TeV gamma rays from PSR 1706-44

P. M. Chadwick, M. R. Dickinson, N. A. Dipper, J. Holder, T. R. Kendall, T. J. L. McComb, K. J. Orford, J. L. Osborne, S. M. Rayner, I. D. Roberts, S. E. Shaw and K. E. Turver
Department of Physics, Rochester Building, Science Laboratories, University of Durham, South Road, Durham DH1 3LE, UK

Abstract

Observations made with the University of Durham Mark 6 atmospheric Čerenkov telescope confirm that PSR B1706-44 is a very high energy $\gamma$-ray emitter. There is no indication from our dataset that the very high energy $\gamma$-rays are pulsed, in contrast to the findings at $< 20$ GeV, which indicate that more than 80% of the flux is pulsed. The flux at $E > 300$ GeV is estimated to be $(3.9 \pm 0.7_{\text{stat}}) \times 10^{-11}$ cm$^{-2}$ s$^{-1}$.

Key words: VHE $\gamma$-ray astronomy – pulsars – PSR B1706-44
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1 Introduction

1.1 PSR B1706-44

PSR B1706-44 is a 102 ms radio pulsar which may be associated with the supernova remnant G343.1-2.3. The pulsar was discovered via its radio emission [1]. Observations of the 102 ms periodicity with the EGRET detector on the Compton Gamma Ray Observatory [2,3] associated the COS-B $\gamma$-ray source 2CG 342-02 [4] with this pulsar; it is one of only seven identified pulsars which emit high energy $\gamma$-rays. Becker et al. [5] showed that PSR B1706-44 also emits X-rays, which may be an indication of the presence of a synchrotron X-ray nebula. McAdam et al. [6] have suggested that PSR B1706-44 is associated with the shell-type supernova remnant G343.1-2.3 (but see [7] for an opposing view). Recent observations of candidate optical counterparts in the PSR B1706-44 field have yielded no evidence for pulsations, suggesting that the optical counterpart has an R-band magnitude of $< 18$ [8].
A number of models of γ-ray emission from pulsars suggest that PSR B1706-44, as well as the Crab, should be a source of very high energy (VHE) γ-rays as there are a number of similarities between the two objects (see, for example, [9]). The Crab nebula, with its associated pulsar, is a well established source of VHE γ-rays, detectable from a few hundred GeV [10,11] to higher energies [12–15]. The Crab pulsar has also been detected in VHE γ-rays [16–18], though later observations using imaging telescopes with greater sensitivity, and operating at lower threshold energy, have failed to show evidence for pulsed emission [19].

Kifune et al. [20], using the CANGAROO telescope, found evidence of TeV γ-ray emission from PSR B1706-44 but detected no pulsations. We have observed this object with the University of Durham Mark 6 γ-ray telescope to extend measurements closer to the energy range of the EGRET measurements.

1.2 The University of Durham Mark 6 VHE γ-ray telescope

The University of Durham Mark 6 VHE γ-ray telescope is situated at Narrabri, NSW, Australia, 200m above sea level. It is an atmospheric Čerenkov telescope; such telescopes detect optical Čerenkov photons emitted as air showers produced by VHE γ-rays and cosmic rays pass through the upper atmosphere. The Mark 6 telescope uses a triple mirror, fast coincidence system, each mirror having an area of 42 m² and a focal length of 7 m. There is a conventional imaging camera consisting of 91 1 inch and 18 2 inch PMTs at the focus of the centre mirror. At the focus of each of the left and right mirrors is a low-resolution triggering camera consisting of 19 hexagonal PMTs. Each 1 inch PMT in the imaging camera has a field of view of 0.25°, giving a total field of view of 7 square degrees. The telescope is described in detail by Armstrong et al. [21]. It is triggered by a 3-fold spatial plus 4-fold temporal coincidence [23], which consist of two elements:

1. The first requirement is that a signal is detected from each of a pair of PMTs viewing the same area of sky in the left and right detectors.
2. The second requirement is that any 2 of the 7 camera PMTs which cover the same area of sky as the left/right PMTs which have responded also produce a signal and that the 2 PMTs are adjacent.

