Very High Energy Gamma Rays from PSR1706-44

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Abstract

We have obtained evidence of gamma-ray emission above 1 TeV from PSR1706-44, using a ground-based telescope of the atmospheric Čerenkov imaging type located near Woomera, South Australia. This object, a γ-ray source discovered by the COS B satellite (2CG342-02), was identified with the radio pulsar through the discovery of a 102 ms pulsed signal with the EGRET instrument of the Compton Gamma Ray Observatory. The flux of the present observation above a threshold of 1 TeV is $\sim 1 \cdot 10^{-11}$ photons cm^{-2} s^{-1}, which is two orders of magnitude smaller than the extrapolation from GeV energies. The analysis is not restricted to a search for emission modulated with the 102 ms period, and the reported flux is for all γ-rays from PSR1706-44, pulsed and unpulsed. The energy output in the TeV region corresponds to about 10^{-3} of the spin down energy loss rate of the neutron star.

Subject headings: gamma rays: observations – pulsars: individual (PSR1706-44) – supernova remnants

1. Introduction

To date, five young pulsars – the Crab (Swanenburg et al. 1981; Nolan et al. 1993), Vela (Swanenburg et al. 1981), Geminga (Bertsch et al. 1992), PSR1706-44 (Kniffen et al. 1992; Thompson et al. 1992) and PSR1055-52 (Fierro et al. 1993) – have been discovered to be bright in the hundreds of MeV to GeV γ-ray energy region. Inspection of these five reveals that the longer the pulsar period, the greater the fraction of the total spin down energy loss that is emitted in high energy γ-rays. The Crab nebula, containing the pulsar with the shortest period of these five, is so far the only established source in which γ-ray emission extends to the very high energy region near 1 TeV (Weekes et al. 1989; Vacanti et al. 1991) and even higher (Baillon et al. 1993; Tanimori et al. 1994). More observational data are needed to understand the processes in these objects which result in greater energy losses at very high energies than any other.

The pulsar PSR1706-44 has been observed with the 3.8m diameter Čerenkov imaging telescope of the CANGAROO Collaboration (Patterson and Kifune 1992; Hara et al. 1993; Gregory et al. 1990) near Woomera, South Australia. This object was detecteded as a γ-ray source (2CG342-02) with the COS B satellite (Swanenburg et al. 1981) and then identified with the radio pulsar through the discovery of 102 ms pulsed signal with the EGRET instrument of the Compton Gamma Ray Observatory (Kniffen et al. 1992; Thompson et al. 1992). The slowing down of the pulsar period indicates that the pulsar has a characteristic age of 17,000 years. X-ray emission was also found with the ROSAT X-ray satellite (Becker et al. 1992), and this may suggest an X-ray synchrotron nebula associated with the pulsar PSR1706-44 similar to the case of the Crab. McAdam, Osborne and Parkinson (1993) recently suggested a possible association of the pulsar with a shell-type supernova remnant. Although these features are somewhat different from the Crab case, a common mechanism of rapid rotation of pulsar magnetosphere is likely to cause VHE γ-ray emission also in PSR1706-44. Cheng and Ding (1994) discussed the energy spectra of γ-ray pulsars at 100 MeV to 10 GeV energies to fit them with parameters based on the 'outer gap' model of the pulsar magnetosphere. The best fit value they have found so far for the γ-ray emission distance from the neutron star suggests that PSR1706-44 should emit double pulses and could be a TeV γ-ray emitter.

Evidence of TeV γ-ray emission was found in data from July and August 1992 (Ogio et al. 1993) and in order to confirm this result observations were undertaken in 1993 (Kifune et al. 1993a). This paper presents the results from these two years of observations.

2. Instrumentation and Analysis Method

Atmospheric Čerenkov telescopes detect optical Čerenkov photons emitted as air showers initiated by very high energy γ-rays and cosmic rays travel through the upper atmosphere. The total number of Čerenkov photons is proportional to the γ-ray energy. The 3.8 m, alt-azimuth mounted, telescope (Hara et al. 1993) has a ~ 1 TeV threshold for detecting γ-rays, and is equipped with a multi-pixel camera of 220 photomultiplier tubes, each of which views a $0.^\circ 12 \times 0.^\circ 12$ area of the sky, with a total camera field of view of about 3°. The camera measures the number of photo-electrons and the pulse arrival time in each tube. The event trigger requires more than three photomultiplier tubes to have a signal of > 3 photo-electrons and the total number of photo-electrons detected to be larger than about 20. The arrival time measurement in each photomultiplier tube is useful for distinguishing the background, randomly incident, light in contrast to the nearly simultaneous Čerenkov photons. The night sky background light is estimated to be about 0.05 photo electrons per 10 ns per photomultiplier tube (Hara et al. 1993), and, thus, the background light which affects the Čerenkov light image consisting typically of 10 photomultiplier tubes is ~ 1 photo-electron. A bright star, of magnitude 3.3 ($\eta\, Scorpii$), is located about 1.4° from PSR1706-44, within the field of view of the camera. By monitoring the singles count rate in each phototube, we were able to monitor the passage of this star around the field of view, and the pointing of the telescope was calibrated. The object PSR1706-44 was kept within $0.^\circ 1$ of the centre of the field of view.

