

# TeV Measurements of Young Pulsars and Supernova Remnants

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## Abstract

Observations have been made with the University of Durham Mark 6 telescope of a number of supernova remnants and young pulsars (Vela pulsar, PSR B1055–52, PSR J1105–6107, PSR J0537–6910 and PSR B0540–69). No VHE gamma ray emission, either steady or pulsed, has been detected from these objects.

## 1 Introduction

The *Compton Gamma Ray Observatory* (CGRO) telescopes have detected pulsed gamma radiation from 7 pulsars so far: Crab, Vela, Geminga, PSR B1509–58, PSR B1706–44, PSR B1951+32 and PSR B1055–52 (see e.g. Thompson et al. 1997). Of these, the Crab and PSR B1706–44 are confirmed VHE gamma ray emitters, and the Vela remnant has been detected by the CANGAROO group. Although the gamma ray emission from all the pulsars detected with the EGRET telescope is pulsed, thus far no imaging VHE gamma ray telescope has detected pulsed radiation at TeV energies from any of the EGRET pulsars.

We have previously presented limits on VHE gamma ray emission from a number of Southern hemisphere pulsars using the University of Durham Mark 3 telescope (Brazier et al. 1990). We present here the results of VHE gamma ray observations of five pulsars using the Mark 6 imaging telescope; two EGRET sources (Vela and PSR B1055–52) and three X-ray emitting pulsars, PSR J1105–6107, PSR J0537–6910 and PSR B0540–69. We have searched for both steady and pulsed emission from these objects.

## 2 Observations

The Durham University Mark 6 telescope is described in detail elsewhere (Armstrong et al., 1999). It consists of three 7 m diameter parabolic flux collectors mounted on a single alt-azimuth platform. A 109-element imaging camera is mounted at the focus of the central mirror, with low-resolution cameras each consisting of 19 pixels mounted at the focus of the outer (left and right) flux collectors. These detectors operate as a 4-fold temporal plus 3-fold spatial triggering system, which provides for a robust muon-free trigger and a low threshold energy ( $\geq 300 - 400$  GeV).

Data from all objects except the PSR J0537–6910/PSR B0540–69 field were taken in 15-minute segments. Off-source observations were taken by alternately observing regions of sky which differ by  $\pm 15$  minutes in RA from the position of the object to ensure that on- and off-source segments have identical zenith and azimuth profiles. Data were accepted for analysis only if the sky was clear and stable and the gross counting rates in each on-off pair were consistent at the  $2.5\sigma$  level. In the case of PSR J0537–6910 and PSR B0540–69, the two objects were tracked and kept in the field of view at all times during the observations.

**2.1 Vela pulsar** The Vela pulsar is comparatively close to Earth ( $\sim 500$  pc distant) and so the surrounding nebula is well studied. X-ray studies show that there is an X-ray jet and so there may be evidence of a pulsar wind (Markwardt & Ögelman 1995). Observations with ASCA have suggested that the jet emission is non-thermal (Markwardt & Ögelman 1997), which leads to the strong possibility of the production of Compton-boosted VHE gamma rays. Extensive observations of the Vela pulsar have been made with EGRET (Fierro et al. 1998). The light curve is double peaked with emission occurring in the phase interval between the two peaks. There is evidence for some weak unpulsed emission ( $4.4\% \pm 0.9\%$  of the total emission) and a spectral turnover is seen at about 1 GeV.

A number of limits to pulsed VHE emission from the Vela pulsar have been obtained using first generation non-imaging detectors. The CANGAROO group have detected DC VHE emission using the 3.8m imaging

Object	Date	No. of ON source scans	Object	Date	No. of ON source scans
Vela pulsar	1996 Apr 14	1	PSR J1105–6107	1997 Mar 31	5
Vela pulsar	1996 Apr 18	4	PSR J1105–6107	1997 Apr 1	6
Vela pulsar	1996 Apr 19	4	PSR J1105–6107	1997 Apr 3	9
Vela pulsar	1996 Apr 20	5	PSR J1105–6107	1997 Apr 4	9
Vela pulsar	1996 Apr 21	5	PSR J1105–6107	1997 Apr 5	7
Vela pulsar	1996 Apr 22	3	PSR J1105–6107	1997 Apr 6	9
Vela pulsar	1997 Feb 6	7	PSR J1105–6107	1997 Apr 7	4
Vela pulsar	1996 Feb 7	6	PSR J1105–6107	1997 Apr 8	2
LMC pulsars	1998 Mar 21	110 mins	PSR J1105–6107	1997 Apr 9	9
LMC pulsars	1998 Mar 22	130 mins	PSR J1105–6107	1997 Apr 10	7
LMC pulsars	1998 Mar 24	100 mins	PSR B1055–52	1996 Mar 19	5
LMC pulsars	1998 Mar 27	90 mins	PSR B1055–52	1996 Mar 20	5
LMC pulsars	1998 Mar 28	80 mins			

Table 1: Observing log for observations of pulsars made with the University of Durham Mark 6 telescope. The number of 15 minute ON-source scans obtained is shown, except for the LMC pulsars where the total exposure time is shown (see text).

telescope obtaining a flux of  $(2.9 \pm 0.5 \pm 0.4) \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$  above  $2.5 \pm 1.0 \text{ TeV}$  (Yoshikoshi et al. 1997) from a region offset from the Vela pulsar position by about  $0.13^\circ$ . They find that the emission was steady over a baseline of 2 years and that there was no evidence for pulsed emission.

**2.2 PSR B1055–52** The radio pulsar PSR B1055–52 was discovered in 1972 by Vaughan & Large (1972). It has a pulse period of 197.11 ms and a characteristic age of 530 kyr. It has been shown (McCulloch et al. 1976) to be in the small class of radio pulsars with a strong interpulse half a cycle away from the main pulse, and as such has a radio light curve similar to that of the Crab pulsar. It was detected as a soft X-ray source by the *Einstein Observatory* (Cheng & Helfand 1983) and later by *EXOSAT* (Brinkman & Ögelman 1987). Neither the *Einstein* nor the *EXOSAT* observation provided evidence for pulsed X-ray emission, but later observations made with the the *ROSAT* telescope showed evidence for pulsed X-ray emission (Ögelman & Finley 1993). The EGRET detector on board *CGRO* discovered high energy gamma ray emission from PSR B1055–52 (Fierro et al. 1993). More extensive observations (Thompson et al. 1998) have shown that the gamma ray emission is complicated. The source has a complex light curve with no detectable unpulsed emission. The gamma-ray energy spectrum is flat, with no evidence for a cut off at energies up to 4 GeV.

**2.3 PSR J1105–6107** PSR J1105–6107 was discovered with the Parkes radio telescope in 1994, with follow-up timing observations being made over the next two years (Kaspi et al. 1997). Its pulse period is 63 ms and it is young, having a characteristic age of 63 kyr. The pulsar is located close to the supernova remnant MSH 11–61A, which may be associated with the pulsar. It is also positionally coincident with the EGRET source 2EG J1103–6106, and if the pulsar is associated with the EGRET object then the observed  $\gamma$ -ray flux suggests an efficiency for conversion of spin-down luminosity to  $\gamma$ -rays of approximately 3%. Significant X-ray emission was detected from PSR J1105–6107 using the *ASCA* observatory (Gotthelf and Kaspi 1998) and *RXTE* (Steinberger, Kaspi & Gotthelf 1998). The X-ray emission shows no evidence for pulsations, and it is suggested that the X-ray emission originates in a pulsar-powered synchrotron nebula.

**2.4 PSR J0537–6910 and PSR B0540–69** These two fast pulsars are within the Large Magellanic Cloud and can be observed simultaneously with the Mark 6 telescope.

PSR J0537–6910 is a fast (16 ms) pulsar embedded in the supernova remnant N157B in the Large Magellanic

Cloud. The pulsar was detected in *RXTE* data by Marshall et al. (1998). The supernova remnant has been suggested to be a Crab-like plerion from its central peaked morphology and flat spectra in both radio and X-ray (Wang & Gotthelf 1998). No pulsed radio emission has been detected (Crawford et al. 1998).

PSR B0540–69 is a 50 ms pulsar in the Large Magellanic Cloud. It was first detected in X-ray data obtained with *Einstein* (Seward, Harnden & Helfand 1984) and is embedded in a young SNR. Optical pulsations have been detected (Middleditch and Pennypacker 1985) but only weak radio emission has been observed (Manchester et al. 1993). Again, the SNR is a synchrotron nebula and the system is Crab-like.