This novel coincidence system has a number of advantages over a single dish telescope, and provides both a very effective suppression of noise due to the night sky background and a complete elimination of events due to local muon triggers. It also gives the lowest practical energy threshold for a given mirror area. We estimate that the telescope, in its present configuration, can reliably detect γ-rays with energies as low as 125 GeV near the zenith, although the
detection efficiency at this energy is \( \leq 10\% \) of the peak detection efficiency. An initial simulation study performed for the telescope inclined at an angle of 20° suggests that the peak differential detection rate for \( \gamma \)-rays occurs at 250 GeV, assuming a source with a power law spectral index of \(-2.4\). Following recent convention, this is taken as the energy threshold of the telescope, but it should be noted that this is the result of a preliminary study only and the systematic error at large zenith angles is estimated to be 50%. For the observations of PSR B1706-44, with a typical zenith angle of \( \sim 30^\circ \), the \( \gamma \)-ray energy threshold is estimated to be 300 GeV.

The telescope’s detectors are calibrated during observations by use of a nitrogen laser coupled to a plastic scintillator, which provides a diffuse source of blue light at the centre of each mirror, thus producing a pool of blue light which is uniform over the face of the detector packages. The laser pulses are separated by random intervals with a mean rate of 50 min\(^{-1}\) throughout all observations. The pedestals of the charge digitisers associated with each PMT channel are also measured throughout observations by means of randomly occurring ‘null’ events, also with a mean rate of 50 min\(^{-1}\). In addition, the telescope is equipped with a comprehensive performance monitoring system, whereby the PMTs’ anode currents and noise rates are recorded throughout observations, and environmental conditions are monitored. Event arrival times are measured using a rubidium oscillator-based clock, monitored against a GPS time signal, to a relative accuracy of 1 \( \mu \)s and an absolute epoch error of 10 \( \mu \)s.

2 Observations

Observations of PSR B1706-44 were made on clear moonless nights at zenith angles between 15° and 50° in May and July 1996. More than 90% of the data were taken between culmination (a zenith angle of 14°) and 35°. An observing log is shown in Table 1. Our method of observation is to make 15 minute exposures on and off source, with an equal total exposure time for each. The total exposure time on source, allowing for dead-time during chopping manoeuvres, was 560 minutes.

Data were selected for analysis if pairs of ON and OFF observations have raw count rates which differ by \( \leq 2.5 \sigma \) and extensive environmental monitoring showed clear and stable skies. The 40 scans which passed this quality threshold are listed in Table 1.
Table 1
Log for observations of PSR B1706-44 with the University of Durham Mark 6 telescope at Narrabri during 1996.

| Date (1996) | No. of scans | Date (1996) | No. of scans |
|------------|--------------|--------------|--------------|
| May 11     | 3            | July 9       | 7            |
| May 12     | 4            | July 11      | 4            |
| May 21     | 5            | July 15      | 4            |
| May 22     | 2            | July 18      | 5            |
| May 24     | 6            |              |              |

3 Analysis procedure

The ‘raw’ event totals shown in Table 2 constitute all the events recorded by the Mark 6 during the observations of PSR B1706-44 and therefore include events near the telescope trigger threshold and events of all sizes which fall near the edge of the camera, as well as events more suitable for conventional imaging analysis. Some of the out-of-geometry events recorded during the ON source observations are likely to be due to the presence of a star (η Scorpii) near the edge of the field of view. Events considered suitable for analysis are those events which are confined within the sensitive area of the camera and which contain sufficient information for reliable image analysis, i.e. which have size of 200 – 20000 digital counts, where 3 digital counts ∼ 1 photoelectron, and 200 digital counts are produced by a 125 GeV γ-ray at the zenith. This selection has the effect of removing any out-of-geometry events induced by η Scorpii together with other events which are considered to contain insufficient information for analysis. The total number of events after this process is included in the ‘SIZE/DISTANCE selected’ row of Table 2.