Monte Carlo simulations indicate that the image shape of Čerenkov light from a γ-ray shower can be approximated by an ellipse, which is elongated towards the source position. A cosmic ray shower produces a broader, more irregularly shaped image. The image can be characterised by parameters such as the 'width', 'length', 'distance' (the distance between the centroid of the image and the centre of the field of view) and the orientation of the image, 'α'. The parameter α is the angle between the major axis of the elliptical image and the line joining the nominal source position (usually the centre of the field of view) to the centroid of the observed image. The definition of these parameters used in our analysis is the same as those of Weekes et al. (1989). The Whipple detections of very high energy γ-rays from the Crab nebula (Vacanti et al. 1991; Lewis et al. 1993) and the galaxy Markarian 421 (Punch et al. 1991) have demonstrated that the γ-ray signal can be distinguished from the cosmic ray background using the image shape. They have shown that γ-ray events from a point source appear as a peak near the origin on a flat background distribution when event rate is plotted as a function of α. The size of this peak will be affected by the choice of the nominal source position used in the determination of α, so that the position of a γ-ray point source within the field of view can be determined to an accuracy of $\sim 0.^\circ 1$.

The procedures of analysing Čerenkov images applied to telescopes with different characteristics can be examined by using the Crab pulsar/nebula as a standard candle of very high energy γ-rays. The result of the Crab observations (Tanimori et al. 1994) with the present telescope was found to be compatible with the energy spectrum reported by the Whipple group (Lewis et al. 1993).

3. Observed Data

The image parameters were calculated for the events that are located well inside, but not at the centre of, the field of view, selecting the events with 'distance' smaller than $0.^\circ 9$ and greater than the 'length'. Those events with compact images (narrower than energy dependent values typically of $0.^\circ 18$ for 'width' and $0.^\circ 45$ for 'length') were then selected to enrich any γ-ray component present. These values for selecting data differ slightly from those applied to the Crab data ($0.^\circ 14$ for 'width' and $0.^\circ 33$ for 'length' (Tanimori et al. 1994)). Larger discrimination values are used in the present analysis as the image size is smaller at the larger zenith angles of the Crab observations (Kifune et al. 1993b). The discrimination values employed here result in a similar fraction of γ-rays passing the selection cut as for the Crab analysis (Tanimori et al. 1994). The average image size of the Crab observations was about 3/4 of that at the zenith, consistent with a Monte Carlo simulation for inclined showers (Tsukagoshi 1994). Comparison with simulations as well as the dependence of the chosen selection criteria on the total yield of photons will be described in a subsequent paper.

The number of analysed events is plotted in Figure 1 as a function of the parameter 'α'. Figure 1a is the plot for all the data sets combined, and Figure 1b, 1c and 1d are from the 1992 data set, July 1993 data set and August 1993 data set, respectively. In order to monitor the cosmic ray background in 'on-source' data, 'off-source' observation runs were also done. In the on-source run, PSR1706-44 was tracked at the centre of the field of view, whereas for off-source runs a point at the same declination as PSR1706-44 but offset in right ascension was tracked. The solid line in the figure indicates the on-source data, and the dotted line shows the off-source data. A peak of events is seen at $\alpha \sim 0^\circ$ for the on-source data but not for the off-source data. In 1992, 18 hours of off-source data and 42 hours of on-source data were recorded and the results shown in Figure 1b. For the 1993 data set, the observation time is 42 hours for both on- and off-source runs. The event rates of on- and off-source observations were equal to each other at $\alpha > 30^\circ$. The peak at $\alpha \sim 0^\circ$ is thus due to an excess of gamma ray events above the background of isotropic cosmic rays. The excess at $\alpha \sim 0^\circ$ is present also when no selection cut was made on 'width', and becomes more prominent as narrower widths are selected, as expected if a γ-ray signal is present. The width of the observed peak is consistent with that estimated from Monte Carlo simulations for γ-ray emission from a point source.

