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Very High Energy Gamma-ray Observations of AGN with CANGAROO

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Abstract: We have observed eight AGN since 1993 in the energy region above several hundred GeV using the CANGAROO telescopes. We observed Mrk 421 for ten nights with the CANGAROO-II 10 m telescope during its active state in early 2001 using the very large zenith angle technique. Our preliminary result implies the detection of gamma-ray emission from Mrk 421 in the energy range above 9.3 TeV. The high energy peaked BL Lacs (HBLs) PKS 2005–489 and PKS 2155–304 have been also observed. No statistically significant signals are found for both HBLs and flux upper limits are obtained. A summary of results of observations of AGN is presented in this paper.

Keywords: BL Lacertae objects: individual (Mrk 421, PKS 2005–489, PKS 2155–304) — galaxies: active — gamma rays: observations

1 Introduction

Using the imaging atmospheric Cerenkov technique, six active galactic nuclei have been reported to emit gamma rays at TeV energies (Punch et al. 1992; Quinn et al. 1996; Neshpor et al. 1998; Catanese & Weekes 1999; Chadwick et al. 1999a; Kajino et al. 1999). Only Mrk 421 and Mrk 501 have been confirmed as very high energy (VHE) sources by multiple groups. They have also been targets of simultaneous multiwavelength campaigns. Their distinctive features are extreme variability on a wide range of timescales and good time correlation between X-ray and VHE gamma-ray intensities (Catanese & Weekes 1999). Their spectral energy distribution seems to be well explained by two components, synchrotron emission produced by relativistic electrons, and inverse Compton photons scattered by the same population of electrons (see e.g. Ulrich, Maraschi, & Urry 1997).

Confirmation of the other sources by other groups is required, although, as these sources are clearly time variable, confirmation is not a simple matter. The detection of gamma rays from such sources will enable gamma-ray emission models to be tested, and will also contribute to estimates of the density of extragalactic background light through VHE gamma-ray absorption.

PKS 2155–304 and PKS 2005–489 are two of the most likely extragalactic objects to be detected by imaging atmospheric Cerenkov telescopes in the southern hemisphere above 100 GeV (Stecker, de Jager, & Salamon 1996). Detection of VHE gamma rays from PKS 2155–304 during a multiwavelength campaign in November 1997 was reported by Chadwick et al. (1999a) which seemed to be correlated with a strong X-ray flare observed by Beppo-SAX.

Prior to 1997, the CANGAROO 3.8 m telescope was used to observe several nearby AGN. Since June 1999 we have observed several southern HBLs with the CANGAROO-II 7 m and 10 m telescopes, including PKS 2005–489 and PKS 2155–304 and also the northern BL Lac object Mrk 421. Here we present the results of analysis of AGN observed with the CANGAROO 3.8 m and CANGAROO-II 7/10 m telescopes.

2 Observation of AGN

After successful operation of the 3.8 m imaging Cerenkov telescope for seven years, we constructed a new telescope, CANGAROO-II, which was initially a 7 m dish and was expanded to its full 10 m diameter in March, 2000. The CANGAROO-II telescope is located near Woomera, South Australia (longitude 137°47′E, latitude 31°06′S, 160 m a.s.l.). The 10 m telescope is described in detail in Mori et al. (2001) and references therein.

The observations were done by the so-called on–off scan mode. We track the target object during on-source scans and track an off-target during the off-source scan, tracing the same range of azimuth and zenith angles as during the on-source scan. Observed targets, year of observation, observation time of on-source scan and so on are summarised in Table 1.

3 Results

3.1 Mrk 421

Mrk 421 is the first extragalactic source from which TeV gamma-ray emission was detected. We observed Mrk 421 for ten clear nights between 24 January and 1 February and from 1 to 4 March, 2001 (Okumura et al. 2001). Our observation was carried out using the very large zenith angle technique. The average zenith angle is about 70 degrees. Such large zenith angles lead to a higher threshold energy, however, with a larger detection area than at the zenith (Sommers & Elbert 1987). The energy threshold and average effective area, calculated from Monte Carlo simulations, are 9.3 TeV and 5×10^9 cm^2, respectively.

* For the CANGAROO Collaboration.

