PKS 2155–304 — a source of VHE $\gamma$-rays

P.M. Chadwick, K. Lyons, T.J.L. McComb, S. McQueen, K.J. Orford, J.L. Osborne, S.M. Rayner, S.E. Shaw, K.E. Turver$^1$, G.J. Wieczorek

Department of Physics, Rochester Building, Science Laboratories, University of Durham, Durham, DH1 3LE, U.K.

Abstract

The close X-ray selected BL Lac PKS 2155–304 has been observed using the University of Durham Mark 6 very high energy (VHE) gamma ray telescope during 1996 September/October/November and 1997 October/November. VHE gamma rays with energy $> 300$ GeV were detected with a time-averaged integral flux of $(4.2 \pm 0.7_{\text{stat}} \pm 2.0_{\text{sys}}) \times 10^{-11}$ cm$^{-2}$ s$^{-1}$. There is evidence for VHE gamma ray emission during our observations in 1996 September and 1997 October/November. The strongest emission was detected in 1997 November, when the object was producing the largest flux ever recorded in high-energy X-rays and was detected in $> 100$ MeV gamma-rays. The VHE and X-ray fluxes are correlated.

Key words: VHE $\gamma$-ray astronomy; Active galactic nuclei; PKS 2155–304

PACS codes: 95.85.Pw; 98.54.Cm; 98.70.Rz

1 Introduction

X-ray selected BL Lacs (XBLs) at small redshift are sources of very high energy (VHE) gamma rays at energies above 300 GeV. The BL Lac first detected as a source of VHE gamma rays was Mrk 421 [1], which is an EGRET gamma-ray source. Mrk 501 is also a source of VHE gamma rays [2], although not detected at GeV energies with EGRET, and it exhibits low-level emission with flaring [3]. The BL Lac 1ES 2344+514 emits episodic VHE gamma rays [4,5]. All of these objects have small redshift ($z \sim 0.03$). There have been no reported detections of VHE gamma rays from radio-selected BL Lacs (RBLs — see e.g. [6,7]).

$^1$ Corresponding author
Stecker et al. [8] have interpreted the gamma ray results in the GeV – TeV range and propose a model in which RBLs will be GeV gamma ray sources and XBLs will be TeV sources. On the basis of this model, PKS 2155–304, despite having a redshift of 0.117, is predicted to be a strong TeV gamma-ray source. PKS 2155–304 was discovered as an X-ray source during observations made with the HEAO-1 satellite [9,10] and PKS 2155–304 may be regarded as the archetypal X-ray selected BL Lac object. It has a history of rapid, strong broadband variability. In 1997 November, contemporaneous with some of the observations reported here, X-ray emission was detected with the Beppo-SAX satellite [11] with a flux equal to the strongest previous outburst, and GeV gamma rays were detected with EGRET [12].

2 Observations

The University of Durham Mark 6 atmospheric Čerenkov telescope has been in operation at Narrabri, NSW, Australia since 1995 [13]. PKS 2155–304 was observed in 1996 September/October/November and 1997 October/November under moonless, clear skies. Data were taken in 15-minute segments. Off-source observations were taken by alternately observing regions of sky which differ by ±15 minutes in right ascension from the position of PKS 2155–304. We have a total of 41 hours of on-source observations with an equal quantity of off-source data.

3 Results

Events considered suitable for analysis are those which are confined within the sensitive area of the camera (i.e. within 1.1° of the centre of the camera) and which contain sufficient information for reliable image analysis, i.e. which have SIZE > 500 digital counts, where 3 digital counts ∼ 1 photoelectron, and 200 digital counts are produced by a 125 GeV gamma ray.

The Čerenkov image can be parameterized using techniques developed by the Whipple group which describe both the shape and the orientation of the image. In addition a measure of the fluctuations between the centroids of the samples recorded by the left and right flux collectors of the Mark 6 telescope provides a further discriminant [14]. Gamma rays are identified on the basis of image shape and left/right fluctuation, and then plotting the number of events as a function of the pointing parameter ALPHA; γ-ray events from a point source will appear as an excess of events at small values of ALPHA (< 22.5°). The number of events remaining ON and OFF source after the application of the standard selections are summarized in Table 1. The ALPHA distribution for
Table 1
The results of various event selections for the PKS 2155–304 data. Data from observations at all zenith angles < 60° have been combined.

|                                | On    | Off   | Difference | Significance |
|--------------------------------|-------|-------|------------|--------------|
| Number of events               | 1021083 | 1023280 | −2197      | −1.5 σ       |
| Number of size and distance selected events | 600856 | 598733 | 213         | 1.9 σ        |
| Number of shape selected events | 37125  | 36151  | 974        | 3.6 σ        |
| Number of shape and ALFA selected events | 6099   | 5370   | 729        | 6.8 σ        |

the whole dataset is shown in Fig. 1. No normalization of ON and OFF data rates has been applied.

3.1 Observed flux

544 excess events identified as γ-rays were detected in 32.5 hours of on-source observation at zenith angles less than 45°. The current selection procedure for data recorded at zenith angles < 45° is estimated to retain between 20 and 50% of the original gamma ray events. We have assumed a value of 20%. The collecting area has been estimated from Monte Carlo simulations and is \( \sim 5.5 \times 10^8 \) cm\(^2\) for these observations. Using this estimate, the γ-ray flux incident on the earth’s atmosphere was found to be \( (4.2 \pm 0.75_{stat} \pm 2.0_{sys}) \times 10^{-11} \) cm\(^{-2}\) s\(^{-1}\) for a threshold > 300 GeV.

