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TeV gamma-ray observations of southern BL Lacs with the CANGAROO 3.8m Imaging Telescope

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Abstract. Observational and theoretical results indicate that low-redshift BL Lacertae objects are the most likely extragalactic sources to be detectable at TeV energies. In this paper we present the results of observations of 4 BL Lacertae objects (PKS0521$-$365, EXO 0423.4$-$0840, PKS2005$-$489 and PKS2316$-$423) made between 1993 and 1996 with the CANGAROO 3.8 m imaging Čerenkov telescope. During the period of these observations the gamma-ray energy threshold of the 3.8m telescope was $\sim$2 TeV. Searches for steady long-term emission have been made, and, inspired by the TeV flares detected from Mkn 421 and Mkn 501, a search on a night-by-night timescale has also been performed for each source. Comprehensive Monte Carlo simulations are used to estimate upper limits for both steady and short timescale emission.

Key words: gamma-rays: observations – BL Lacertae objects: individual: PKS0521$-$365, EXO 0423.4$-$0840, PKS2005$-$489, PKS2316$-$423

1. Introduction

Only two extragalactic sources have been confirmed to emit gamma-rays above 300 GeV: Mkn 421 (Punch et al. 1992, Macomb et al. 1995, Petry et al. 1996) and Mkn 501 (Quinn et al. 1996, Aharonian et al. 1997). In addition, an as yet unconfirmed detection has been made of 1ES 2344+514 (Catanese et al. 1997a). All three have redshifts less than 0.05 and are, based on their values of log (F_X/F_r), classified as X-ray–selected BL Lacs (XBLs). Observations of more than 30 candidates of other source types over a range of redshifts have not yielded any other extragalactic TeV emitters (e.g. Kerrick et al. 1995). From theoretical considerations Stecker et al. (1996) have proposed that low redshift XBLs may be the only extragalactic gamma-ray sources observable at TeV energies.

The CANGAROO data set, containing data collected over more than 5 years, includes observations of four low redshift active galactic nuclei (AGN) of the BL Lacertae class (PKS0521$-$365, EXO 0423.4$-$0840, PKS2005$-$489 and PKS2316$-$423). In this paper we present the results of searches for TeV emission from these objects. A comparison of on-source and off-source regions of sky is used to search for an excess of gamma-ray–like events from these sources over a typically two-week observing period.

The detection of a large flare from the BL Lac Mkn 421 by the Whipple Collaboration (Gaidos et al. 1996) has encouraged us to analyze the data with particular emphasis on shorter timescale flare searches. The Whipple result has shown that at TeV energies, BL Lacs are capable of extremely energetic flares on timescales of less than 1 day. Preliminary analysis of the Mkn 421 gamma-ray spectrum indicates that photon energies extend beyond 5 TeV (McEnery et al. 1997). Similar strong, short duration flares at TeV energies have also been

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Send offprint requests to: M.D. Roberts reported from Mkn 501, showing gamma-ray emission extending to energies of at least 10 TeV (Aharonian et al. 1997, Quinn et al. 1997). The lack of high energy turnover in the observed spectrum implies that the interaction of the gamma-rays with the cosmic infra-red background is at the lower end of expectations (cf Stecker et al. 1992). The results from Mkn 421 and Mkn 501 indicate that the CANGAROO 3.8 m telescope, with a relatively high gamma-ray energy threshold, is capable of detecting such extragalactic sources of TeV gamma-rays.

2. The CANGAROO imaging atmospheric Čerenkov telescope

The CANGAROO 3.8 m imaging telescope is located near Woomera, South Australia (longitude $137°47'$E, latitude $31°06'$S, 160 m a.s.l). The reflector is a single 3.8 m diameter parabolic dish with $f/1.0$ optics. The imaging camera consists of a square-packed array of 10mm × 10mm Hamamatsu R2248 photomultiplier tubes. The camera originally contained 224 photomultiplier tubes, and was increased to 256 pixels (16 × 16 square array) in May 1995. The tube centers are separated by $0.18°$, giving a total field of view (side-side) of $\sim 3.0°$. The photo-cathode of each tube subtends $0.12° \times 0.12°$, giving a photo-cathode coverage of about 40% of the field of view. For a more detailed description of the 3.8 m telescope see Hara et al. 1993.

In the current configuration an event trigger is generated when a sufficiently large number of tubes (3∼5) exceed their discriminator threshold. Individual tube discriminator levels are believed to be around 4 photo-electrons. Under these triggering conditions the current gamma-ray energy threshold of the 3.8 m telescope is estimated to be ∼1.5 TeV. Prior to mirror re-coating in November 1996 (which includes all data presented in this paper) the energy threshold was somewhat higher. Using Monte Carlo simulations we estimate that this energy threshold (as defined by the peak of the differential energy spectrum) was 2.5 TeV. When calculating integral fluxes and flux limits we define our threshold as 2 TeV. This figure is obtained by rebinning the lower energy gamma-rays to produce an integral spectrum defined by a single power law with a sharp cutoff at the threshold energy.

Since starting observations in 1991 the CANGAROO 3.8 m telescope has been used to observe a number of galactic and extragalactic candidate TeV gamma-ray sources (Roberts et al. 1997). From these observations we have evidence for gamma-ray emission from three galactic sources — PSR1706−44 (Kifune et al. 1995), the Crab nebula (Tanimori et al. 1994) and the Vela SNR (Yoshikoshi et al. 1997).

As an indication of the sensitivity of the 3.8 m telescope to extragalactic sources we can use Monte Carlo simulations to estimate the response of the telescope to fluxes observed from Mkn 421 and Mkn 501. Assuming that the gamma-ray emission from Mkn 421 and Mkn 501 extends up to 10 TeV the integral fluxes above 2 TeV are as follows.

For Mkn 421:
F(>2TeV) $\sim 2.2 \times 10^{-12}$ photons $\mathrm{cm^{-2}s^{-1}}$
(adopting the average 1996 Whipple flux with an assumed integral spectral index of -1.56, McEnery et al. 1997.)

For Mkn 501:
F(>2TeV) $\sim 6.5 \times 10^{-12}$ photons $\mathrm{cm^{-2}s^{-1}}$
(adopting the March 1997 HEGRA flux assuming an integral photon spectral index of -1.49, Aharonian et al. 1997.)

If any of the sources examined in this paper were capable of providing a steady flux at the level of Mkn 421 or Mkn 501 it would be detectable by the CANGAROO 3.8 m telescope, albeit at low significance.

Observations by the Whipple group of Mkn 421 have shown that it is capable of extremely energetic flares on timescales of hours to days. A flare similar to that seen on 7 May 1996 by the Whipple telescope (McEnery et al. 1997) with a flux of F(>250GeV) $\sim$ 5.7×10^{-10} photons $\mathrm{cm^{-2}s^{-1}}$ (F(>2TeV) $\sim 3.8 \times 10^{-11}$ photons $\mathrm{cm^{-2}s^{-1}}$ for a -1.56 spectral index and maximum photon energy of 10 TeV) lasting two hours would be easily detectable by CANGAROO at a significance of around 7σ.

3. Data sample

When selecting AGN as observation targets for the 3.8 m telescope we have used a number of criteria including the proximity of the source and measurements from X-ray and gamma-ray satellite experiments. As mentioned earlier, Stecker et al. 1996 have suggested that nearby XBLs are the most promising sources of detectable TeV gamma-ray emission. Multi-frequency studies of blazar emission (Sambruna et al. 1996) suggest that XBLs may be more compact and have higher electron energies and stronger magnetic fields than their radio selected counterparts. The current status of ground based TeV observations adds support to this belief. We present here the results of observations on two XBLs and two radio selected BL Lacs (RBLs). While RBLs are perhaps less promising as TeV sources, well placed upper limits in the TeV range could help to confirm fundamental differences between XBLs and RBLs. The four sources reported in this paper are described in the following sub-sections.

3.1. PKS0521−365

PKS0521−365 (RA$_{J2000}$ = $05^h23^m2.0$, Dec$_{J2000}$ =−36°23’2”, z = 0.055) is a radio selected BL-Lac. It was first detected as a strong radio source more than 30 years ago (Bolton et al. 1964). The spectral energy distribution of PKS0521−365 shows a double peaked structure that is typical of blazars (Pian et al. 1996). The first peak in the energy distribution occurs in the far IR ($10^{13} - 10^{14}$Hz) and is assumed to be from synchrotron emission from the electrons in the jet. The second component, possibly from IC emission from the same electron population, peaks at around 100MeV.

PKS0521−365 was viewed by the EGRET experiment on the CGRO during 1992 from May 14 to June 4 (Lin et al. 1995).

A point source, consistent with the position of PKS0521−365 was detected at a statistical significance of 4.3 σ, with an integral source flux above 100MeV of $(1.8 \pm 0.5) \times 10^{-7}$ photons $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The photon spectrum from the EGRET observation can be fitted with a single power law

$$dN/dE = (1.85 \pm 1.14) \times 10^{-8}(E/1\mathrm{GeV})^{-2.16\pm0.36}$$
photons $\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{GeV}^{-1}$

The hardness of the EGRET photon spectrum and the proximity of the source make PKS 0521-365 a candidate source for detectable levels of TeV gamma-ray emission.

The CANGAROO data set for this object consists of 52 on/off pairs of observations with a total of 89 hours of on-source and 84 hours of off-source data.

3.2. EXO 0423.4−0840

EXO 0423.4−0840 (RA$_{J2000}$ = $04^h25^m50.7$, Dec$_{J2000}$ =−08°33’43”, z = 0.039) was reported as a serendipitous discovery as part of the high galactic latitude survey in the 0.05–2.0 keV range by EXOSAT (Giommi et al. 1991). Associating the source with the galaxy, MCG –01–12–005 (incorrectly given in Giommi et al. 1991 as MCG +01–12–005) and noting the high X-ray luminosity ($> 10^{43}$ ergs s^{-1}) of the source, Giommi et al. (1991) proposed the source as a candidate BL Lac object. This would make the source the third closest such object known (after Mkn 421 and Mkn 501), and the closest in the southern hemisphere. We note however that Kirhakos & Steiner 1990 determine a redshift of 0.0392 for the source they designate IRAS 04235-0840B and identify with the HEAO source 1H 0422-086, and which they classify as a type 2 Seyfert. Clearly higher resolution X-ray studies are required to firmly establish the identity of this source.

We have observed EXO 0423.4−0840 during October 1996 obtaining a total raw data set comprising 20 hours of on-source and 17 hours of off-source data.

3.3. PKS2005−489

PKS2005−489 (RA$_{J2000}$ = $20^h09^m25.4$, Dec$_{J2000}$ = −48°49’54”, z=0.071) is an XBL. X-ray measurements of PKS2005−489 by EXOSAT show extremely large flux variations on timescales of hours (Giommi et al. 1990). Initially reported as a marginal EGRET detection (von Montigny et al. 1995), a more accurate background estimation decreased the significance below the level required for inclusion in the Second EGRET Catalog (Thompson et al. 1995). However the fluxes above 1 GeV are more significant than those above 100 MeV suggesting that the source, in a part of the sky that has received relatively poor EGRET exposure, may indeed be detectable at higher energies (Lin et al. 1997).

We have observed PKS2005−489 during August of 1993 and during August/September 1994 obtaining 41 hours of on-source and 38 hours of off-source data.

3.4. PKS2316−423

PKS2316−423 (RA$_{J2000}$ = $23^h19^m05.8$, Dec$_{J2000}$ = −42°06’48”, z= 0.055) is a radio selected BL Lac object. Assuming a magnetic field strength of $B \leq 10^{-3}$G, the emission from radio through to X-ray wavelengths is consistent with synchrotron radiation from electrons with $E > 10^{13}$eV (Crawford & Fabian 1994). PKS2316−423 is not detected by the EGRET telescope on the CGRO.

The CANGAROO 3.8 m telescope observed PKS2316−423 during July 1996 for a total of 26 hours of on-source data and 25 hours of off-source data.

4. Image analysis and Monte Carlo simulations

Prior to image analysis a data integrity check is performed to test for the presence of cloud or electronics problems. For a subset of observations tracking calibration is tested by monitoring changes in single-fold rates as local stars rotate through the field of view. Using this method the pointing direction can be inferred to an accuracy of around $0.05°$.

For each event trigger the tubes associated with the image are selected using the following criteria: (i) The TDC of the tube must indicate that the tube has exceeded its discrimination threshold within 50 ns around the trigger time of the event, and (ii) The ADC signal in the tube must be at least 1 standard deviation above the RMS of background noise for that tube.

An image is considered suitable for parameterization if it contains more than 4 selected tubes, and if the total signal for all tubes in the image exceeds 200 ADC counts (around 20 p.e.). About 25% of raw images are rejected by these two selection conditions. Surviving images are parameterized after Hillas 1985, with the gamma-ray domains for our observations being :

$0.5° <$ Distance $< 1.1°$
$0.01° <$ Width $< 0.08°$
$0.1° <$ Length $< 0.4°$
$0.4 <$ Concentration < 0.9
alpha $< 10°$

The cumulative percentages of events passing each selection condition are given in Table 1. The numbers shown are based on image cuts applied to Monte Carlo gamma-rays and protons. The efficiency of the cuts for the Monte Carlo protons is consistent with that seen for real data.

To estimate fluxes and upper limits for our data we use an exposure calculation based on a detailed Monte Carlo simulation of the response of our telescope to gamma-ray initiated EAS. Simulations have been based on the MOCCA simulation package (Hillas 1982) which models all relevant particle production processes and includes atmospheric absorption effects for the Čerenkov photons that are produced. The energies of simulated gamma-ray primaries were selected from a power law with integral exponent −1.4, with a minimum primary energy of 500 GeV. Core distances were selected from an appropriate

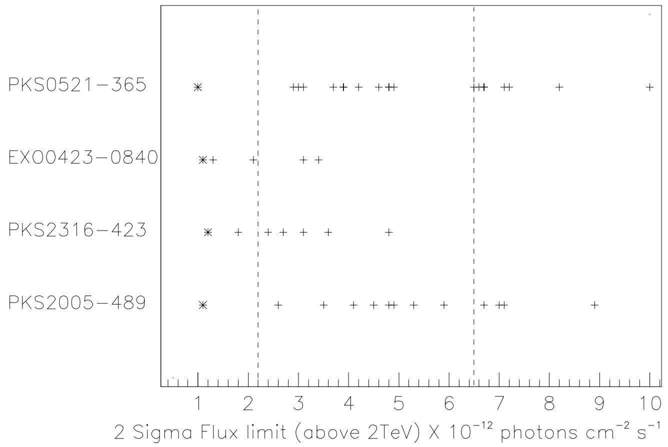

Fig. 1. Scatter plot of night by night 2σ flux limits for each of the sources (indicated by crosses). Also shown are the 2σ flux limits for the total data set for each source (stars). The two dashed lines show the >2TeV fluxes from Mkn 421 (left) and Mkn 501 (right) (see text for details).

Table 1. Cumulative percentages of events passing gamma-ray selection cuts.

Cut	Gammas	Protons
Raw data	100%	100%
ADC sum>200	90.0	77.5
Distance	65.4	44.6
Width	54.8	20.4
Length	54.0	16.5
Concentration	40.3	10.9
alpha	38.8	1.3

distribution out to a limiting core distance of 250 m. Simulated gamma-ray images were then subjected to the same selection criteria as the real data. Fluxes and upper limits are calculated by comparing measured gamma-ray excess rates to those predicted by the simulations. If we assume that our telescope model is correct, this method of flux estimation has only two free parameters — the source spectral index and source cutoff energy. For total flux calculations the estimate of cutoff energy is not critical — the generally steep nature of gamma-ray source spectral indices ensures that the bulk of the flux is around the threshold energy.

5. Results

The total data set for each source has been tested for the presence of gamma-ray signals. The significance of gamma-ray excesses have been calculated using a method based on that of Li & Ma 1983:

$$S = \sqrt{2}\left\{N_{on}\ln\left[\frac{1+\beta}{\beta}\left(\frac{N_{on}}{N_{on}+N_{off}}\right)\right]\right.$$
$$\left. + N_{off}\ln\left[(1+\beta)\left(\frac{N_{off}}{N_{on}+N_{off}}\right)\right]\right\}^{1/2} \qquad (1)$$

Table 2. The 2σ flux upper limits, F(>2TeV) ($\times 10^{-12}$ photons cm^{-2} s^{-1}) and approximate MJD (-40000) for each on-source observation.

PKS0521		PKS2005		PKS2316		EXO0423	
MJD	F	MJD	F	MJD	F	MJD	F
9655.7	2.9	9220.5	4.5	10304.8	4.8	10367.7	2.1
9663.7	6.5	9221.6	5.3	10305.7	2.7	10368.7	1.3
9684.6	6.7	9222.6	7.1	10306.7	3.1	10369.7	3.1
9685.7	3.9	9576.7	4.9	10307.8	2.4	10370.7	3.4
9686.7	3.1	9577.7	4.8	10308.7	1.8		
9687.7	4.8	9597.5	7.0	10311.5	3.6		
9688.7	3.7	9599.5	2.6				
9690.7	4.6	9600.5	3.5				
9691.7	7.1	9601.5	5.9				
9713.6	4.9	9602.5	6.7				
9714.7	10.0	9604.6	8.9				
9715.6	7.2	9605.6	4.1				
9717.6	4.8						
9718.6	8.2						
9719.6	3.0						
9720.5	4.2						
9722.6	6.6						

where S is the statistical significance and β is the ratio of events in the on-source observation to those in the off-source observation in the range $30° < \mathrm{alpha} < 90°$ (where alpha is the image parameter describing image orientation). The values of N_{on} and N_{off} are calculated from the gamma-ray selected (alpha $< 10°$) data for the on and off-source observations respectively. This method tends to slightly overestimate the significances because it does not account for the statistical uncertainty in calculating the value of β. Based on Monte Carlo simulations we estimate that this effect is small — and less than the typical systematic differences caused by the variations in parameter distributions between on and off-source observations. In the total data set for each source no significant excess is seen for those events in the gamma-ray domain. The calculated excesses are -0.27σ (PKS0521−365), -0.99σ (EXO 0423.4−0840), -0.91σ (PKS2005−489) and $+0.22\sigma$ (PKS2316−423). Upper limits to steady emission have been calculated after Protheroe 1984 and are shown in the scatter plot in Fig. 1.

We have also searched our data set for gamma-ray emission on a night by night basis. In general our observations of a source consist of a long (several hours) on-source run, with a similar length off-source run, offset in RA to provide the same coverage of azimuth and zenith. The flare search has been performed by calculating the on-source excess for each pair of on/off observations each night. In cases where there is no matching off-source run, an equivalent off-source run from another nearby night is used. Fig. 2 shows the distribution of on-source significances for all three sources. There is no evidence for gamma-ray flares on the timescale of $\sim$ 1 night for any of the sources. The most significant nightly excess (from PKS0521-365) has a nominal significance of 3.7σ but after allowing for the number of searches performed this significance is reduced to less than 3σ. The upper

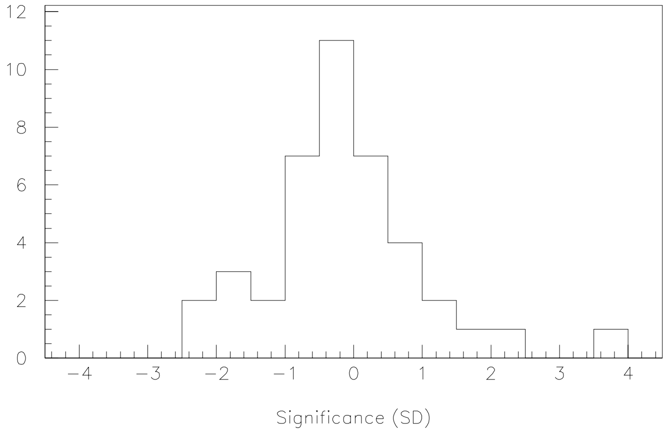

Fig. 2. Distribution of the significances of night by night excesses for all sources.

limits to gamma-ray emission for these observations are shown in Fig. 1. We have also included, in Table 2, a list of upper limits to gamma-ray emission for each individual observation.

6. Discussion

The interpretation of upper limits from BL Lacs is difficult, because at the present time there is no detailed model to predict TeV fluxes from the different classes of BL Lacs. Stecker et al. 1996 have attempted to predict TeV fluxes from a number of nearby XBLs by assuming that all XBLs have similar spectral characteristics to the known TeV emitter Mkn 421. Macomb et al. 1995 argue that the observed X-ray/TeV gamma-ray flux increases from Mkn 421 during flares indicate that the TeV gamma-rays are produced by a synchrotron self-Compton (SSC) mechanism. Stecker et al. 1996 note that the Compton emission from the electrons in the jet has a similar spectrum to the synchrotron component, but upshifted by the square of the maximum Lorentz factor (estimated to be $\sim\ 10^{4.5}$ for Mkn 421) of the electrons. For Mkn 421 and PKS2155−304 (both XBLs detected by EGRET) the luminosities in the Compton and synchrotron regions are nearly equal. Assuming that other XBLs also have $L_C/L_{syn}\ \sim\ 1$, Stecker et al. 1996 derive the following relationship between X-ray and TeV source fluxes :

$$\nu_{TeV} F_{TeV} \sim \nu_x F_x$$

where ν is the frequency and F the flux in each energy band. Using an assumed $E^{-2.2}$ spectral index for all XBLs, and absorption of TeV gamma-rays in the intergalactic infra-red based on an average of Models 1 and 2 from Stecker & de Jager 1997, they estimate TeV fluxes above 1 TeV from a number of nearby XBLs based on EXOSAT X-ray flux measurements. It should be noted that a more recent paper (Stecker & de Jager 1998) concludes that the absorption of TeV gamma-rays in the infrared background is overestimated in Stecker & de Jager 1997. Allowing for this, the predicted flux for PKS2005−489 above 1 TeV is F$(>1\mathrm{TeV}) = 1.3\times10^{-12}$ photons $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Above 2 TeV (the threshold of CANGAROO in this analysis) this flux would be F$(>2\mathrm{TeV}) = 0.34\times10^{-12}$ photons $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, below the flux sensitivity of the measurement made in this paper. The photon spectral index assumed in Stecker et al. 1996 is now incompatible with recent measurements of Mkn 421 and Mkn 501. It is also possible that the SSC mechanism is not primarily responsible for the TeV gamma-ray emission and a number of other mechanisms have been suggested (Mannheim 1993, Dermer & Schlickeiser 1994 and references therein).

Of the other predictions of Stecker et al. 1996, Kerrick et al. 1995 derive an upper limit to the $>$0.3 TeV emission for the XBL 1ES 1727+502 that is above the calculated flux. It is also worth noting that a deep exposure of the RBL BL Lacertae with the Whipple telescope did not yield a detection (Catanese et al. 1997b).

Current and future observations of a range of BL Lacs by ground based Čerenkov telescopes should help to clarify the mechanisms for the production of high energy photons in these sources.

7. Conclusion

Analysis of CANGAROO data shows no evidence for long-term or short-term emission of gamma-rays above 2 TeV from the BL Lacs PKS0521−365, EXO 0423.4−0840, PKS2005−489, PKS2316−423. The 2σ upper limits to steady emission are $1.0\times10^{-12}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (PKS0521−365), $1.1\times10^{-12}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (EXO 0423.4−0840), $1.1\times10^{-12}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (PKS2005−489), and $1.2\times10^{-12}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (PKS2316−423). For the XBL PKS2005−489 the flux limits presented in this paper do not constrain the TeV emission levels predicted by the simple model of Stecker et al. 1996.

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