Monte Carlo simulations indicate that the image shape of the Čerenkov light from a γ-ray shower can be approximated by an ellipse, the major axis of which is oriented towards the source position, whereas a cosmic ray (hadronic) shower produces a broader, more irregularly shaped image [22]. The image can be parameterised 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 samples recorded by the left and right flux collectors of the Mark 6 telescope provides a further discriminant [23]. γ-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. The cuts applied to the data are shown in Table 3.
Table 2
The results of selecting events on the basis of their shape and value of \textit{ALPHA}.

|               | ON   | OFF  | Difference | Significance |
|---------------|------|------|------------|--------------|
| Raw           | 251412 | 248405 | 3007       | 4.3 \(\sigma\) |
| \textit{SIZE/DISTANCE} Selected | 130295 | 129380 | 915        | 1.8 \(\sigma\) |
| Shape Selected | 1161   | 989   | 172        | 3.7 \(\sigma\) |
| Shape and \textit{ALPHA} < 22.5° | 368    | 225   | 143        | 5.9 \(\sigma\) |

Table 3
The cuts applied to the data from PSR B1706-44.

| Parameter          | Limits (high energy events) | Limits (low energy events) |
|--------------------|-----------------------------|-----------------------------|
| \textit{SIZE}      | 800 – 20000 d.c.            | 200 – 800 d.c.             |
| \textit{DISTANCE}  | 0.35° – 0.75°              | 0.35° – 0.75°              |
| \textit{ECCENTRICITY} | 0.35 – 0.75               | —                           |
| \textit{WIDTH}     | < 0.26°                    | < 0.18°                    |
| \textit{LENGTH}    | —                          | 0.18° – 0.38°              |
| \textit{CONCENTRATION} | < 0.25                     | —                           |
| \text{D}_{\text{dist}} | 0.02° – 0.09°             | < 0.12°                    |

The number of events remaining ON and OFF source after the application of the cuts described above is summarized in Table 2. The \textit{ALPHA} distributions of the ON and OFF source events have been plotted, and the results are shown in Figure 1. No normalization of the ON and OFF data has been applied. There is an excess of events at small \textit{ALPHA}, the expected \(\gamma\)-ray domain, and imposing a \(\gamma\)-ray cut of \textit{ALPHA} < 22.5° yields a \(\gamma\)-ray detection significant at the 5.9 \(\sigma\) level. There may be scope to decrease the width of the alpha plot peak by correcting our data for the effects of such factors as the Earth’s geomagnetic field and the optical performance of the telescope mirrors [24].

To demonstrate that this excess of \(\gamma\)-ray like events originates from the source direction we have calculated the number of events passing the \textit{ALPHA}-cut for a number of different assumed source positions (a ‘false source’ analysis). We show the results of this analysis in Figure 2. As the telescope is alt-azimuth mounted, the field of view rotates around its centre with time; the effect of this rotation has been allowed for in the analysis using a software correction. Note that during these observations, the position of the source in the telescope’s field of view, known to an accuracy of 0.02°, was displaced from the centre of the camera by \(\sim 0.2°\) degrees; this reduces the chance that the observed excess is a result of a geometrical bias towards the camera centre. We have also investigated the effects of the bright star \(\eta\) Scorpii on the alpha distribution,
Fig. 1. (a). The \textit{ALPHA} distributions ON and OFF source for PSR B1706-44. The dotted line refers to OFF source data. (b). The difference between ON and OFF source data.

Fig. 2. The results of a false source analysis for PSR B1706-44. The grey scale is such that black corresponds to a detection probability of > 6 $\sigma$. Contours are at 0.6 $\sigma$ intervals and conclude there are none [25].