An analysis was performed in which the 'source' position was deliberately shifted (in software) from PSR1706-44. This procedure leads to a change in calculated values of 'α'. We then studied how the peak strength at $\alpha \sim 0°$ for these 'false sources' varied as a function of the shift. The contour map of the significance of the peak (calculated from the number of events in $\alpha < 10°$ compared with $\alpha > 30°$) is shown in Figure 2 as a function of the position around PSR1706-44. Since the telescope is alt-azimuth mounted, the field of view rotates around its center with time. The 'de-rotation' to correct for this effect was made to the data in software. The highest significance is obtained when the source location is set at the centre of the field of view, the true position of PSR1706-44.

The number of data samples in each map in Figure 2 is 1681. We would therefore expect a few $\pm 3\sigma$ statistical fluctuations. However, deviations of about 4σ are evident near the outer regions of the map. In the analysis to obtain Figure 2, the requirement that 'distance' be smaller than $0.°9$ was applied to the 'distance' of the centroid of image from each 'false source' position as well as the usual 'distance' from the center of field of view. This procedure resulted in unequal areas in the field of view which contribute to the data for different assumed source positions, and led to poorer statistics for the 'false source' positions near the edge of the field of view. A strict comparison between 'source' and 'false source' should be made to similarly sized data-bases (as proposed in Fomin et al. 1994). In the present case, this condition is met only at the center of the field of view. However, the inequality of the angular area is not large for the positions near the center, and 'false sources' in this central region do not produce fluctuations larger than expected from statistics. The significance obtained for the true position of PSR1706-44 is the only one that exceeds statistical expectations near the center. The existence of 4σ fluctuations near the edges of the map suggests a limitation to this contour map method when applied to 'false source' locations considerably removed from the center of the field of view.

The selection of 'distance' less than $0.°9$ is found effective in suppressing any effects of the tendency for images located near the edge of field of view to appear elongated along the outer boundary of the camera, *i.e.* having values of α near $90°$. Enrichment of $\alpha > 30°$ events as a consequence of this effect would result in the number of events at $\alpha \sim 0°$ becoming smaller than the rate estimated from α of larger values.

We examined the data for the presence of any systematic effect. The events that contribute to the peak are distributed over the full range of γ-ray energy as estimated from the total yield of Čerenkov photons. Thus, the peak at $\alpha \sim 0°$ is not caused by a spurious effect near the limit of detection sensitivity. The plot of the centroid positions in the image plane shows a uniform distribution indicating no correlation with any specific position, such as that of $\eta\,Scorpii$. This star is offset from PSR1706-44 by 0.°64 in right ascension and by 1.°25 in declination: a location beyond the upper right edge in the map of Figure 2. The separation of this star from PSR1706-44 is greater than the 0.°9 discrimination value on 'distance', and, thus, it is unlikely that the analysed images are affected by $\eta\,Scorpii$.

The event rate of the cosmic ray background has a flat distribution as a function of the parameter α. By estimating the background from the rate in the range $\alpha = 30° \sim 90°$, the excess counts within the bins with $\alpha < 10°$ in Fig. 1a has a significance of 12 σ. The number of events in the peak is constant within statistical fluctuations when the data are divided into shorter sub-sets. The γ-ray intensity is, therefore, consistent with steady emission during the observation period.

The effective detection area is a product of the area of the Čerenkov light pool and the detection efficiency of the telescope. The detection efficiency is a function of γ-ray energy and (the location of telescope in) the lateral spread of a Čerenkov light pool, and also depends on the trigger conditions and on the selection criteria of events for analysis. Results of a Monte Carlo simulation study under way to estimate the detection efficiency for these observations, suggest an effective area of approximately 5×10^8 cm^2 at a γ-ray energy of 1 TeV. Adopting this area, the flux of γ-ray events is $7 \cdot \eta^{-1} \times 10^{-12}$ cm^{-2} s^{-1}, where η is the efficiency for γ-rays passing through the data reduction procedures. The number of excess counts which constitute the peak at $\alpha \sim 0°$ was compared between the two cases with and without the selection cuts on 'width' and 'length'. Ninety per cent of the peak events survive after the cuts, similar to the case of the Crab data (Tanimori et al. 1994). By putting η equal to 0.9, we obtain a γ-ray flux of 7×10^{-12} cm^{-2} s^{-1}, integrated above the threshold energy of 1 TeV. We estimate that the systematic error in the flux and γ-ray energy may be as large as ~ 30 % from uncertainties in the adopted values of effective area and efficiency η. Searches for pulsed emission correlated with the 102 ms period (in preparation for publication) indicate that it is unlikely that a major portion of the detected flux is pulsed.

