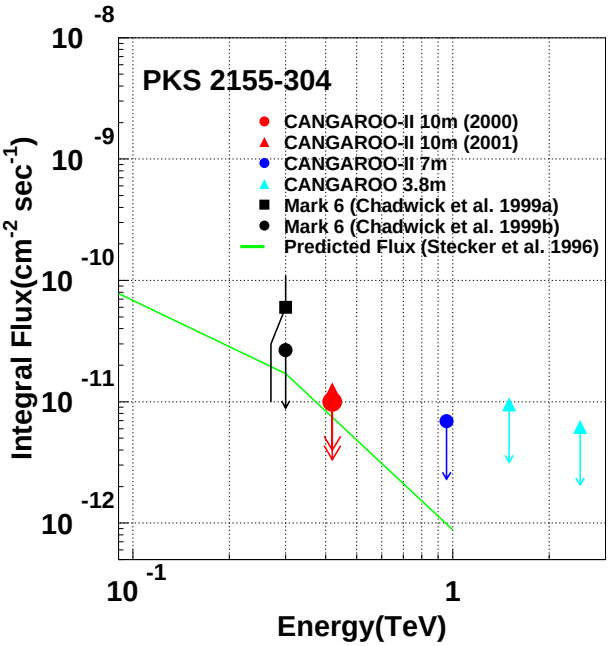

Fig. 1. Upper limits of integral flux for PKS 2155−489 in 2000 (squares) and 2001 (triangles)

density [25]. A very large radio halo, extending for over ∼10 kpc [5] [12], suggests the existence of a population of very high-energy cosmic ray sources.

A total of ∼75 h of observations were made for NGC 253 in 2000 and 2001. After selecting gamma-ray–like events using the likelihood event discrimination method, gamma-ray signals were obtained with high statistical significance level of 11.1 σ. The energy threshold is estimated to be around 500 GeV. As the *alpha* distribution (Fig. 2.) is broader than the expected point spread function, the spatial distribution of gamma-rays from NGC 253 is inconsistent with emission from the point source assumption. Further analysis results, including energy spectrum and morphology, can be found elsewhere [13] [14].

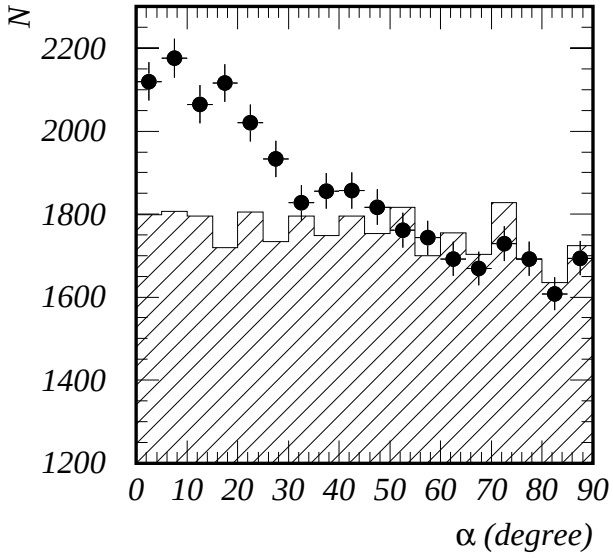

Fig. 2. Alpha distribution obtained by NGC 253 observation

2.3. Observation of E>10 TeV gamma-rays from Markarian 421

Recent precise measurements of gamma-rays from Mrk 501 and Mrk 421 have revealed a cutoff feature in the energy spectra [1] [15]. This feature is probably caused by photon-photon interactions with the inter-galactic infrared background [10] [18] [23], with the effects most prominent at higher energies (>10 TeV).

Mrk 421 culminates at an elevation angle of just over 20 degrees from the CANGAROO-II telescope site. Very large zenith angle observations provide a larger effective area ($\sim 5 \times 10^9 \mathrm{cm}^2$ at E=20 TeV), but also a higher energy threshold of ∼10 TeV. This observation technique is therefore suitable for probing smaller gamma-ray fluxes at higher energies. Observations of Mrk 421 were

conducted in January and March 2001 during the extremely high state of this AGN [4]. From 14 h ON-source exposure, an excess of 293 ± 52 gamma-ray–like events were detected with 5.7 σ significance, as shown in the left panel of Fig. 3.. The derived differential energy spectrum was
$dN/dE = (3.3 \pm 0.9_{stat.} \pm 0.3_{syst.}) \times 10^{-13}\ (E/10\ \mathrm{TeV})^{-(4.0\,^{+0.9}_{-0.6}\,_{stat.} \pm 0.3_{syst.})}$
ph./cm^2/sec/TeV which does not contradict the exponential cutoff reported by other experimental groups [3] [15]. However, a larger cutoff energy of ∼8 TeV is required to explain the observed spectrum. More details of data analysis and results are described elsewhere [20] [21].