Fluxes have been estimated on the basis of the number of excess events recorded with \textit{ALPHA} < 22.5° divided by the time taken to make the observations, which gives a $\gamma$-ray detection rate of 0.26 ± 0.05 per minute. The $\gamma$-ray retention factor is approximately 20 %, giving an estimated incident $\gamma$-ray rate 1.3 ± 0.3 per minute. The energy threshold for this object, which is at an average zenith angle of $\sim$ 30° is estimated to be 300 GeV. The collecting area of the telescope has been estimated using Monte Carlo simulations and is
\( \sim 5.5 \times 10^8 \) cm\(^2\) for these observations. The integral flux from PSR B1706-44 is therefore \((3.9 \pm 0.7_{\text{stat}}) \times 10^{-11} \) cm\(^{-2}\) s\(^{-1}\) at \(E > 300\) GeV, subject to a systematic error of \(\sim 50\%\). This corresponds to a luminosity of \(1.4 \times 10^{34}\) erg s\(^{-1}\) at \(E > 300\) GeV, assuming a distance to the source of 2.8 kpc [26], a spectral index of \(-2.8\), and that the emission is isotropic. This is \(\sim 0.3\%\) of the total spindown energy of PSR B1706-44.

3.1 Periodicity

A pulsar timing analysis has been performed. The event times were reduced to the Solar System Barycentre and analysed for periodicity using the Rayleigh Test at the contemporary pulsar period derived from the pulsar timing database maintained at Princeton University\(^1\). We have no evidence for periodicity from PSR B1706-44 in the dataset reported here. A 3 \(\sigma\) flux limit was calculated by equating the Rayleigh statistic \(\exp(-NR^2)\) where \(N\) is the number of events and \(R\) is the fractional strength of the pulsed signal) to the probability required for a 3 \(\sigma\) detection. The 3 sigma flux limit for pulsed emission thus calculated at less than 35\% of the observed \(\gamma\)-ray flux, which corresponds to a flux limit of \(\sim 1.4 \times 10^{-11} \) cm\(^{-2}\) s\(^{-1}\).

4 Discussion

Our observations of VHE \(\gamma\)-ray emission from PSR B1706-44 confirm the earlier reports by Kifune et al. [20] that this object emits in the VHE \(\gamma\)-ray waveband. The lowest energy events recorded were \(\sim 125\) GeV.

Our dataset does not show evidence for pulsations at the known pulsar frequency. This is in contrast to the result obtained with the EGRET experiment, which suggest that \(< 20\%\) of the total emission above 100 MeV can be ascribed to unpulsed emission, and that this fraction decreases as energy increases [3]. Kifune et al. also find no evidence for pulsed TeV emission. The flux measured with the Durham Mark 6 telescope is compatible with the extrapolation of the EGRET spectrum above 1 GeV (see Figure 3). These measurements suggest that the emission mechanisms at 1 GeV < \(E < 5\) GeV and \(E > 300\) GeV are very similar, and so it is significant that the proportion of the \(\gamma\)-ray emission which is pulsed changes from greater than 80\% to less than 35\%. It is of interest to investigate the lowest energy events detected by the Mark 6 telescope as this opens up the possibility of establishing emission at energies down to \(\sim 125\) GeV and hence identifying the range of energy within which

\(^1\) Available at web address [http://pulsar.princeton.edu/ftp/grd](http://pulsar.princeton.edu/ftp/grd)
Fig. 3. The integral γ-ray spectrum of PSR B1706-44. The shaded area indicates the EGRET spectrum for this object. ▼ represents the unpulsed flux detected with the Mark 6 telescope, and ● represents the upper limit to the pulsed flux. ■ represents the measurement of Kifune et al. [20]. Note that the point of Kifune et al. has been moved to correspond with the revised energy threshold of 2 TeV for CANGAROO at the time of the PSR B1706-44 measurements [27].

the transition from pulsed to unpulsed γ-radiation occurs. More data will be needed to increase sensitivity at these low energies.

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