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Table 1. AGN observation summary. Present work including preliminary results with the CANGAROO-II 7/10 m telescope is indicated by c in the last column. Other data are taken from a: Roberts et al. (1998a), b: Roberts et al. (1998b), and d: Rowell et al. (1999), which were all obtained with the 3.8 m telescope

Target	z	Year	Time (hr)	E (TeV)	Flux ($cm^{-2}\,s^{-1}$)	Ref
EXO 0423.4–0840	0.039	1996	20	2.0	$<1.1 \times 10^{-12}$	a
PKS 0521–365	0.055	1995–96	89	2.0	$<1.0 \times 10^{-12}$	a
PKS 0548–322	0.069	1997	26	1.5	$<4.3 \times 10^{-12}$	b
		1999	16.6	1.0	$<1.0 \times 10^{-11}$	c
		2000	2.6			
PKS 2005–489	0.071	1993–94	41	2.0	$<1.1 \times 10^{-12}$	a
		1997	17	1.5	$<7.0 \times 10^{-12}$	b
		1999	26.2	1.1	$<6.6 \times 10^{-12}$	c
		2000	32.6	0.45	$<6.4 \times 10^{-12}$	c
PKS 2155–304	0.116	1997	18	1.5	$<9.5 \times 10^{-12}$	b
		1999	58.5	0.96	$<6.9 \times 10^{-12}$	c
		2000	35.6	0.40	$<1.2 \times 10^{-11}$	c
PKS 2316–423	0.055	1996	26	2.0	$<1.2 \times 10^{-12}$	a
Cen A	3.5 Mpc	1995	23	1.5	$<5.5 \times 10^{-12}$	d
Mrk 421	0.031	2001	14.4	9.3		c

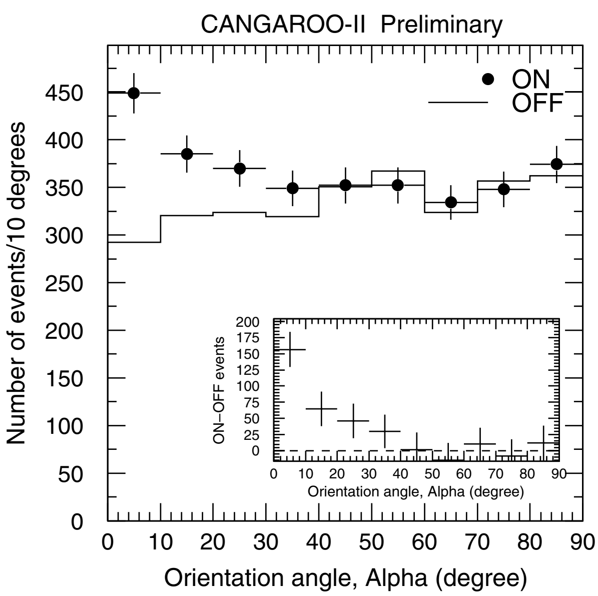

Figure 1 Distribution of image orientation angle *alpha* of Mrk 421 observed by the CANGAROO-II 10 m telescope. Closed circles with error bars are on-source data and the solid histogram indicates the off-source data. The subtracted background distribution is also shown.

Figure 1 shows the distribution of image orientation angle *alpha*. The excess events within 20 degrees after subtraction of background is 221 ± 39 events, which corresponds to a significance of 5.6σ. The broader *alpha* distribution is consistent with the prediction from gamma-ray simulations at very large zenith angles.

3.2 *PKS 2005–489*

PKS 2005–489 was observed many times with the 3.8 m, 7 m, and 10 m telescopes, as shown in Table 1. RXTE observations were carried out from 28 July to 1 August, and from 25 August to 3 September, 2000, during the CANGAROO observing periods.

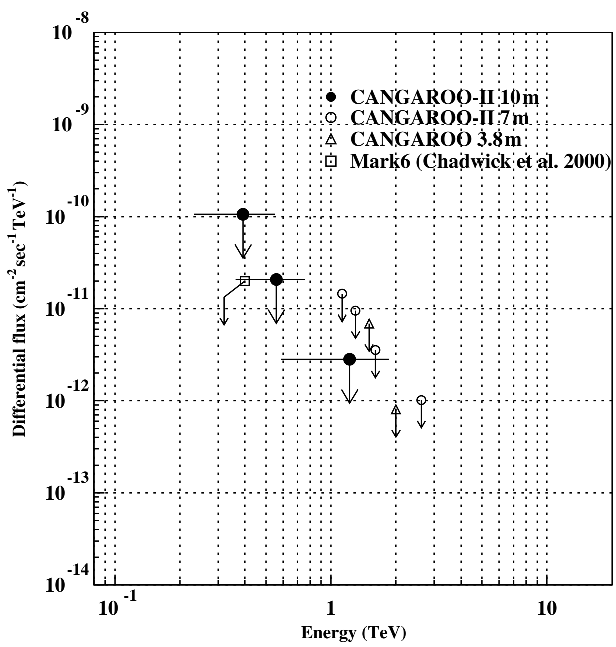

Figure 2 Differential energy spectrum of PKS 2005–489. The 2σ flux upper limits from the present work are denoted by the closed circles. The open circles and open triangles show the upper limits obtained from quick-look analysis of CANGAROO-II 7 m and CANGAROO 3.8 m observations (Roberts et al. 1998a,b), respectively. The open square indicates the upper limit reported by Chadwick et al. (2000).

We have seen no evidence for persistent gamma-ray emission from PKS 2005–489. During our observation periods, it remained in a low level state. Flux upper limits (2σ) obtained for each threshold energy with each telescope are shown in Table 1. The differential fluxes are plotted in Figure 2. All points are 2σ upper limits.

The upper limit calculated from the integral flux reported by Chadwick et al. (2000) is also plotted in the same figure. We have also searched for gamma-ray emission on a night-by-night basis, but no significant excess was detected on any night.

3.3 PKS 2155–304

As shown in Table 1, we have observed PKS 2155–304 for more than 100 hours including participation in the multi-wavelength campaign from 27 to 31 August, 2000. No X-ray flares were detected during our observations.

We have seen no evidence for persistent gamma-ray emission from PKS 2155–304. Flux upper limits (2σ) for PKS 2155–304 are summarised in the same table. The differential energy spectrum is shown in Figure 3. Our data are all upper limits. The estimated differential flux in the high level state reported by the Durham group (Chadwick et al. 1999a) is plotted together with their upper limit from a low level state (Chadwick et al. 1999b). A night-by-night basis analysis shows no evidence for gamma-ray flares on the timescale of about one day during our observations.

3.4 Other AGN

The results of observations of other AGN are also summarised in Table 1. There is no evidence for gamma-ray emission from any of these objects. For some, we have searched on night-by-night timescales for flares of emission: no significant excess has been detected on this timescale.

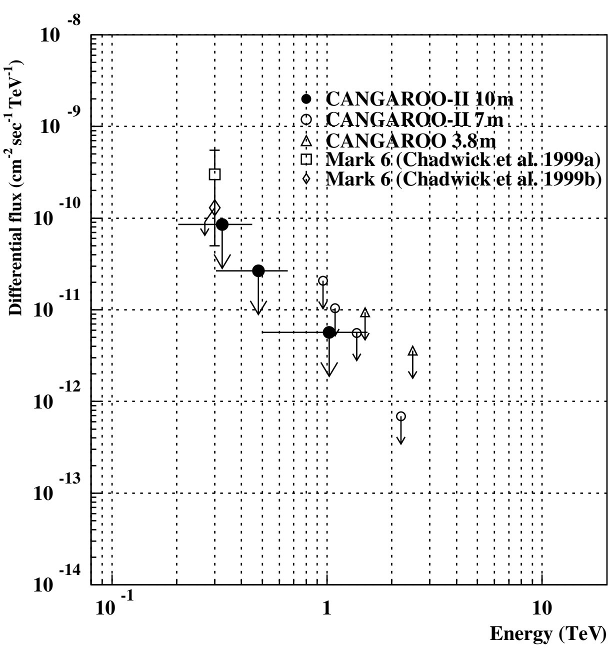

Figure 3 Differential energy spectrum of PKS 2155–304. The 2σ flux upper limits from the present work are shown by the closed circles. The open circles and open triangles show the upper limits obtained from quick-look analysis of CANGAROO-II 7 m and CANGAROO 3.8 m observations (Roberts et al. 1998a,b), respectively. The open square and open diamond indicate the flux and the flux upper limit reported by Chadwick et al. (1999a,b).

4 Discussion

The result shown in Figure 1 implies the detection of gamma rays from Mrk 421 in the energy range above 10 TeV. However, a further refined analysis will be needed to place constraints on the extragalactic infrared background.

The interpretation of upper limits from HBLs is difficult because of the lack of models which predict sub-TeV gamma-ray fluxes. Broad band spectral energy distributions (SEDs) have been studied by many authors (e.g. Sambruna, Maraschi, & Urry 1996; Kubo et al. 1998). Some of the models, based on simple SSC models to fit the SED of the synchrotron component, predict TeV emission at a detectable level particularly in high X-ray states. To increase the chance of detecting TeV gamma rays from these HBLs and constrain the model of emission mechanisms, further observations of these sources are needed, particularly at the same time as observations at other wavelengths.

5 Conclusion

We have observed eight AGN since 1993. A preliminary analysis of observations of Mrk 421 during the TeV high-state in early 2001 indicates the detection of gamma-ray emission in the energy range above 9.3 TeV. There is no evidence of gamma-ray emission from any of the other AGN we have observed.

Acknowledgments

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