### 3 Data Analysis

Data reduction and analysis followed our standard procedure, which has been described in detail previously (Chadwick et al. 1999). The selection criteria applied to the data are summarized in Table 2; these are a standard set of criteria developed from our successful observations of PKS 2155–304, and allow for the variation of image parameters with image size.

To check for the presence of a pulsed signal, the phase of each event was evaluated using the ephemeris nearest the observation date from the Princeton database or other published sources. For data from the Vela pulsar, PSR B1055–52 and PSR J1105–6107 the events were then binned in 20 phase bins. No single bin showed a significant excess compared with the mean. Rayleigh and  $\chi^2$  tests were performed on the binned data. No light curve showed significant Rayleigh power. The pulsed flux limit quoted is the limit to 5% duty cycle emission implied by the lack of a significant excess in any bin. The data from PSR J0537–6910 and PSR B0540–69, for which no suitably accurate ephemerides were available, were subjected to a Rayleigh test over a small range of periods about the most likely period. No significant Rayleigh power was detected at any period.

### 4 Results

The dataset for each source has been tested for the presence of both pulsed and steady gamma ray signals as described above. In addition, as the Vela SNR source reported by the CANGAROO group is  $\sim 0.13^\circ$  from the pulsar position, a false source analysis has been performed for this object. The threshold energy for the observations has been estimated on the basis of preliminary simulations, and is in the range 300 to 400 GeV for these objects, depending on the elevation at which observations were made. The collecting areas which have been assumed are  $5.5 \times 10^8 \text{ cm}^2$  at an energy threshold of 300 GeV and  $1 \times 10^9 \text{ cm}^2$  at 400 GeV. These are subject to systematic errors estimated to be  $\sim 50\%$ . We have assumed that our current selection procedures retain  $\sim 20\%$  of the  $\gamma$ -ray signal. We have no evidence for the emission of either steady or pulsed VHE gamma rays from any of the plerions, and the flux limits are summarized in Table 2. All steady flux limits are  $3\sigma$  limits, based on the maximum likelihood ratio test (Gibson et al. 1982). Pulsed flux limits for PSR

Object	Estimated Threshold (GeV)	Flux Limit (DC) ( $\times 10^{-10} \text{ cm}^{-2} \text{ s}^{-1}$ )	Flux Limit (pulsed) ( $\times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1}$ )	Ephemeris reference
Vela pulsar	300	0.50	1.3	[1]
PSR B1055–52	300	1.3	6.8	[2]
PSR J1105–6107	400	0.22	0.53	[3]
PSR J0537–6910	400	0.61	1.0	[4]
PSR B0540–69	400	0.61	1.1	[5]

Table 2: Flux limits for observations of pulsars made with the University of Durham Mark 6 Telescope. Refs. [1] Arzoumanian et al. 1992 GRO/radio timing data base, unpublished; [2] Kaspi et al. 1996, unpublished; [3] Kaspi et al. 1997, Ap. J., 485, 820; [4] Wang & Gotthelf 1999 ApJ, 509, L109; [5] Deeter et al. 1999, ApJ, 512, 300.

J0537–6910 and PSR B0540–69 are based on the percentage pulsed flux which would be required to produce a  $3\sigma$  pulsed detection using the Rayleigh test. The pulsed flux limits for the other objects are based on the pulsed flux that would be required to yield a  $3\sigma$  excess in any single bin of a 20 bin lightcurve.

## 5 Discussion

The only object considered in this paper which has been detected at TeV energies is the Vela pulsar/nebula. An extrapolation of the flux detected with the CANGAROO telescope at  $2.5 \pm 1.5$  TeV to our threshold energy of about 300 GeV suggests that we might expect to have detected the offset source described by Yoshikoshi et al. (1997). However, taking into account the errors on our flux and threshold energy estimates, CANGAROO's flux and energy threshold estimates and the errors on the measured spectral index, we find that our result is not incompatible with that of Yoshikoshi et al. (1997).

PSR B1055–52 is a topical object, with the recent publication of the detailed analysis of the EGRET results (Thompson et al., 1998). Extrapolating the EGRET spectrum to TeV energies indicates an expected flux which is very close to our flux limit. If further observations do not yield a detection of this object at 400 GeV, then we may have evidence for a break in the power law spectrum.

Both PSR J0537–6910 and PSR B0540–69 are good candidates for TeV emission on the basis of their radio and X-ray characteristics. However, their distance from the earth (they are both situated in the LMC) means that considerable further exposure is likely to be necessary to detect a significant flux.

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