Very High Energy Gamma-Ray Observation of Southern AGNs with CANGAROO-II Telescope

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Abstract. The high-energy peaked BL Lacs (HBLs) PKS 2005−489 and PKS 2155−304 have been observed using the CANGAROO-II imaging atmospheric Cherenkov telescope between July and October 2000. Our estimates of the threshold energy of the analysed data are ~400 GeV for PKS 2155 −304 and ~450 GeV for PKS 2005−489. These HBLs remained in a low state during our observations. No statistically significant excess of events from the direction of either HBL was found. The derived 2σ flux upper limits for gamma-ray emission are $1.2 \times 10^{-11}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ above 400 GeV for PKS2155−304 and $6.4 \times 10^{-12}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ above 450 GeV for PKS2005−489. Some parts of the observations were carried out during multiwavelength campaigns.

1 Introduction

Using the imaging atmospheric Cherenkov technique, six active galactic nuclei have been reported to emit gamma-rays at TeV energies; Mrk421 (Punch et al., 1992), Mkn501 (Quinn et al., 1996), PKS 2155−304 (Chadwick et al., 1999a), 1ES 1959+650 (Kajino et al., 1999), 1ES 2344+514 (Catanese and Weekes, 1999) and 3C66A (Neshpor et al., 1998). All except 3C66A are low redshift HBLs. Only Mkn421 and Mkn501 have been confirmed as very high energy (VHE) sources by multiple groups. They also have been targets of simultaneous multiwavelength campaigns. Their distinctive features are extreme variability on a wide range of time scales and good time correlation between X-ray and VHE gamma-ray intensities (Catanese and 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 and Urry (1997)). However the origin of seed photons for the Compton process is still under debated (e.g., Jones et al. (1974); Dermer et al. (1992); Sikora et al. (1994)). The other four VHE gamma-ray sources have been detected with high significance but by a single group in limited time interval. Confirmation of these detections 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

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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 Cherenkov telescopes in the southern hemisphere above 100 GeV(Stecker et al., 1996). PKS 2155−304 is one of the brightest HBLs (Lamer et al., 1996) though the redshift of $z = 0.116$ is relatively high. PKS 2005−489 is a bright nearby ($z = 0.071$) HBL with a broad band spectrum which is very similar to that of the confirmed TeV source Mkn421 (Sambruna et al., 1995). Detection of VHE gamma rays from PKS 2155−304 during a multiwavelength campaign in 1997 November was reported by Chadwick et al. (1999a) which seemed to correlate with a strong X-ray flare observed by Beppo-SAX.

Prior to 1997 the CANGAROO 3.8m telescope was used to observe several HBLs, including PKS 2155−304 and PKS 2005−489. The results showed no evidence for gamma-ray emission above an energy of about 2 TeV (Roberts et al., 1998a,b). Since June 1999 we have observed several southern AGNs, again including PKS 2005−489 and PKS 2155−304, with the CANGAROO-II 7 m and 10 m telescope. Here we present the results of analysis of PKS 2005−489 and PKS 2155−304 observed by the CANGAROO-II 10 m telescope. Data obtained at the time of some multiwavelength campaigns are included.

2 Observation by the CANGAROO-II telescope

CANGAROO-II imaging atmospheric Cherenkov telescope, which was initially a 7 m dish and was expanded to its full 10 m diameter in March, 2000, is located near Woomera, South Australia (longitude 137°47′E, latitude 31°06′S, 160m a.s.l.). The camera consists of 552 PMTs. The field of view of one pixel is $0.115^\circ \times 0.115^\circ$ and the camera covers $2.76^\circ \times 2.76^\circ$ in total. The trigger region is the inner 256 pixels and an event trigger is generated when the number of PMTs which exceed their discriminator threshold is greater than a set number and the sum of the number of photoelectrons of any 4×4 square array exceeds another threshold value. The data are recorded through charge sensitive ADCs for charge and multi-hit TDCs for timing. The 10 m telescope is described in detail in Mori et al. (2001) and references therein.

PKS 2155−304 was observed from August to October 2000, and PKS 2005−489 was observed from July to September 2000, with all data taken with the 10 m telescope. 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 but trace the same range of azimuth and zenith angles as during the on-source scan. The summary of observation time for each HBL is shown in Table 1. The total observation time of on-source scans for both HBLs are about 67 hours. Multiwavelength observations with RXTE which were done from July 28 through August 1 and from August 25 through September 3 for PKS 2005−489 and from August 27 through 31 for PKS 2155−304 are included in these periods.