3.2 Time variability

We show in Fig. 2 the variation in the detected γ-ray flux for observations in 1996 September, October and November and in 1997 October and November. The strength of the γ-ray emission is defined as the number of γ-ray candidates (shape and orientation selected events) to the number of background protons during the same observation. This makes allowance for variations in the sensitivity of our telescope as the zenith angle changes. Using the test for
constancy of emission used by the EGRET group [15], the data suggest that
the VHE $\gamma$-ray emission is time variable.

4 Discussion

PKS 2155–304 is the fourth X-ray emitting BL Lac to be established as a VHE
emitter and, thus far, the most distant TeV emitter from earth with a redshift
of 0.117. The emission shows the features of time variability demonstrated by
the other X-ray selected BL Lacs detected at VHE energies.

In Fig. 3 we show the spectral energy distribution (SED) from PKS 2155–304
from radio to VHE gamma ray energies, including the present results. The
SED is consistent with those for the other VHE-emitting blazars. The VHE
Fig. 2. The variation of the VHE gamma ray flux from PKS 2155–304 averaged over the observing periods in 1996 September, October and November and in 1997 October and November.

Fig. 3. The spectral energy distribution of PKS 2155–304. The VHE point is from the present work. Other data is from the work of [18–20] and the prediction is from [8].

behave is in general agreement with the predictions of Ghisellini et al. [16] and, as for the other three established VHE blazars, indicates the success of the unified model of AGNs in explaining the gross features of VHE emission.

During our observations of PKS 2155–304 measurements of the daily average of its 2 – 10 keV X-ray emission were available from the ASM on RXTE[2]. In Fig. 4 we show the relation between the average VHE emission during each of the five months and the X-ray rate from the RXTE quick look analysis averaged over the days when TeV observations were made. The correlation coefficient for the data is 0.66 for 4 degrees of freedom (df). The general correlation between X-ray and VHE emission in PKS 2155–304 is in agreement.

2 Available on the web at http://space.mit.edu/XTE/asmlc/pks2155-304.html.
Fig. 4. The correlation between VHE emission from PKS 2155–304 and the X-ray flux measured by the RXTE satellite when averaged over an observing period (~ 10 days); the correlation coefficient is 0.66 (4 df).

with multiwavelength observations of Mrk 421 and Mrk 501 (reviewed by e.g. Ulrich et al. [17]). These suggest that the same population of electrons produces the X-ray and TeV emission. The strongest VHE emission from PKS 2155–304 occurred in 1997 November (during a multiwavelength campaign). We note that the strongest X-ray emission ever observed from this object was detected by Beppo-SAX during observations in 1997 November 22 – 24 [11]. EGRET also detected GeV gamma-rays, again at a flux considerably higher than previous detections, during an observation from 1997 November 11 – 17, just before the onset of our November observation [12]. A recent analysis of RXTE and EGRET data [21] suggests that our 1997 November VHE gamma ray observations were preceded by a strong flare.

Acknowledgements

We are grateful to the UK Particle Physics and Astronomy Research Council for support of the project. This paper uses quick look results provided by the ASM/RXTE team and uses the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, Caltech, under contract with the National Aeronautics and Space Administration.

References

[1] M. Punch et al., Nature 358 (1992) 477
[2] J. Quinn et al., Astrophys. J. 456 (1996) L83
[3] M. Catanese et al., Astrophys. J. 487 (1997) L143
[4] M.A. Catanese et al., in: Proc. 25th Int. Cosmic Ray Conf., Durban, Vol. 3 ed. M.S. Potgieter, B.C. Raubenheimer and D.J. van der Walt (Potchefstroom University for CHE, Potchefstroom, 1997) 277
[5] M.A. Catanese et al., Astrophys. J. 501 (1988) 616
[6] A.D. Kerrick et al., Astrophys. J. 452 (1995) 588
[7] M.D. Roberts et al., Astron. Astrophys. 337 (1998) 25
[8] F.W. Stecker et al., Astrophys. J. 473 (1996) L75
[9] D.A. Schwartz et al., Astrophys. J. 229 (1979) L53
[10] R.E. Griffiths et al., Astrophys. J. 234 (1979) 810
[11] L. Chiappetti,, V. Torroni IAU Circular 6776 (1997)
[12] P. Sreekumar, T. Vestrand, IAU Circular 6774 (1997)
[13] P. Armstrong et al., Experimental Astron. (1998), in press
[14] P.M. Chadwick et al., Astrophys. J. 503 (1998) 391
[15] M.A. McLaughlan et al., Astrophys. J. 473 (1996) 763
[16] G. Ghisellini et al., astro-ph/9807317 (1998)
[17] M.-H. Ulrich et al., Ann. Rev. Astron. Astrophys. 35 (1997) 445
[18] P. Giommi et al., Astron. Astrophys. Suppl. 109 (1995) 267
[19] G. Lamer et al., Astron. Astrophys. 311 (1996) 384
[20] W.T. Vestrand et al., Astrophys. J. 454 (1996) L93
[21] W. T. Vestrand et al., these proceedings.