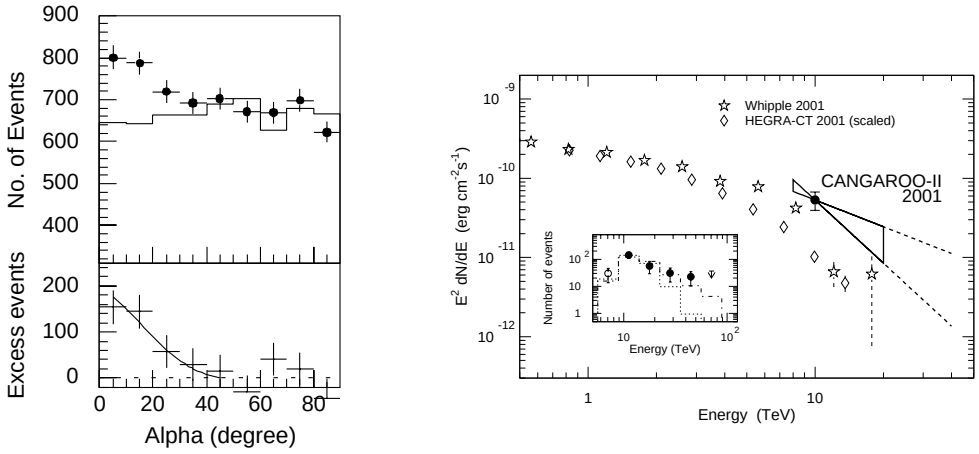

Fig. 3. Alpha distribution (left) and differential energy flux (right) for Markarian 421

3. Summary

Several extra-galactic objects were explored by observations in the energy range from sub-TeV to several 10 TeV using the CANGAROO-II 10-m telescope. An integral flux upper limit of greater than ∼400 GeV was obtained for southern BL Lac, PKS 2155−304, based on observations in 2000 and 2001. NGC 253 was discovered as the first of a new class of objects detectable at TeV energies. Large zenith angle observations of Mrk 421 successfully resolved high-energy gamma-rays of greater than 10 TeV during a flare.

References

[1] Aharonian, F. A. et al. 1999, A&A, 349, 11

[2] Aharonian, F. et al. 2002, A&A, 384, L23

[3] Aharonian, F. A. et al. 2002, A&A, 393, 89

[4] Börst, H. G., Götting, N & Remillard, R 2001, IAU Circ. 7568

[5] Carilli, C. L., Holdaway, M. A., Ho, P. T. P., & de Preee, C. G. 1992, ApJ, 399, L59

[6] Catanese, M. et al. 1998, ApJ, 510, 616

[7] Chadwick P. M. et al. 1999, Astropart. Phys. 11, 145

[8] Chadwick P. M. et al. 2000, A&A, 364, 450

[9] Götting, N et al. 2001, talk presented at Proc. 27th ICRC, Hamburg

[10] Gould, R. J. & Schrèder, G. 1967, Phys. Rev., 155, 1408

[11] Horan, D. et al. 2002, ApJ, 571, 753

[12] Hummel, E., Smith, P. & van der Hulst, J. M. 1984, A&A, 137, 138

[13] Itoh, C., et al. 2002, in these proceedings

[14] Itoh, C., et al. 2002, A&A, 396, L1

[15] Krennrich, F. et al. 2001, ApJ, 560, L45

[16] Mori M. et al. 2001, Proc. 27th Int. Cosmic Ray Conf. (Hamburg), 5, 283

[17] Nakase, T., Nishijima, K. et al. 2002, in these proceedings

[18] Nikishov, A. I. 1962, Sov. Phys. JETP, 14, 393

[19] Nishiyama, T. et al. 1999 Proc. 26th ICRC, Vol. 3, 370

[20] Okumura, K. et al. 2002, in these proceedings

[21] Okumura, K. et al. 2002, ApJ, 579, L9

[22] Roberts, M. D. et al. 1999, A&A, 343, 691

[23] Stecker, F. W., de Jager, O.C., Salamon, M.H. 1992, ApJ, 390, L49

[24] Vaucouleurs, G. de 1978, ApJ, 224, 710

[25] Voelk, H. J., Aharonian, F. A., & Breitschwerdt, D. 1996, Space Sci. Rev., 75, 279