4. Discussions

The present yield of γ-rays corresponds to $\sim 1 \cdot 10^{-11}$ erg cm^{-2} s^{-1} at 1 TeV. For a distance of 1.5 kpc to PSR1706-44, the TeV luminosity is $\sim 3 \cdot 10^{33}$ erg s^{-1} assuming isotropic emission. This is 10^{-3} of the loss rate of the total spin down energy of $3.4 \cdot 10^{36}$ erg s^{-1} of the neutron star. The TeV luminosity is smaller by an order of magnitude than the luminosity of $2.6 \cdot 10^{34}$ erg s^{-1} in the 100 MeV – 10 GeV range, but greater than the X-ray luminosity of $1 \cdot 10^{32}$ erg s^{-1} in the 0.1 – 2.4 keV range detected with the ROSAT. The energy spectrum of the pulsed signal reported in Thompson et al. 1992 is very flat up to several GeV with a differential spectral index of -1.7. When extrapolated to 1 TeV the integral flux is as high as 1.6×10^{-9} photons cm^{-2} s^{-1} (time-averaged over the period). The flux at 1 TeV from the present observation is smaller by two orders of magnitude than this extrapolated value.

We note that Nel et al. (1993) has reported an upper limit of 5.8×10^{-12} cm^{-2} s^{-1} for $>$ 2.6 TeV on the γ-ray flux that is modulated with the pulsar period. However, our analysis is not restricted to a search for pulsed emission, and is sensitive to any γ-rays from PSR1706-44 – pulsed and unpulsed.

It has been reported by McAdam, Osborne and Parkinson (1993) that PSR1706-44 is located near the edge of a shell-shaped supernova remnant of about a half degree diameter. If the production mechanism of TeV γ-rays is similar to that of the Crab, then pulsar PSR1706-44 may also have a synchrotron X-ray nebula like the Crab, and the ROSAT result may be an indication of this. Although the peak of the α-distribution is consistent with a point source, the angular resolution of the telescope, $\sim 0.1^\circ$, corresponding to a size $\lesssim 3$ pc at a distance of 1.5 kpc, does not preclude such extended emission. Multi-wavelength studies of this object will be needed in order to investigate the production mechanism for the very high energy γ-rays reported here.

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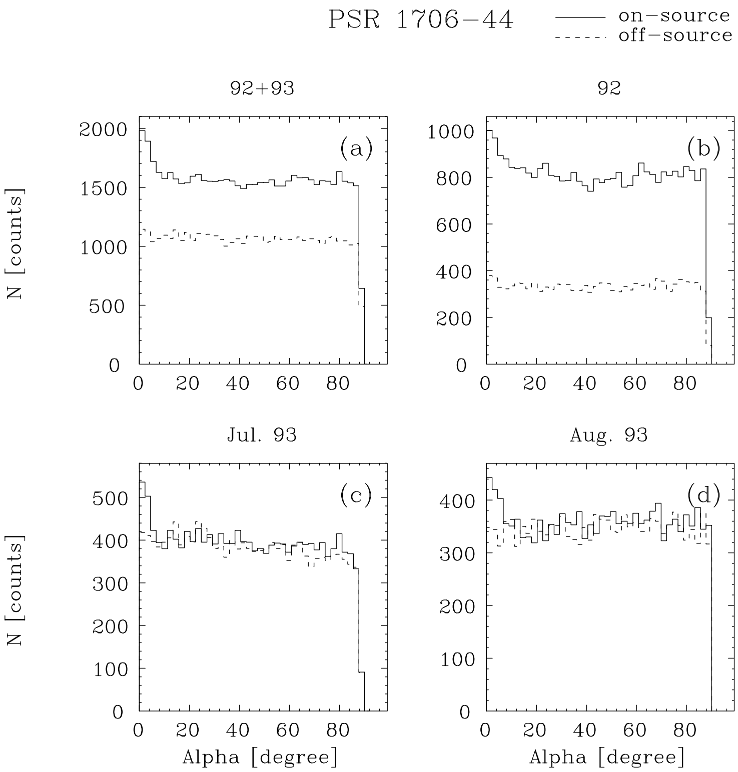
Figure legends

FIG. 1 The number of observed events as a function of the orientation angle α of the Čerenkov light image. On- and off-source data are indicated by the solid and dotted lines, respectively. (The on-source and off-source observing times are not equal.) (a) All data. (b) The data from 1992. (c) The data from July 1993. (d) The data from August 1993.

