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# TeV gamma-ray observations of three X-ray selected BL Lacs

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**Abstract.** Despite extensive surveys of extragalactic TeV gamma-ray candidates only 3 sources have so far been detected. All three are northern hemisphere objects and all three are low-redshift X-ray selected BL Lacs (XBLs). In this paper we present the results of observations of the three nearest southern hemisphere XBLs (PKS0548−322, PKS2005−489 and PKS2155−304) with the CANGAROO 3.8m imaging telescope. During the period of observation we estimate that the threshold of the 3.8 m telescope was ∼1.5 TeV. Searches for both steady and short timescale emission have been performed for each source. Additionally, we are able to monitor the X-ray state of each source on a daily basis and we have made contemporaneous measurements of optical activity for PKS0548−322 and PKS2155−304.

**Key words:** Gamma rays: observations - BL Lacs: individual: PKS0548−322 , PKS2005−489, PKS2155−304

## 1. Introduction

At the highest photon energies observable by satellite borne detectors, the bulk of detectable sources are active galaxies of the blazar class. These, and similar objects, make a natural sample for observation by ground based atmospheric Cherenkov detectors. At present only three extragalactic sources have been found, from Cherenkov imaging observations, to emit gamma-rays above 300 GeV: Mkn 421 (Punch et al. 1992, Macomb et al. 1995), Mkn 501 (Quinn et al. 1997, Aharonian et al. 1997) and 1ES 2344+514 (Catanese et al. 1997a). All three sources are nearby (z<0.05) BL Lacs and, based on their log $(F_X/F_r)$ ratios, are classified as XBLs.

The $\nu F_\nu$ spectral energy distributions (SEDs) of blazars show a characteristic "double humped" structure which is naturally explained in terms of a synchrotron self-Compton (SSC) mechanism, with the lower energy peak due to synchrotron emission, and the higher energy peak due to Compton scattering of the synchrotron photons from the same electron population (see e.g. Maraschi et al. 1992). Other mechanisms, including different sources of seed photons for the Compton process (Dermer & Schlickeiser 1994, Sikora et al. 1994) and the possibility of production of gamma-rays from protons in the jet (Mannheim 1993), have also been proposed. Comparisons of SEDs between XBLs and radio selected BL Lacs (RBLs) suggest that XBLs may have more compact emission regions, with higher electron energies and stronger magnetic fields than RBLs (Sambruna et al. 1996). An important feature of BL Lacs

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is their strong variability at all wavelengths. At TeV energies Mkn 421 has been seen to increase in luminosity by a factor of more than 10 in less than one hour (McEnery et al. 1997).

Multiwavelength studies have shown that the X-ray luminosity of XBLs is most strongly correlated with the changes in TeV luminosity. Based on X-ray measurements Stecker et al. (1996) have produced a catalogue of XBLs that are most likely to produce detectable levels of TeV emission. Assuming an SSC mechanism Stecker et al. (1996) note that the Compton and synchrotron emission spectra have similar shapes, but that the Compton component is upshifted in energy by the square of the Lorentz factor of the electrons in the jet. Under the further assumption that the Compton and synchrotron luminosities are nearly equal for XBLs (as is the case for Mkn 421 and PKS2155−304), Stecker et al. (1996) derive the following relationship between X-ray and TeV fluxes :

$$\nu_{TeV} F_{TeV} \sim \nu_x F_x \tag{1}$$

where $\nu$ is the frequency and $F$ the flux in each energy band. Another important consideration for estimating detectability at TeV energies is the proximity of the source as the gamma-rays interact via pair production with intergalactic soft photon fields. At TeV energies most absorption occurs due to interaction with infra-red photons. Stecker et al. (1996) have estimated the attenuation of the TeV signal based on models of the IR background published in Stecker & de Jager (1997). Recent observations of Mkn 421 and Mkn 501 (McEnery et al. 1997, Aharonian et al. 1997, Quinn et al. 1997), however, show that the TeV emission spectrum is unmodified up to energies of at least 5 TeV, indicating that the density of the IR background assumed in Stecker & de Jager (1997) may be too high. A more recent estimation of the opacity of the IR background has been made in Stecker & de Jager (1998).

Prior to 1997 the CANGAROO 3.8m telescope was used to observe a number of extragalactic objects, including RBLs and XBLs (Roberts et al. 1998). Following the success of TeV observations of Mkn 421 and Mkn 501 in conjunction with multiwavelength campaigns, we have concentrated observations on nearby XBLs. We have paid special attention to contemporaneous monitoring of these highly variable sources, where possible, at optical and X-ray wavelengths. Presented here are observations of the three most promising southern hemisphere TeV candidates from Stecker et al. (1996) : PKS0548−322, PKS2005−489 and PKS2155−304.

## 2. The CANGAROO 3.8m telescope

The CANGAROO 3.8m imaging telescope is located near Woomera, South Australia (longitude 137°47′E, latitude 31°06′S, 160m a.s.l). The telescope consists of a single 3.8m diameter parabolic reflector with a 3.8m focal length. A high resolution imaging camera is located at the prime focus consisting of 256 Hamamatsu R2248 photomultiplier tubes arranged in a 16 × 16 grid. The photomultipliers are separated by 0.18°, giving a total field of view (side-side) of 2.9°. The photo-cathode of each tube subtends 0.12° × 0.12° representing 40% of the total field of view.

An event trigger is generated when 3-5 phototubes exceed the discriminator threshold (which is estimated to be 3 photo-electrons). Under this triggering condition the current gamma-ray energy threshold of the 3.8m telescope is estimated to be 1.5 TeV, and the vertical trigger rate due to background cosmic rays is around 2Hz. More detailed descriptions of the CANGAROO 3.8m telescope can be found in Hara et al. (1993), Yoshikoshi et al. (1997) and Roberts et al. (1998).

As well as TeV observations we also have roughly contemporaneous X-ray and optical (for PKS2155−304 and PKS0548−322) data available. Optical observations were made from the Woomera site, using a Celestron C14 Schmidt-Cassegrain telescope with an Optec UBVRI filter set and SBIG ST-6 CCD. Exposures were 180 seconds in duration with the start times of time-series recorded from a UT clock (±1 second); timing within time-series runs was from a PC clock (maximum duration about 2 hours) with, at most, only a few seconds of expected error. The errors in optical flux are around 1% — much smaller than the flux variations that have been observed from these sources.

We are able to monitor the X-ray state of each source via daily observations by the Rossi X-ray timing explorer satellite (RXTE). The all sky monitor (ASM) on this satellite provides nearly continuous X-ray coverage of the whole sky in the energy range 2-10keV.

## 3. Data analysis

Prior to image analysis the arrival times of the raw events are binned into one minute intervals and the rate distribution is checked for the presence of cloud or any electronics problems. ADCs and TDCs are calibrated using LED “flasher” data taken at the beginning of each observation. The phototubes that are included in the image are selected on the following criteria:

1: The TDC of the tube must have fired (tube must have exceeded discrimination threshold)

2: The ADC signal in the tube must be at least 1 SD above the RMS of background noise for that tube

An image is considered suitable for parameterization if it contains at least 5 tube signals, and if the total signal for all tubes in the image exceeds 150 ADC counts (around 20 p.e.). The images are parameterized as a simple ellipse, after the method of Hillas (1985). The parameters used and their gamma-ray selection domains are :

$0.5° < \text{Distance} < 1.2°$
$0.01° < \text{Width} < 0.1°$

$0.1^\circ <$ Length $< 0.35^\circ$
alpha $< 10^\circ$

The gamma-ray parameter domains have been optimized on Monte Carlo simulations of the response of the CANGAROO 3.8m telescope to both gamma-ray and proton initiated EAS. We estimate that our image selection rejects ~99% of the cosmic ray background while retaining ~40% of the gamma-ray signal. For more details of the image selection used for the CANGAROO 3.8m see Yoshikoshi et al. (1997) and Roberts et al. (1998).

The set of total observations for each source have been tested for the presence of a gamma-ray signals. The significances of the on-source excesses have been estimated using a method based on that suggested by Li & Ma (1983):

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

where S is the statistical significance and $\beta$ is the ratio of events in the on-source to off-source exposure. In practice we estimate $\beta$ from the ratio of on-source to off-source events in the range $30^\circ <$ alpha $< 90^\circ$ (where alpha is the image orientation parameter) for all images that are considered suitable for parameterization. While the calculation of S is not strictly correct, the error introduced by the uncertainty in $\beta$ is small compared to the statistical uncertainties in $N_{on}$ and $N_{off}$. As well as testing for DC emission, we have also tested for shorter timescale gamma-ray emission. Each night's observation consists generally of a matched pair of on and off-source runs but where no matching off-source run was collected, an off-source observation from a nearby night is used. For both steady DC and night by night excess searches we calculate upper limits on gamma-ray emission after Protheroe (1984).

For optical observations data reduction was performed via differential aperture photometry relative to the local field standards given in Smith & Sitko (1991). Dark subtraction was performed during observation, and twilight flat-fields were applied during the reduction procedure. The magnitude differences between the comparison stars in the PKS2155−304 and PKS0548−322 fields, obtained in the Woomera photometry, were compared with the differences found from Smith & Sitko (1991). In all cases, the values agreed within error (VRI filters for both fields), but with the delta(I) value for the PKS0548−322 comparisons being at the limit of the errors. Thus, it was assumed that the differential magnitudes for the AGN could be converted directly to standard magnitudes by using the Smith & Sitko (1991) magnitudes for the comparison stars. By observing the optical state of the AGN we are able to monitor the general activity of the sources, and compare this activity to historical levels. While the correlation between optical and TeV luminosity seen in Mkn 421 during short intense TeV flares has been relatively weak (Macomb et al. 1995), multiwavelength observations of PKS2155−304, for example, show flux variations that are remarkably similar for wavelengths between infrared and X-ray (Edelson et al. 1995).

The strong correlation between X-ray and TeV emission has been well documented (Macomb et al. 1995, Catanese et al. 1997b), and we are able to monitor the X-ray state of all three candidates via the ASM on the RXTE. Adopting the method of Catanese et al. (1997b), we convert the ASM counts (2-10 keV) from the quicklook analysis of each source to an X-ray flux by assuming that each candidate source has a similar photon spectrum to the Crab Nebula (in the range 2-10 keV) and normalizing the ASM data to the known flux of the Crab. Using the method suggested by Stecker et al. (1996) (see Eq. 1) we can use the RXTE flux to predict the level of TeV emission from each source. In this paper we will normalize the predicted TeV flux using the TeV to RXTE(2-10keV) ratio measured by the Whipple collaboration from Mkn 501 during the period $9^{th}$ - $15^{th}$ of April 1997 (Catanese et al. 1997b). Extrapolation of fluxes from the Whipple telescope energy threshold (350 GeV) to that of the CANGAROO telescope are made assuming an integral photon spectrum of index −1.5. It is further assumed that the photon energies of the candidates extend to at least 10 TeV. We will assume an absorption of TeV gamma-rays in the cosmic IR based on the largest interaction length model from Stecker & de Jager (1998). This model predicts that the spectrum of a source such as Mkn 501 will not be strongly affected below 30TeV, which is consistent with the most recent observations from the HEGRA collaboration (Krawczynski 1998).

The ASM quicklook data provides an X-ray daily average from a number of "dwells" taken throughout each day, while the on-source TeV observations are made during a typically 4-8 hour period each night. The X-ray and TeV fluxes of XBLs are known to vary on timescales of less than hours, so care must be taken when interpreting X-ray/TeV correlations from short-term flare activity. Given this, and the relative insensitivity of the daily X-ray and TeV measurements, we will not present our data on timescales of less than the typically 1-2 week TeV observation period of each source.

## 4. PKS0548−322

At a distance of z=0.069, PKS0548−322 is the closest known southern hemisphere XBL (although it is still twice as distant as the nearest known northern XBL). X-ray observations have shown that this object undergoes rapid changes in both luminosity and spectral hardness. PKS0548−322 has not been detected by the CGRO EGRET, but the X-ray brightness, flat X-ray spectrum and proximity of this object make it a candidate for detection at TeV energies. CANGAROO observations of PKS0548−322 cover two new-moon periods from the $28^{th}$ of October to the $27^{th}$ of November 1997. For this period we have 9 nights of analyzable observations, yielding a total of ∼ 22 hours of off-source and ∼ 26 hours of on-source data. Analysis of this dataset shows no evidence for an on-source excess of events in the gamma-ray selection domain. The significance of the on-source excess is $-1.1\sigma$ with a corresponding $2\sigma$ flux limit above 1.5 TeV of $4.3 \times 10^{-12}$ photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. A night by night search of the dataset shows no evidence for detectable flare activity on the scale of ∼ 1 day.

X-ray measurements over the total CANGAROO observation period of PKS0548−322 show an average ASM count rate of $0.14 \pm 0.07$, where the error is the quadrature error derived from the error in each daily average X-ray count rate. For comparison the ASM count rate for Mkn 501 for the same period is 0.946, and ∼ 75 for the Crab Nebula. Based on the measured X-ray flux, and using the simple model described in section 3 we predict that the flux of gamma-rays above 1.5TeV should be $0.57 \times 10^{-12}$ photons $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. An examination of the entire ASM data base for this source from JD2450493 to JD2450863 shows an average ASM count rate of $0.14 \pm 0.02$. A sliding window of the same length as the total duration of the CANGAROO observations (∼ 31 days) shows that the maximum average X-ray flux within this timescale in the ASM dataset is $0.45 \pm 0.08$.

The optical activity of PKS0548−322 was monitored from Woomera on 9 consecutive nights from the $29^{th}$ of October until the $6^{th}$ of November (excluding the $31^{st}$ of October). There is no evidence for any variation between the 180s exposures for any night, and furthermore, no evidence for any variability between the nights. The average magnitude measured in the R band (649nm) was $14.59 \pm 0.04$ (stat.) corresponding to an average flux at this wavelength of 4.48 mJy, similar to other reported optical measurements (see e.g Xie et al. 1996).

The optical and X-ray measurements show that PKS0548−322 was at a fairly typical level of activity during the period of the CANGAROO observations.

## 5. PKS2005−489

The radio to X-ray SED of PKS2005−489 (z=0.071) is very similar to that of the confirmed TeV emitter Mkn 421 (Sambruna et al. 1995). As with Mkn 421, X-ray observations show that the X-ray spectrum of PKS2005−489 hardens with increasing source intensity (Giommi et al. 1990). Although 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). PKS2005−489 is the only XBL that has previously been observed with the CANGAROO 3.8m telescope albeit at a slightly higher gamma-ray energy threshold than the observations presented here. A combined dataset containing 41 hours of on-source observations taken in 1993 and 1994 provided an upper limit to gamma-ray emission above 2TeV of $1.1 \times 10^{-12}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (Roberts et al. 1998). In 1997 we observed PKS2005−489 with the CANGAROO telescope from the $27^{th}$ of August until the $9^{th}$ of September. The analyzable data consist of 8 nights of observations, containing a total of ∼ 15 hours of off-source and ∼ 17 hours of on-source data. An analysis of these data shows no evidence for detectable gamma-ray emission above 1.5TeV, either in the total dataset or for any of the individual nights. The significance of the on-source gamma-ray selected excess is $+0.01\sigma$ with a $2\sigma$ flux upper limit above 1.5 TeV of $7.0 \times 10^{-12}$ photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$.

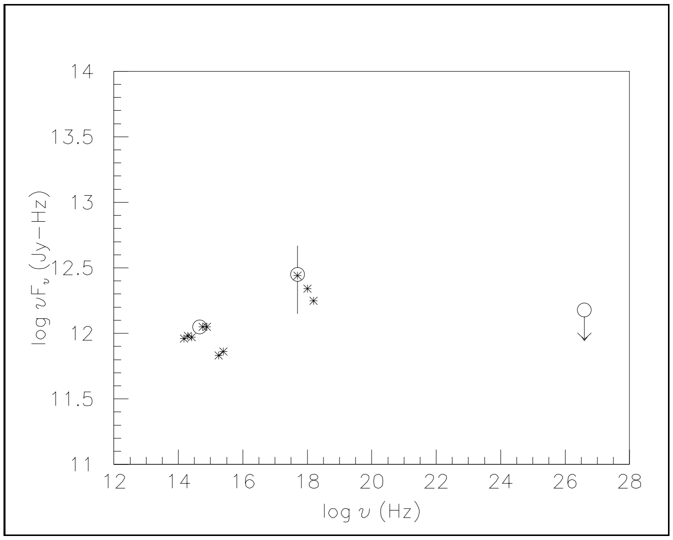

**Fig. 1.** SED for PKS0548−322. The open circles indicate our measurements and the contemporaneous RXTE flux and the stars are non-contemporaneous measurements adapted from Ghosh & Soundararajaperamal (1995).

The ASM RXTE data for PKS2005−489 show an average X-ray count rate of $0.8 \pm 0.1$ for the period of CANGAROO observations. The predicted TeV emission from this rate is $3.3 \times 10^{-12}$ photons $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The average ASM count rate from JD2450612 to JD2450863 was $0.36 \pm 0.14$ and the maximum count rate for any 13 day period was $0.917 \pm 0.12$.

We have made no optical observations of PKS2005−489.

## 6. PKS2155−304

PKS2155−304 (z=0.116) is one of the brightest BL Lacs at X-ray energies (Lamer et al. 1996), and has shown large and rapid variations in intensity at all wavelengths (Edelson et al. 1995). PKS2155−304 was in the CGRO EGRET field a number of times during observation phases I and II, but yielded only low significance excesses,

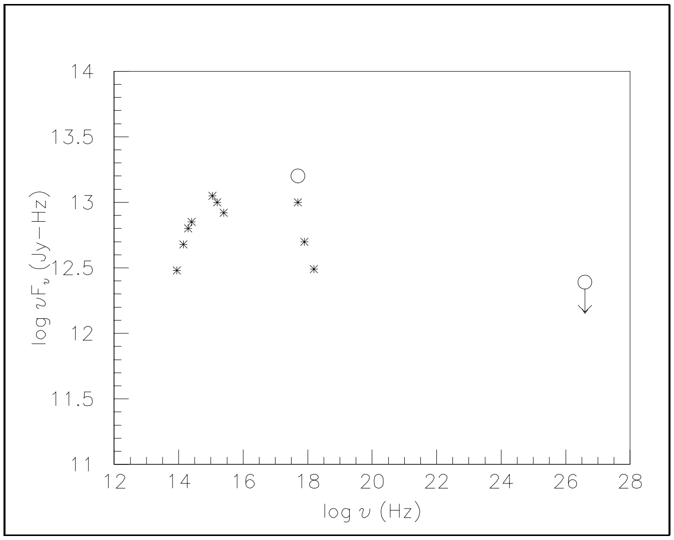

**Fig. 2.** SED for PKS2005−489. The open circles show our measurement and the contemporaneous X-ray flux, the stars are historical (non-contemporaneous) measurements adapted from Ghosh & Soundararajaperamal (1995).

below the nominal $4\sigma$ EGRET source detection limit. PKS2155−304 was detected, however, during a two week observation made in November 1994. This detection shows a hard photon spectral index of $\sim 1.7$ at EGRET energies. As in the case of Mkn 421, the gamma-ray $\nu F_\nu$ SED seems to peak at energies above the EGRET energy range (Vestrand et al. 1995).

We have made two distinct sets of CANGAROO observations in 1997. The first, taken from the $27^{th}$ of September until the $8^{th}$ of October, contains 7 nights of observations with $\sim$ 14 hours of off-source and $\sim$ 13 hours of on-source data. The second set of observations were taken to (partially) coincide with a PKS2155−304 multiwavelength campaign undertaken between the $11^{th}$ and $25^{th}$ of November 1997. A quick look analysis of EGRET data taken in the first three and a half days of this campaign showed a detection at a significance of $3.9\sigma$ indicating a high source state at GeV energies. Unfortunately, due to the phase of the moon and poor weather, we could not start observations until the 24th of November. We continued observations until the $1^{st}$ of December, collecting roughly 5 hours of both on and off-source data over 5 nights. Due to the lateness in the year of these observations we could only observe PKS2155−304 for about 1 hour each night, and at elevations between 55° and 45°. We estimate that the average energy threshold of the 3.8m telescope for these observations was $\sim$ 2.5 TeV. No evidence for gamma-ray emission has been seen in 1997 observations of PKS2155−304. The significances are $+0.8\sigma$ and $-0.2\sigma$ for the low and high zenith angle observations respectively, with corresponding flux limits of

$$F(>1.5\mathrm{TeV}) < 9.5 \times 10^{-12} \text{ photons cm}^{-2}\mathrm{s}^{-1}$$
$$F(>2.5\mathrm{TeV}) < 6.2 \times 10^{-12} \text{ photons cm}^{-2}\mathrm{s}^{-1}$$

The ASM count rates corresponding to the TeV observations at small and large zenith were $0.38 \pm 0.07$ and $0.8 \pm 0.3$ respectively. The average ASM count rate for the PKS2155−304 dataset is $0.38 \pm 0.02$ and the peak X-ray count rate for any 12 day period was $0.9 \pm 0.1$. Based on the X-ray flux we predict TeV gamma-ray fluxes of

$$F(>1.5\mathrm{TeV}) \sim 0.85 \times 10^{-12} \text{ photons cm}^{-2}\mathrm{s}^{-1}$$
$$F(>2.5\mathrm{TeV}) \sim 0.6 \times 10^{-12} \text{ photons cm}^{-2}\mathrm{s}^{-1}$$

We have contemporaneous optical observations for four nights from the $28^{th}$ of September to the $2^{nd}$ of October. A clear change in the optical flux can be seen over this period, from $36.7 \pm 0.3$ mJy to $33.4 \pm 0.4$ mJy. The range of R band fluxes observed is comparable with other measurements of PKS2155−304 (see e.g. Courvoisier et al. 1995 and references therein).

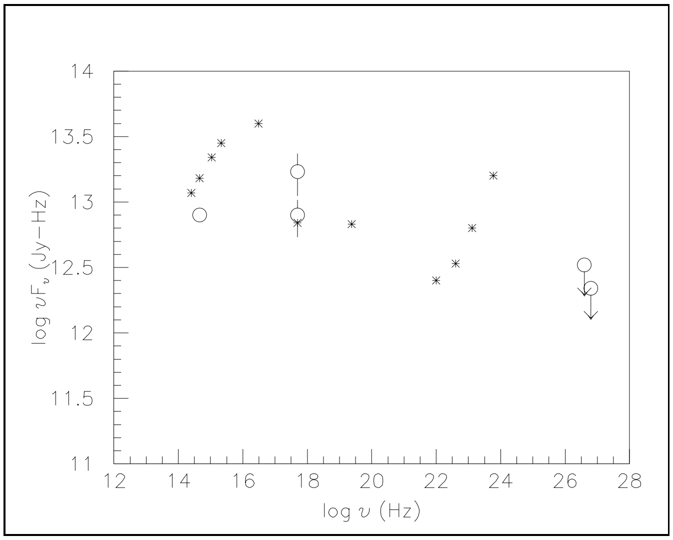

**Fig. 3.** SED for PKS2155−304. Our observations and the contemporaneous RXTE measurement are indicated by open circles, while the non-contemporaneous historical measurements are indicated by stars. The historical IR to X-ray data are adapted from Edelson et al. (1995) , the CGRO OSSE data point from McNaron-Brown et al. (1995) and the CGRO EGRET data points from Vestrand et al. (1995).

## 7. Discussion

Current knowledge about the exact location and production mechanism for gamma-rays of energy above 300GeV in XBLs is still quite poor. Interpretation of observational results is also hindered by the lack of a large catalogue of contemporaneous wideband SED measurements for these sources. Ground based gamma-ray observations of XBLs have shown that all three of the closest XBLs are observable TeV sources, while none of the more distant XBLs have so far been detectable (see e.g. Catanese et al. 1997a, Petry et al. 1997). While the statistics are clearly very limited and biased by selection effects, it is suggestive that XBLs as a class do emit detectable levels of TeV photons (at least during active phases), but the more distant sources are not detectable due to photon attenuation in the IR background. The flux upper limits in this paper are below or roughly equal to the predictions based on contemporaneous X-ray fluxes. The predictions are based on a simple model which uses the X-ray flux to determine the expected level of TeV emission, assuming that the SED (and hence the TeV/X-ray ratio) is the same between the known TeV sources Mkn 421, Mkn 501 and the sources reported here.

Of particular importance for TeV gamma-ray production are the maximum electron energy in the jet and the bulk Lorentz factor of the jet, which limit the maximum energy of gamma-rays that can be produced. For PKS2155−304, for example, a recent very long exposure observation by *BeppoSAX* has been used to provide an upper limit to the maximum energy of the electrons in the jet ($\gamma_o \leq 1.6 \times 10^5$) which rules out TeV gamma-rays unless there is a very high degree of beaming in the source (Giommi et al. 1998). It is not clear, however, how much the maximum electron energy increases during flaring in XBLs. The *BeppoSAX* observation of PKS2155−304, and other X-ray observations of XBLs (see e.g. Giommi et al. 1990) indicate spectral changes during flaring (hardening of the spectrum with increased flux). Additionally, it has been suggested that the strong TeV flares seen in Mkn 421 are due to brief increases in the maximum electron energies in the jet (Macomb et al. 1995).

Of the observations presented here the most promising candidate for TeV detection is PKS2005−489. The RXTE results show that we have observed this source during a relatively active phase, and previous multi-wavelength campaigns show a SED between radio and X-ray that is similar to Mkn 421 (Sambruna et al. 1995).

Optical and X-ray flux measurements indicate that PKS0548−322 was at a fairly typical level of activity during the period of CANGAROO observations. The X-ray spectrum of PKS0548−322 is one of the hardest of all XBLs, although it shows considerable variation which does not appear to be strongly correlated with the X-ray flux (Tashiro et al. 1995, Kubo et al. 1998). The lack of correlated change in the radio spectral index indicates that the X-ray emission is most likely synchrotron emission, with an average synchrotron turnover frequency that is just below X-ray wavelengths and comparable to or higher than that seen in Mkn 421 and Mkn 501. While the position of the synchrotron turnover alone might not be a reliable indicator of TeV emission, it is one of the defining differences between XBLs, which are known to emit TeV gamma-rays, and RBLs, which are not. The upper limit to TeV emission presented here does not constrain our X-ray–based prediction, but further observations of this source by the current CANGAROO telescope, particularly during periods of X-ray activity, would be easily justified.

## 8. Conclusion

Analysis of CANGAROO observations of the three nearest southern hemisphere X-ray selected BL Lacs shows no evidence for gamma-ray emission above an energy of 1.5 TeV. The $2\sigma$ upper limits to steady emission are $4.3 \times 10^{-12}\text{cm}^{-2}\text{s}^{-1}$ (PKS0548−322), $7.0 \times 10^{-12}\text{cm}^{-2}\text{s}^{-1}$ (PKS2005−489), and $9.4 \times 10^{-12}\text{cm}^{-2}\text{s}^{-1}$ (PKS2155−304). Further observations of PKS2155−304, taken at larger zenith angles, give a $2\sigma$ upper limit of $6.2 \times 10^{-12}\text{cm}^{-2}\text{s}^{-1}$ above 2.5 TeV. Contemporaneous X-ray and optical observations (for PKS0548−322 and PKS2155−304) have been used to monitor the activity state of these sources. A simple empirical model, based on the measured X-ray flux, has been used to predict the level of TeV emission from each source. The predicted TeV fluxes are roughly equal to or below the upper limits derived from our observations.

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