Table 1. Summary of observation time (hrs) for PKS 2155−304 and PKS 2005−489 in 2000.

Obs. Epoch	On-source	Off-source
PKS 2155−304		
2000 Aug/Sep	11.6	10.8
2000 Sep/Oct	24.6	24.3
PKS 2005−489		
2000 July/Aug	21.2	19.9
2000 Aug/Sep	11.4	9.4

3 Data calibration, reduction and analysis

In order to calibrate the gain and the timing for each PMT, data from an LED run was used. Before and after each normal run, the camera is uniformly illuminated by weak pulsed light from a blue LED which is set at the center of the composit mirror.

Shower images are selected and cleaned before image analysis by using information of the number of photoelectrons and the timing of signals. At first, pixels which exceed a photoelectron threshold and are clustered together are selected to remove night-sky background triggers. Then a timing cut is applied. The obtained shower rate is about 3 Hz. Considering the variation of shower rate and the record of other data acquisition monitors, the data which were taken under bad night sky conditions are excluded. The number of events and their live times after reduction of data for image analysis are summarized in Table 2.

Table 2. The number of events which were used for image analysis after reduction of data. The live times in hours are given in parentheses.

Obs. Targets	On-source	Off-source
PKS 2155−304	146,007(17.8)	118,368(15.2)
PKS 2005−489	140,974(16.9)	127,862(15.4)

Image analysis using Hillas parameters (Hills , 1995) are applied to the final sample data. Taking into account of the energy dependence of parameters, we used four parameters: *width*, *length*, *distance* and *alpha*.

4 Result

4.1 PKS 2155−304

No evidence for steady gamma-ray emission from PKS 2155 −304 has been seen in the 2000 observations. After applying *alpha* parameter cut, the calculated excess using a method based on the that of Li and Ma (1983) is 1.07σ. To estimate the flux upper limit for our data we used a method of Monte Carlo simulation of the response of our telescope to gamma-ray initiated extensive air showers. Here we assumed a power law energy spectrum with a spectral index of −2.5. The energy threshold estimated from the Monte Carlo study is 400 GeV at an average elevation of 80°. Using the average effective area evaluated from the Monte Carlo simulation, the time averaged 2σ flux upper limit is calculated to be $1.2 \times 10^{-11}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$ at 400 GeV. The data are divided by three energy bins and we calculate the differential flux for each bin. The results are shown in Fig.1 together with our results of quick-look analysis obtained by 1999 observations with the 7 m telescope and also with the flux and upper limit which are calculated from the integral flux reported by Chadwick et al. (1999a) and Chadwick et al. (1999b).

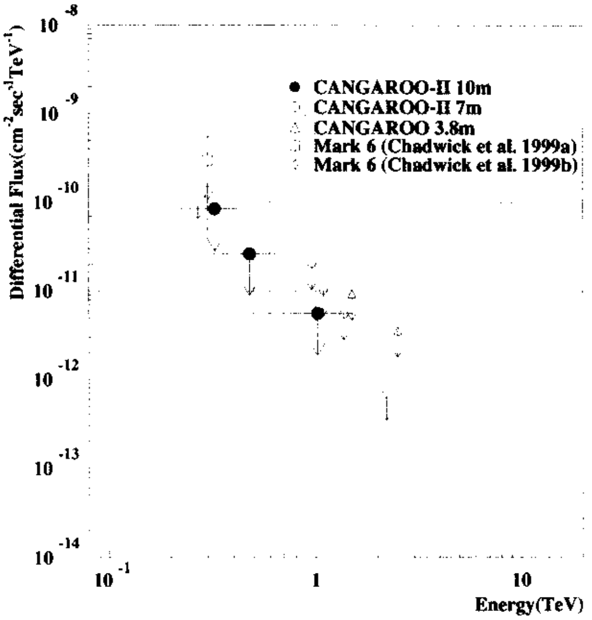

Fig. 1. Differential energy spectrum of PKS 2155−304. Our 2σ upper limits are shown by closed circles together with the upper limits obtained by CANGAROO 3.8m observations (Roberts et al., 1998b)(open triangle) and by the CANGAROO-II 7m observation in 1999 (open circle:preliminary). The open square and open diamond show flux and upper limit reported by Chadwick et al. (1999a,b).

4.2 PKS 2005−489

The analysis of data taken in 2000 shows no evidence for detectable gamma-rays emission from PKS 2005−489. After applying the *alpha* parameter cut, the calculated excess is -0.32σ. The threshold energy is estimated by the same procedure as for PKS 2155−304. Monte Carlo simulations for the average elevation of 70° during observation of PKS 2005 −489 yield a threshold energy of ~450 GeV. The 2σ flux upper limit of steady gamma-ray emission is then calculated to be $6.4 \times 10^{-12}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$ above 450 GeV. The differential fluxes are plotted in Fig.2. The results reported by Roberts et al. (1998a) and Roberts et al. (1998b) and the preliminary results obtained from 1999 observations are also shown in the same figure. The upper limit calculated from the integral flux reported by Chadwick et al. (2000) is also plotted.

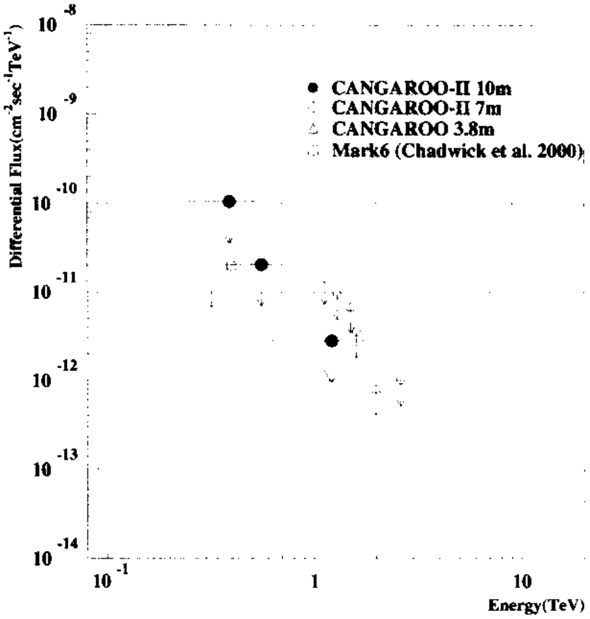

Fig. 2. Differential energy spectrum of PKS 2005−489. The 2σ flux upper limits from the present work are denoted by the closed circles. The open circles and open triangles show the upper limits obtained from quick-look analysis ofCANGAROO-II 7m observation and from CANGAROO 3.8m observation(Roberts et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

5 Discussion

The upper limits obtained here are more than a factor two lower than the previous limits around the 1 TeV region which we obtained from observations with the CANGAROO 3.8 m (Roberts et al., 1998a,b) and the CANGAROO-II 7 m telescopes (see Fig.1 and Fig.2). Our upper limit is lower than the flux reported by Chadwick et al. (1999a) for PKS 2155−304 in an active flaring state at X-ray energies, and is also lower than the upper limit of (Chadwick et al., 1999b) in an X-ray low state. However, for PKS2005-489, our observation time is not enough to lower the upper limit obtained by the University of Durham group around the 400 GeV region.

The interpretation of upper limits from HBLs is difficult because of the lack of models which predict sub-TeV gamma-ray fluxes. However the predicted sub-TeV fluxes of PKS 2155−304 and PKS 2005−489 by Stecker et al. (1996) are roughly equal to the upper limits derived from our observations. Their prediction is based on the assumption that the synchrotron self-Compton(SSC) scenario (Jones et al., 1974) applied to Mkn421 is applicable to the other XBLs. However their model may underestimate the TeV gamma-ray flux because of the over estimation of extragalactic background radiation (EBR) (Stecker and de Jager , 1998).

Broad band spectral energy distributions (SEDs) have been studied by many authors (e.g., Kubo et al. (1998); Chiappetti et al. (1999) for PKS 2155−304 and Sambruna et al.

(1996); Tagliaferri et al. (2001) for PKS 2005−489). Some of the models based on simple SSC models to fit the SED of synchrotron component predict TeV emission at a detectable level particularly in high X-ray states. To increase the chance to detect TeV gamma-rays from those HBLs and constrain the model of emission mechanisms, further observation of these sources are needed.

As already mentioned, time variability of VHE gamma-ray emission correlated with X-ray intensity variation has been reported for Mkn421 and Mkn501 (e.g., Quinn et al. (1999)). We have searched for excesses of events from PKS 2155−304 and PKS 2005−489 on a night by night basis. The data sets used for this analysis consist of complete pairs of on-source and off-source scans each night. Figure 3 and 4 show the daily excess fluxes for PKS 2155−304 and PKS 2005−489, respectively. There is no evidence for gamma-ray flares on the time scale of about one night for either source. The periods corresponding to RXTE multiwavelength campaigns are also indicated in the figures. Quick-look results of ASM/RXTE data show no flares during these periods. However combining the TeV data with the X-ray data, may enable constraints to be placed on emission models.

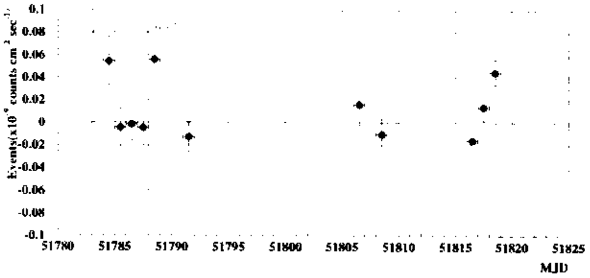

Fig. 3. The number of excess events for PKS 2155−304 night by night. Vertical error bars indicate 1σ statistical errors.

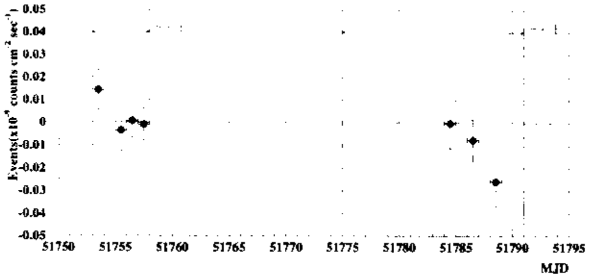

Fig. 4. The night by night number of excess events for PKS 2005−489. Vertical error bars indicate 1σ statistical errors.

6 Conclusion

We have observed the HBLs PKS 2155−304 and PKS 2005 −489, the most promising southern candidates for TeV detection, with the CANGAROO-II 10m telescope. No evidence of detection of gamma-rays can be found. The derived flux upper limits of gamma-ray emission at the 2σ level are $1.2 \times 10^{-11}\,\mathrm{cm^{-2}\,s^{-1}}$ above 400 GeV for PKS 2155−304 and $6.4 \times 10^{-12}\,\mathrm{cm^{-2}\,s^{-1}}$ above 450 GeV for PKS 2005−489.

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References

Catanese, M., and Weekes, T.C., PASP 111, 1193, 1999
Chadwick, P.M., et al., ApJ 513, 161, 1999a
Chadwick, P.M., et al., Proc. 26th ICRC (Salt Lake City), 3, 338, 1999b
Chadwick, P.M., et al., A&A 364, 450, 2000
Chiappetti, L., et al., ApJ 521, 552, 1999
Dermer, C.D., Schlickheiser, R., and Mastichiadis, A., A&A 256, L26, 1992
Hillas, M., Proc. 19th ICRC (La Jolla) 3, 445, 1995
Jones, T.W., O'Dell, S.L., and Stein, W.A., ApJ 188, 353, 1974
Kajino, F., et al., Proc. 26th ICRC (Salt Lake City), 3, 370, 1999
Kubo, H., et al., ApJ 504, 93, 1998
Lamer, G., et al., A&A 311, 384, 1996
Li, T.-P., and Ma, Y.-Q., ApJ 272, 317, 1983
Mori, M., et al., in these proceedings, 2001
Neshpor, Y.I., et al., Astron. Letts. 24, 134, 1998
Punch, M., et al., Nature 358, 477, 1992
Quinn, J., et al., ApJ 456, L83, 1996
Quinn, J., et al., ApJ 518, 693, 1999
Roberts, M.D., et al., A&A 337, 25, 1998a
Roberts, M.D., et al., A&A 343, 691, 1998b
Sambruna, R.M., et al., ApJ 449, 567, 1995
Sambruna, R.M., Maraschi, L., and Urry, C.M, ApJ 463, 444, 1996
Sikora, M., Begelman, M.C., and Rees, M.J., ApJ 421, 153, 1994
Stecker, F.W., de Jager, O.C., and Salamon, M.H., ApJ 473, L75, 1996
Stecker, F.W., and de Jager, O.C., A&A 334, L85, 1998
Tagliaferri, G., et al., astro-ph/0012503 (accepted for publication in A&A) 2001
Ulrich, M.-H., Maraschi, L., and Urry, C.M., ARA&A 35, 445, 1997