FIG. 2 The contour map of statistical significance for various directions in the sky around the PSR1706-44 position. In calculating the significance, the assumed position of the 'γ-ray point source' was artificially varied around the known position of PSR1706-44 and the significance of any resulting peak in the α distribution calculated. The result shown in the figure is from the data set of July and August 1993. Contours of an equal significance are shown in the lower figures against the two dimensional directions in units of degrees. The upper figures are the corresponding lego plots. In order to have the same scale both in on- and off-source plots to facilitate comparison, an artificial highest significance of 8.5 σ was inserted in the farthest left-hand bin. The figures on the left are for on-source data and those on the right for off-source data.



PSR 1706−44
on−source
off−source
92+93
92
Jul. 93
Aug. 93
(a)
(b)
(c)
(d)
N [counts]
Alpha [degree]

Figure 1:

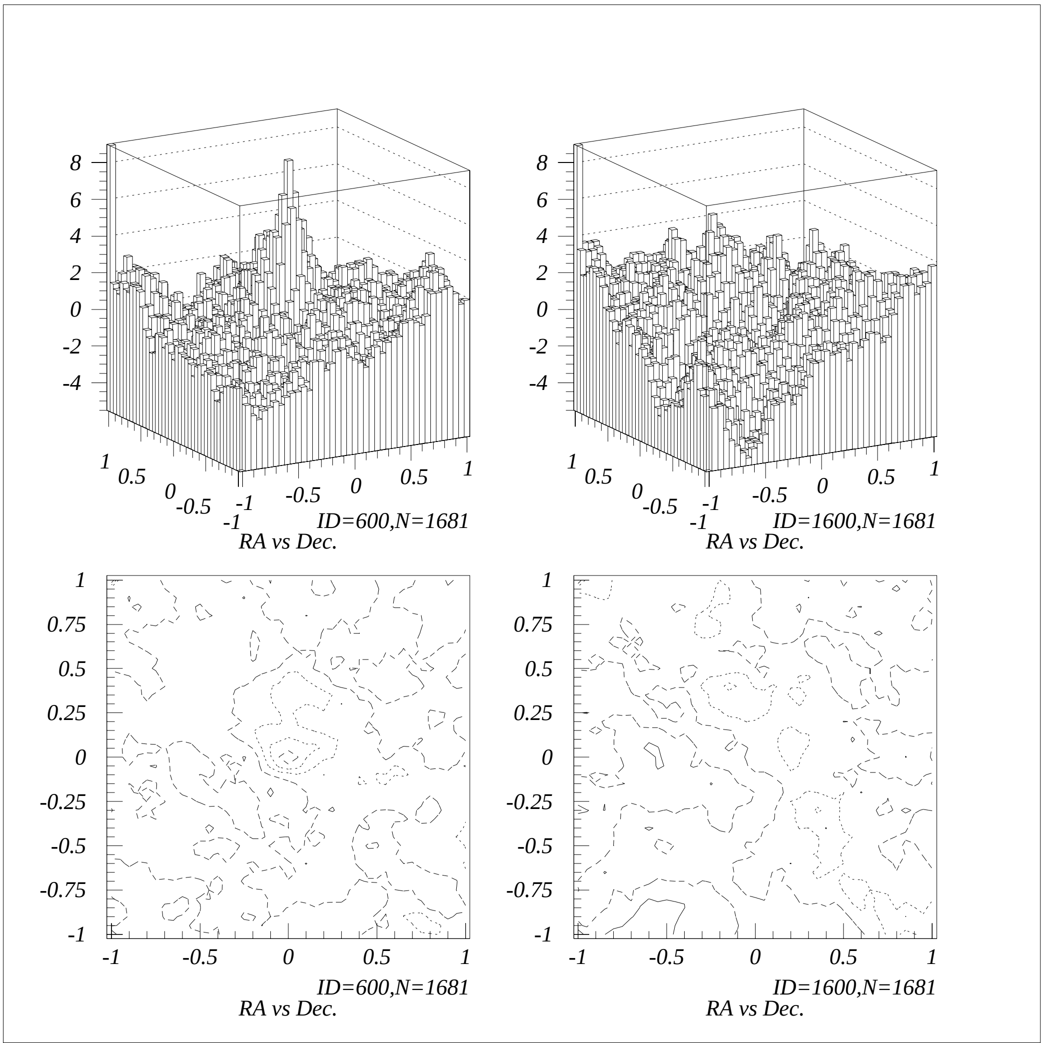

ID=600,N=1681
RA vs Dec.
ID=1600,N=1681
RA vs Dec.
ID=600,N=1681
RA vs Dec.
ID=1600,N=1681
RA vs Dec.

Figure 2: