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VERY HIGH ENERGY GAMMA RAYS FROM YOUNG PULSARS AND SUPERNOVA REMNANTS IN THE SOUTHERN HEMISPHERE

P. M. CHADWICK, K. LYONS, T. J. L. MCCOMB,[1] K. J. ORFORD, J. L. OSBORNE,
S. M. RAYNER, S. E. SHAW,[2] AND K. E. TURVER
Department of Physics, Rochester Building, Science Laboratories, University of Durham, Durham, DH1 3LE, UK
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ABSTRACT

Observations have been made with the University of Durham Mark 6 telescope of a number of southern hemisphere supernova remnants and young pulsars (Vela pulsar, PSR B1055−52, PSR J1105−6107, PSR J0537−6910, and PSR B0540−69). No very high energy gamma-ray emission, either steady or pulsed, has been detected from these objects. The implications of these results for theories of high-energy gamma-ray production in plerions and young pulsars are discussed.

Subject headings: gamma rays: observations —
pulsars: individual (Vela pulsar, PSR B1055−52, PSR J1105−6107,
PSR J0537−6910, PSR B0540−69)

1. INTRODUCTION

Emission from young pulsars is a well-established feature of the gamma-ray sky. At energies around 100 MeV, the Crab and Vela pulsars were detected by the *SAS-2* and *COS-B* satellites. Later, the bright *COS-B* gamma-ray source Geminga was shown to be a pulsar following the discovery of a 237 ms periodicity in its X-ray emission (Halpern & Holt 1992) and subsequently from archival gamma-ray data (Bignami & Caraveo 1992). The *Compton Gamma Ray Observatory* (*CGRO*) telescopes have detected pulsed gamma radiation from nine pulsars: the Crab (Nolan et al. 1993); Vela (Kanbach et al. 1994); Geminga (Bertsch et al. 1992; Mayer-Hasselwander et al. 1994); PSR B1509−58 (Ulmer et al. 1993; Kuiper et al. 1999), although it is not detected by EGRET (Brazier et al. 1994); PSR B1706−44 (Thompson et al. 1992; Thompson et al. 1994); PSR B1951+32 (Ramanamurthy et al. 1995; Kuiper et al. 1998); PSR B1055−52 (Fierro et al. 1993; Thompson et al. 1999); PSR B0656+14 (Ramanamurthy et al. 1996); and PSR B1046−58 (Kaspi et al. 2000).

Of these medium-and high-energy gamma-ray pulsars, the Crab (Weekes et al. 1989) and PSR B1706−44 (Kifune et al. 1995; Chadwick et al. 1998) are confirmed very high energy (VHE) gamma-ray emitters, and the Vela remnant has been detected by the CANGAROO group (Yoshikoshi et al. 1997). Although the gamma-ray emission from each of the pulsars detected with the EGRET telescope has a pulsed component (Thompson et al. 1996; Ramanamurthy et al. 1995, 1996), thus far no imaging VHE gamma-ray telescope has detected pulsed radiation at TeV energies from any of the EGRET pulsars. Amongst limits to pulsed VHE emission are those appropriate to the Crab (Vacanti et al. 1992; Aharonian et al. 1999), Vela (Yoshikoshi et al. 1997), and PSR B1706−44 (Kifune et al. 1995; Chadwick et al. 1998). In many cases, the EGRET data show evidence for a cutoff in the pulsed spectrum above a few GeV (Thompson et al. 1997), consistent with the VHE limits.

Gamma-ray emission from young pulsars pulsed at the neutron star rotation period is probably produced inside the magnetosphere by particles accelerated to high energy (for a review see, e.g., Harding & de Jager 1997). There are two competing models for the acceleration process—the polar cap models (e.g., Daugherty & Harding 1982, 1996) and the outer gap models (e.g., Cheng, Ho, & Ruderman 1986; Romani 1996). One powerful discriminant between these two classes of model is the energy at which the pulsed gamma-ray spectrum is cut off. Polar cap models predict a cutoff at comparatively low energies, typically between a few GeV and a few 10s of GeV, while outer gap models predict pulsed emission extending up to TeV energies. Thus VHE observations can constrain models for pulsed emission from young pulsars.

Plerions, where the relativistic wind from a pulsar is confined by a more slowly expanding shell of a surrounding supernova remnant, are also thought to be potential TeV sources. The spin-down energy of the pulsar is channelled into accelerating particles at the shock front, which then radiate by synchrotron processes leading to TeV emission via the inverse Compton mechanism (Gould 1965). This approach has been used to provide predictions of the unpulsed TeV emission from a number of X-ray plerions (de Jager et al. 1995; Harding & de Jager 1997).

We have previously reported limits on pulsed VHE gamma-ray emission from a number of southern hemisphere pulsars using the University of Durham Mark 3 nonimaging telescope (Brazier et al. 1990; Bowden et al. 1991, 1993). We present here the results of VHE gamma-ray observations of five plerions 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. PREVIOUS OBSERVATIONS

2.1. *Vela Pulsar*

The Vela pulsar (PSR B0833−45) is comparatively close to Earth (∼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 nonthermal (Markwardt & Ögelman

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[1] t.j.l.mccomb@dur.ac.uk.

[2] Present address: Department of Physics and Astronomy, Southampton University, Highfield, Southampton SO17 1BJ, UK.

1997), which leads to the strong possibility of the production of inverse Compton-boosted VHE gamma rays. Extensive observations of the Vela pulsar have been made with EGRET (Fierro et al. 1998). The gamma-ray light curve is double-peaked, with emission occurring in the phase interval between the two peaks. There is evidence for some weak unpulsed gamma-ray emission (4.4% ± 0.9% of the total emission) and a pulsed spectral turnover is seen at an energy of about 1 GeV.

A number of limits to pulsed VHE emission from the Vela pulsar have been obtained using first-generation nonimaging detectors. Grindlay et al. (1975) reported upper limits for pulsed emission of $(1.0 \pm 0.3) \times 10^{-11}$ cm^{-2} s^{-1} at energies above 300 GeV and $(7 \pm 3) \times 10^{-13}$ cm^{-2} s^{-1} at energies above 5000 GeV based on measurements made in 1972 and 1973 using the University of Sydney stellar interferometer as a gamma-ray telescope. The Tata group made observations of the Vela pulsar at threshold energies in the range 5–12 TeV between 1978 and 1985 (Bhat et al. 1980, 1987). They found weak evidence for emission of TeV gamma rays pulsed at the radio period. There is also some evidence for time variability of the pulsed flux. The Potchefstroom group has published a limit to pulsed emission from the Vela pulsar of 6×10^{-12} cm^{-2} s^{-1} at an energy threshold of 2.3 TeV based on measurements using the Nooitgedacht telescope during 1989 and 1992 (Nel et al. 1992, 1993). The Adelaide group using the BIGRAT telescope has produced a limit to pulsed emission of 6.7×10^{-11} cm^{-2} s^{-1} above 800 GeV from data recorded in 1989 March and April (Edwards et al. 1994).

The Durham group observed the Vela pulsar using the Mark 3 (nonimaging) telescope during 1987 January 22–February 7 and 1989 March 2–10 (Brazier et al. 1990). We derived a limit to VHE gamma-ray emission pulsed at the radio period of 6.0×10^{-11} cm^{-2} s^{-1} for an energy threshold of ~300 GeV (Bowden et al. 1991).

The CANGAROO group has detected unpulsed VHE emission using the 3.8 m imaging telescope obtaining a flux of $(2.9 \pm 0.5_{\mathrm{stat}} \pm 0.4_{\mathrm{sys}}) \times 10^{-12}$ cm^{-2} s^{-1} above 2.5 ± 1.0 TeV from a region offset from the Vela pulsar position by about $0\overset{\circ}{.}13$ (Yoshikoshi et al. 1997). There was no evidence for variation in the signal strength on a timescale of 2 yr nor was there any evidence for pulsed emission. A 95% confidence upper limit to the pulsed emission was found to be $(3.7 \pm 0.7) \times 10^{-13}$ cm^{-2} s^{-1} above 2.5 ± 1.0 TeV.

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 is 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 (McCulloch et al. 1976). It was detected as a soft X-ray source by the *Einstein Observatory* (Cheng & Helfand 1983) and later by *EXOSAT* (Brinkmann & Ögelman 1987). Neither the *Einstein* nor the *EXOSAT* observation provided evidence for pulsed X-ray emission, but later observations made with 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 have shown that the gamma-ray emission is complicated (Thompson et al. 1999). The source has a complex gamma-ray light curve with no detectable unpulsed emission. The gamma-ray energy spectrum is flat, with no evidence for a cutoff at energies up to 4 GeV.

At VHE energies, the Potchefstroom group has reported observations of PSR B1055−52 using the Nooitgedacht telescope. They report a 2 σ pulsed flux limit of 3.6×10^{-11} cm^{-2} s^{-1} for an energy threshold of ~2 TeV (Nel et al. 1992).

Using the Mark 3 telescope, the Durham group reported observations totaling 63 hr made in 1987, 1989, and 1993. These data showed no evidence for pulsed emission at the radio pulse period, and led to a 3 σ pulsed flux limit of 5×10^{-11} cm^{-2} s^{-1} for an energy threshold of ~300 GeV (Brazier et al. 1990; Bowden et al. 1993).

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 2 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, with which it may be associated. It is also positionally coincident with the EGRET source 2EG J1103−6106, and if the pulsar is associated with this object then the observed gamma-ray flux suggests an efficiency for conversion of spin-down luminosity to gamma rays of approximately 3%. However, Kaspi et al. (2000) find no evidence for pulsations at the pulsar period in the EGRET data. Significant X-ray emission was detected from PSR J1105−6107 using the *ASCA* observatory (Gotthelf & Kaspi 1998) and *RXTE* (Steinberger, Kaspi, & Gotthelf 1998). The X-ray emission shows no evidence for pulsations, and it is suggested that this 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 within the field of 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). There have been no previous reports of VHE observations of this object.

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 supernova remnant (SNR). Optical pulsations have been detected (Middleditch & 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. EGRET data have been used in a search for this pulsar (Thompson et al. 1996), both pulsed at the radio period and as a steady source at threshold energies of 300 MeV and 1 GeV. No gamma rays have been detected. The Durham group observed this pulsar with the Mark 3 telescope between 1986 and 1989. A search for pulsed VHE gamma rays was performed at the pulsar period. A 3 σ limit to the pulsed flux of 1.2×10^{-11} cm^{-2} s^{-1} at an estimated energy threshold of 400 GeV was obtained (Brazier et al. 1990; Bowden et al. 1991).

3. OBSERVATIONS

The University of Durham 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 altitude-azimuth platform. A 109-element imaging camera with $0\overset{\circ}{.}25$ pixels is mounted at the focus of the central mirror, with low-resolution cameras each consisting of 19 pixels ($0\overset{\circ}{.}5$) mounted at the foci of the outer (left and right) flux collectors. These detectors operate with a fourfold temporal plus threefold spatial triggering system, which provides for a robust muon-free trigger and a low threshold energy ($\geq$300–400 GeV). The central camera is used to enhance the gamma-ray signal through rejection of the cosmic-ray background, which is identified using cuts based on the standard Hillas parameters for the camera image and additional constraints from the data from our left/right collectors.

Data from all objects except the PSR J0537−6910/PSR B0540−69 field were taken in 15 minute segments. Off-source control observations were taken by alternately observing regions of sky which differ by $\pm$15 minutes in R.A. from the position of the object to ensure that on- and off-source segments have identical zenith and azimuth profiles and cosmic ray background response. The choice of alternate off-source segments which precede and follow the on-source segment allow for any small residual secular effects. Data were accepted for analysis only if the sky was clear and stable and the gross counting rates in each on-off segment pair were consistent at the 2.5 σ level. In the case of PSR J0537−6910 and PSR B0540−69, the field containing the two objects was tracked and kept in the field of view at all times during the observations. The mean source position was placed $0\overset{\circ}{.}25$ off-center, alternately left and right of the center at 3 minute intervals. The image rejection parameters were calculated with respect to the true source position and its mirror image about the camera center.

A total of 36.5 hr of on-source observations under clear skies of the five objects was completed, and an observing log is shown in Table 1.

4. DATA ANALYSIS

4.1. *Search for Steady Emission*

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

The threshold energy for the observations has been estimated on the basis of preliminary simulations (Chadwick et al. 1999b), and is in the range 300–400 GeV for these objects, depending on the elevation at which observations were made. The collecting areas which have been assumed are 5.5×10^8 cm^2 at an energy threshold of 300 GeV and 1×10^9 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. All steady flux limits are 3 σ limits, based on the maximum likelihood ratio test (Gibson et al. 1982).

TABLE 1

Observing Log for Observations of Pulsars Made with the University of Durham Mark 6 Telescope

Object	Date	Number of On-Source Scans	Object	Date	Number 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 minutes	PSR J1105−6107	1997 Apr 9	9
LMC pulsars	1998 Mar 22	130 minutes	PSR J1105−6107	1997 Apr 10	7
LMC pulsars	1998 Mar 24	100 minutes	PSR B1055−52	1996 Mar 19	5
LMC pulsars	1998 Mar 27	90 minutes	PSR B1055−52	1996 Mar 20	5
LMC pulsars	1998 Mar 28	80 minutes			

Note.—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).

TABLE 2

The Image Parameter Selections Applied to the Data

	Size Ranges (steady)				
Parameter	500–800	800–1200	1200–1500	1500–2000	2000–10000
Width	<0.10°	<0.14°	<0.19°	<0.32°	<0.32°
Concentration	<0.80	<0.70	<0.70	<0.35	<0.25
D_{dist}	<0.18°	<0.18°	<0.12°	<0.12°	<0.10°

Note.—From Chadwick et al. 1999a. The distance range is $0\overset{\circ}{.}35$–$0\overset{\circ}{.}85$, and the eccentricity range is 0.35–0.85.

4.2. *Search for Pulsed Emission*

Every event time is recorded to 1 μs precision using a 10 MHz signal derived from a rubidium oscillator. The drift rate of this oscillator, routinely monitored by comparison with a GPS signal, is found to be less than 10^{-11} s s^{-1} and is stable. The recorded event times are corrected for the measured drift rate, leading to an absolute accuracy in recorded event times of better than 0.1 ms. The event times are corrected to the solar system barycenter using the JPL DE200 planetary ephemeris (Standish 1982).

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 (Arzoumanian, Nice, & Taylor 1992) 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. Rayleigh and χ^2 tests were performed on the binned data. The pulsed flux limits for these objects are based on the pulsed flux that would be required to yield a 3 σ excess in a single bin of a 20 bin light curve.

The data from PSR J0537−6910 and PSR B0540−69, for which no sufficiently accurate ephemerides were available, were subjected to a Rayleigh test over a small range of periods about the most likely period. Pulsed flux limits for PSR J0537−6910 and PSR B0540−69 are based on the percentage pulsed flux which would be required to produce a 3 σ pulsed detection using the Rayleigh test.

5. RESULTS

5.1. *Vela Pulsar*

The data set has been tested for the presence of a steady gamma-ray signal as described above. No source is detected and the *ALPHA*-plot based on the origin of the emission from the position of the pulsar in the SNR is shown in Figure 1. In addition, as the Vela SNR source reported by the CANGAROO group is ∼0°.13 from the pulsar position, a false source analysis has been performed for these data. In this analysis, a matrix of potential source positions is used to recalculate the image parameters and to reapply the event selection. Again, there is no evidence for DC emission from this offset position or, indeed, from anywhere within 1° of the pulsar position. The contour plot obtained from the false source analysis is shown in Figure 2. A periodicity analysis has been made of the gamma-ray candidate events, using the position of the pulsar as the source of any emission. The data have been folded at the contemporary radio pulsar period using the ephemeris of Arzoumanian et al. (1992). The resulting light curve is shown in Figure 3. We find no evidence for pulsed emission of VHE gamma rays from this source. The flux limits obtained are shown in Table 3.

5.2. *PSR B1055−52*

The PSR B1055−52 data set has been tested for the presence of a steady VHE gamma-ray signal. No signal has been found and the DC flux limit is given in Table 3. The accurate ephemeris of Kaspi et al. (1996, unpublished) allows us to form a light curve by epoch-folding our data. The resulting light curve is shown in Figure 4 and again shows no evidence for pulsed VHE emission. The flux limit for pulsed emission is given in Table 3.

5.3. *PSR J1105−6107*

Data from PSR J1105−6107 show no evidence for a steady VHE gamma-ray signal when tested in the manner

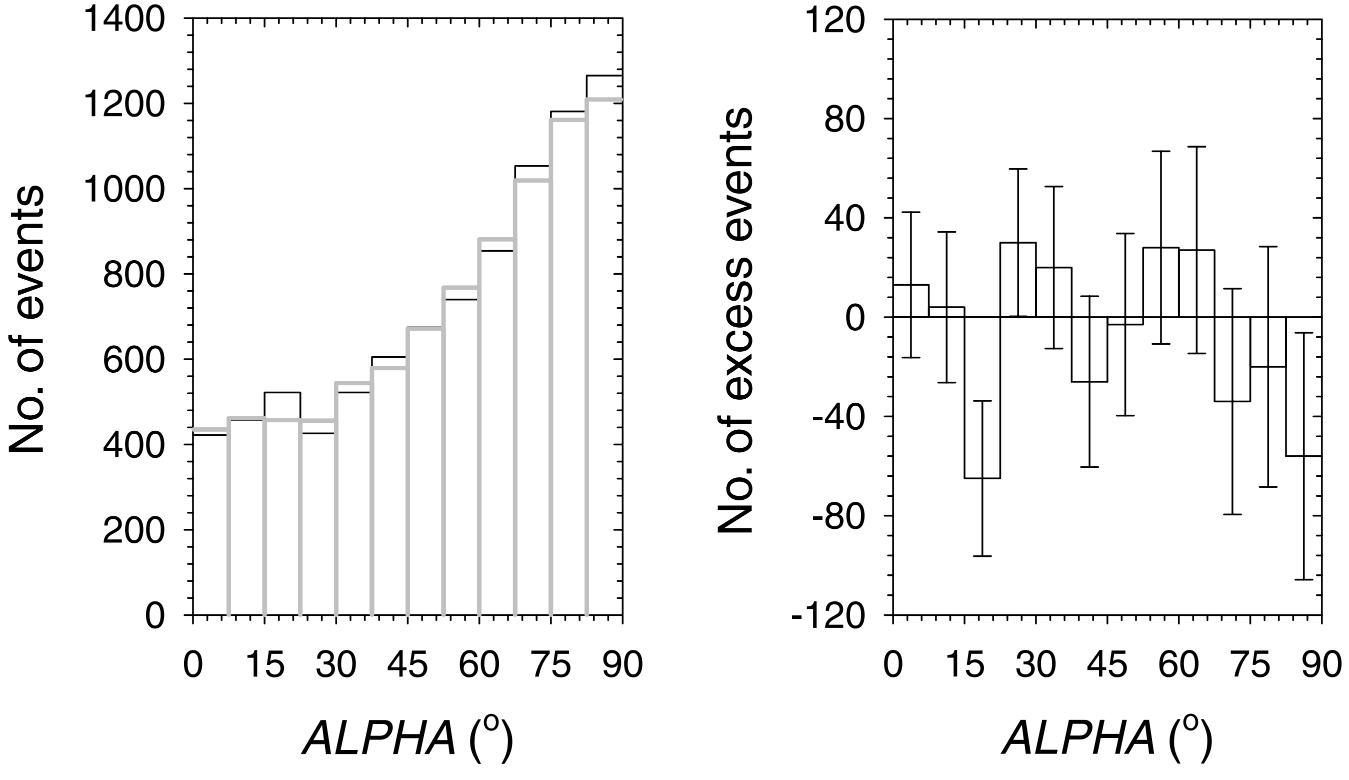

FIG. 1.—(*a*) *ALPHA* distributions on- and off-source for the observation of the Vela pulsar. The dotted line refers to the on-source data. (*b*) The difference in the *ALPHA* distributions for on- and off-source events.

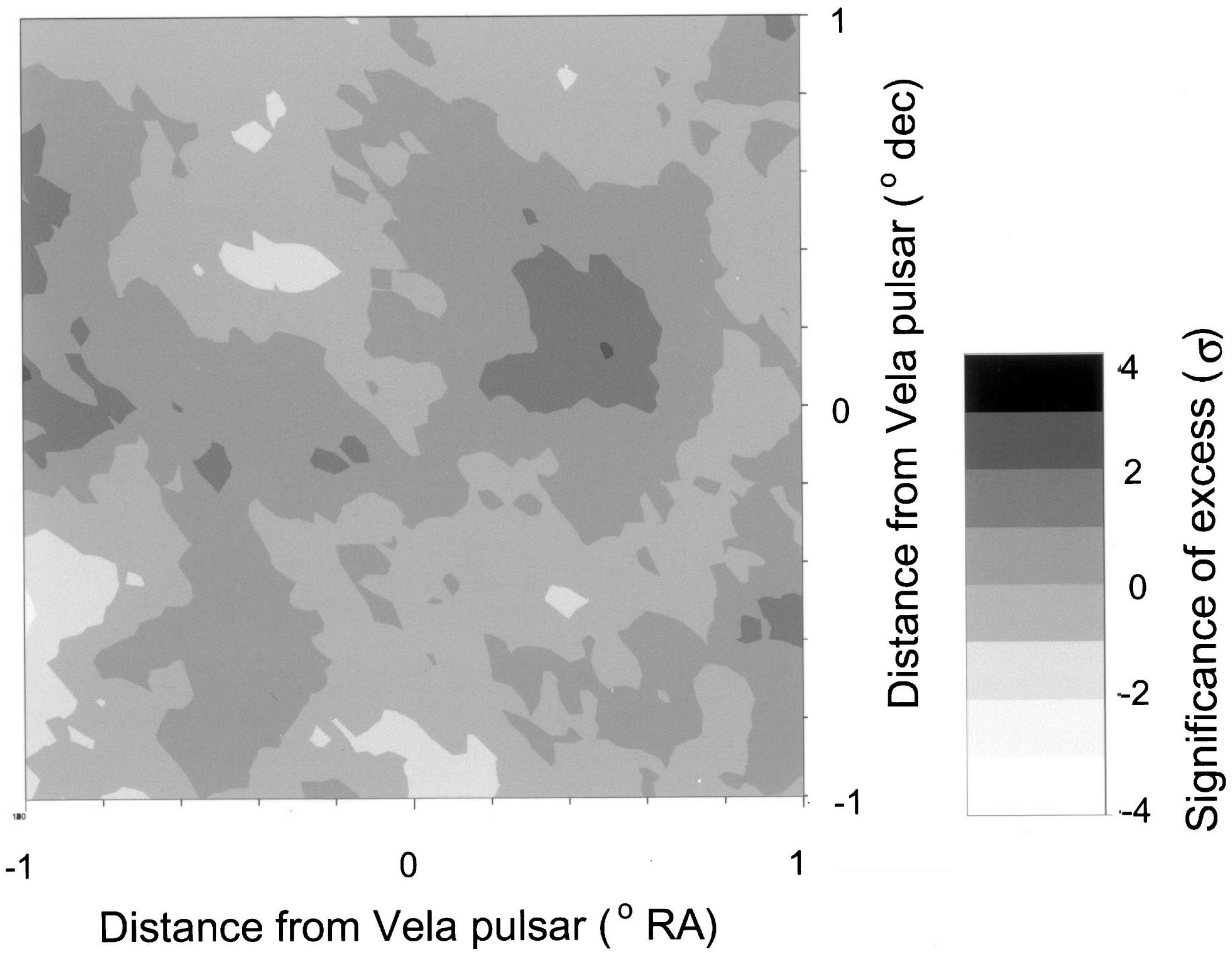

FIG. 2.—Significance of the number of any excess events (in σ) as a function of assumed source position for the observation of the Vela pulsar/nebula region.

described above. The radio ephemeris of Kaspi et al. (1997) has been used to epoch fold the VHE data, and the resulting light curve is shown in Figure 5. Flux limits for steady and pulsed emission are given in Table 3.

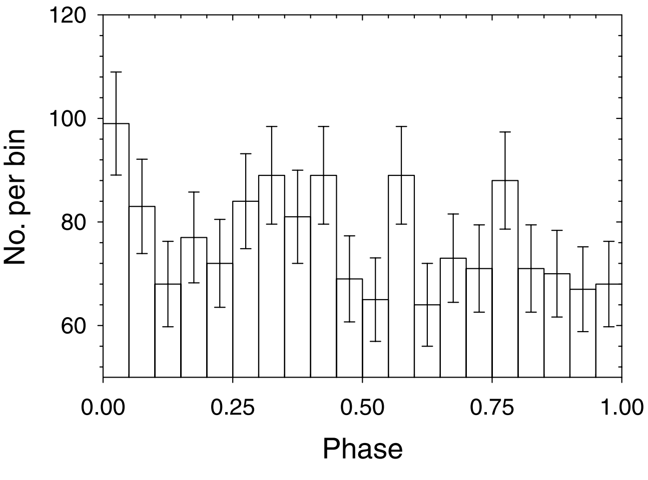

FIG. 3.—Light curve obtained by folding the gamma-ray–selected events for the Vela pulsar at the pulsar period using the ephemeris of Arzoumanian et al. (1992). The accuracy of the ephemeris is such that the phase of the radio main pulse is unknown at our observation epoch.

5.4. *PSR J0537−6910*

The available ephemerides for PSR J0537−6910 are not accurate enough to enable data taken at our observing epoch to be epoch-folded and so we have searched for periodicity around the predicted period using the Rayleigh test, using the ephemeris of Wang & Gotthelf (1999). No significant evidence for periodicity was found, and the result is given in Table 3, along with the limit for steady emission.

We note that Marshall et al. (1998) have found evidence for at least one glitch in the pulsar period of PSR J0537−6910, between observations in 1993 and 1996. Other young pulsars experience timing glitches on timescales of order years. However, Wang & Gotthelf (1998) found no evidence for timing glitches during an *EXOSAT* exposure covering ∼10 days. Although we cannot exclude the possibility of a timing glitch occurring within our 8 day observation period (which would partially invalidate the above analysis), the timescale for glitching activity suggests that this is unlikely. Thus, this limit to pulsed VHE emission is probably reliable.

We can adopt a conservative approach and analyze individual nights by searching for periodicity using the Rayleigh test, and then combine the individual nights without assuming a phase relationship between them. Adopting

TABLE 3

3 σ FLUX LIMITS FOR OBSERVATIONS OF PULSARS MADE WITH THE UNIVERSITY OF DURHAM MARK 6 TELESCOPE

		FLUX LIMIT		
OBJECT	ESTIMATED THRESHOLD (GeV)	DC ($\times 10^{-10}$ cm^{-2} s^{-1})	Pulsed ($\times 10^{-11}$ cm^{-2} 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

NOTE.—The reliability of the limit to the pulsed flux for PSR J0537−6910 is discussed in the text.

REFERENCES.—(1) Arzoumanian et al. 1992; (2) Kaspi et al. 1996, unpublished; (3) Kaspi et al. 1997; (4) Wang & Gotthelf 1999; (5) Deeter, Nagase, & Boynton 1999.

such an approach leads to a limit for pulsed emission of 1.8×10^{-11} cm^{-2} s^{-1}.

5.5. *PSR B0540−69*

The ephemeris of Deeter, Nagase, & Boynton (1999) is of limited accuracy when extrapolated to our observing epoch, and we have again had to search a range of periods when testing for pulsed emission from this object. No significant Rayleigh power is found and the resulting limit is given in Table 3, along with the limit for constant emission.

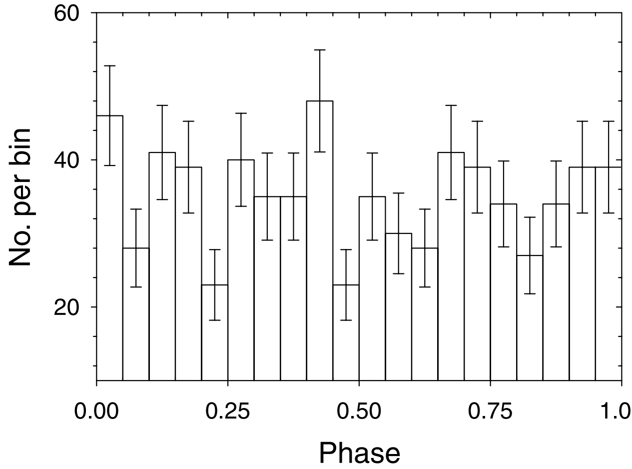

FIG. 4.—Light curve obtained by folding the gamma-ray–selected events for PSR B1055−52 at the pulsar period using the ephemeris of Kaspi et al. (1996, unpublished). The accuracy of the radio ephemeris is such that the phase of the radio main pulse is unknown at our observation epoch.

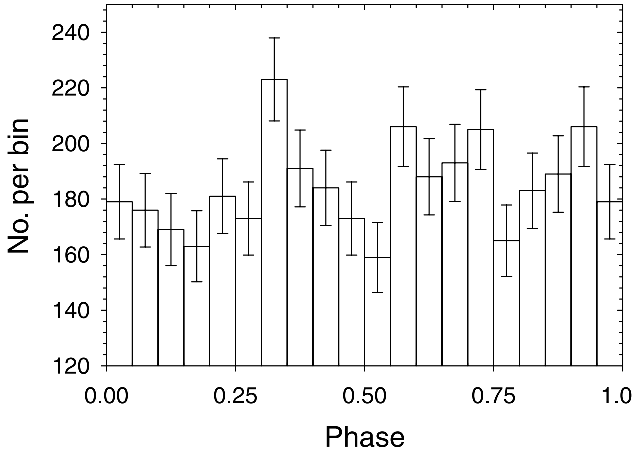

FIG. 5.—Light curve obtained by folding the gamma-ray–selected events for PSR J1105−6107 at the pulsar period using the ephemeris of Kaspi et al. (1997). The accuracy of the radio ephemeris is such that the phase of the radio main pulse is unknown at our observation epoch.

6. DISCUSSION

The only object considered in this study which has been detected previously at TeV energies is the Vela pulsar/nebula. An extrapolation of the flux detected with the CANGAROO telescope at 2.5 ± 1.5 TeV to our threshold energy of about 300 GeV suggests that we expect to have detected the offset source described by Yoshikoshi et al. (1997). However, taking into account the possible systematic errors on our flux and threshold energy estimates, CANGAROO's flux and energy threshold estimates and the errors on the measured spectral index, it is possible that our result may be compatible with that of Yoshikoshi et al. (1997).

Harding & de Jager (1997) have predicted the unpulsed TeV flux that might be expected from a number of pulsars (including Vela and PSR B1055−52) on the basis of the model of de Jager et al. (1995). Extrapolating these predictions to our energy threshold using their value of the spectral index leads to expected integral fluxes of 6.4×10^{-11} cm^{-2} s^{-1} for Vela and 2.9×10^{-11} cm^{-2} s^{-1} for PSR B1055−52. Our measured flux limit is not in conflict with these predictions for PSR B1055−302. Taking into account the errors in the flux and energy threshold measurements, our upper limit for steady emission from Vela is also not in conflict with these predictions.

Both PSR J0537−6910 and PSR B0540−69 are good candidates for steady 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 an extended exposure will be necessary to detect a significant flux.

We show in Figure 6 the multiwavelength spectral energy distributions for several of the known gamma-ray pulsars, based on that of Thompson et al. (1997), to which have been added pulsed flux limits for the Vela pulsar and PSR B1055−52 (present work), PSR B1706−44 (Chadwick et al. 1998), and PSR B1509−58 (Bowden et al. 1993). For each of these objects, the addition of limits at ∼300 GeV emphasizes the appearance of a turnover in the spectrum in the 10–300 GeV region, following the pattern established in the extensive observations of the Crab pulsar.

The establishment of a pronounced spectral steepening above 10 GeV or so in the majority of these young gamma-

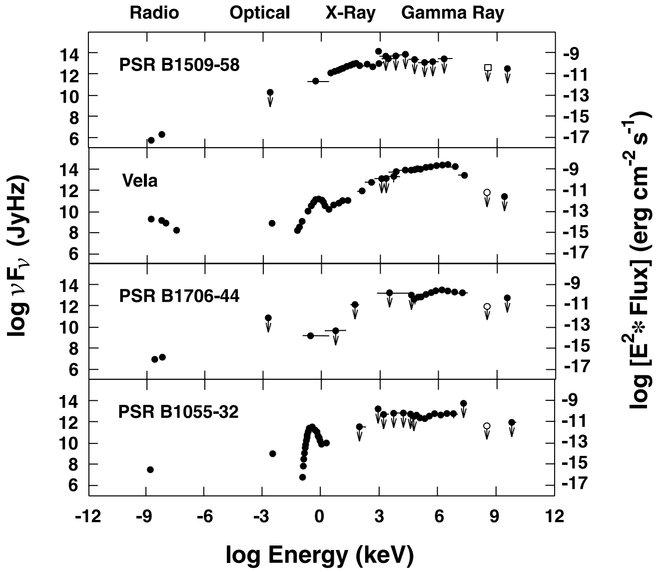

FIG. 6.—Multiwavelength spectral energy distributions for a selection of the known gamma-ray pulsars (based on that of Thompson et al. 1999). 2 σ flux limits are shown. Additional limits: open circles = this work, open squares = Bowden et al. (1993).

ray pulsars may help to constrain models of gamma-ray production in pulsars. Early versions of the outer gap model (e.g., Cheng, Ho, & Ruderman 1986) predicted large fluxes of pulsed TeV gamma rays from Vela-type pulsars, produced via the inverse Compton scattering of infrared photons by primary electrons. The observations reported here emphasize that this class of model is unable to reproduce the TeV observations.

Detailed predictions of the expected spectrum of pulsed high-energy photons from several pulsars have been made for a number of models. Daugherty & Harding (1996), using the polar cap model, have predicted a very sharp cut-off in the pulsed high-energy gamma-ray spectrum of the Vela pulsar, with no emission occurring above 10 GeV. The polar cap model of Sturner, Dermer, & Michel (1995), where the high-energy gamma rays are produced via inverse Compton scattering rather than curvature radiation, also predicts that no pulsed TeV emission should be seen from the Vela pulsar.

Modern versions of the outer-gap model (e.g., Romani 1996) predict a cut-off in the pulsed spectrum of the Vela pulsar at around 10 GeV, due to the cut-off in the curvature radiation spectrum. However, this model predicts another component in the pulsed high-energy spectrum due to inverse Compton scattering of the primary electrons on soft photons from the pulsar gap. This will result in an additional component peaking at an energy of a few TeV. The results reported here present no support for such an additional component; however, Burdett et al. (1999) have pointed out that the absence of such a peak does not rule out the Romani model since the appearance of the TeV peak depends on the density of local soft photons, which may not be correctly estimated.

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REFERENCES

Aharonian, F., et al. 1999, A&A, 346, 913
Armstrong, P., et al. 1999, Exp. Astron., 9, 51
Arzoumanian, Z., Nice, D., & Taylor, J. H. 1992, GRO/Radio Timing Database (Princeton: Princeton Univ.)
Bertsch, D. L., et al. 1992, Nature, 357, 306
Bhat, P. N., Gupta, S. K., Ramana Murthy, P. V., Sreekantan, B. V., Tonwar, S. C., & Viswanath, P. R. 1980, A&A, 81, L3
———. 1987, A&A, 178, 242
Bignami, G. F., & Caraveo, P. A. 1992, Nature, 357, 287
Bowden, C. C. G., et al. 1991, Proc. 22d Int. Cosmic-Ray Conf. (Dublin), 1, 424
———. 1993, Proc. 23rd Int. Cosmic-Ray Conf. (Calgary), 1, 294
Brazier, K. T. S., et al. 1990, Proc. 21st Int. Cosmic-Ray Conf. (Adelaide), 2, 304
———. 1994, MNRAS, 268, 517
Brinkmann, W., & Ögelman, H. B. 1987, A&A, 182, 71
Burdett, A. M., et al. 1999, Proc. 26th Int. Cosmic-Ray Conf. (Salt Lake City), 3, 448
Chadwick, P. M., et al. 1998, Astropart. Phys., 9, 131
———. 1999a, ApJ, 513, 161
———. 1999b, Proc. 26th Int. Cosmic-Ray Conf. (Salt Lake City), 5, 227
Cheng, A. F., & Helfand, D. J. 1983, ApJ, 271, 271
Cheng, K. S., Ho, C., & Ruderman, M. A. 1986, ApJ, 300, 500
Crawford, F., et al. 1998, preprint (astro-ph/9808358)
Daugherty, J. K., & Harding, A. K. 1982, ApJ, 252, 337
———. 1996, ApJ, 458, 278
Deeter, J. E., Nagase, F., & Boynton, P. E. 1999, ApJ, 512, 300
de Jager, O. C., Harding, A. K., Baring, M. G., & Mastichiadis, A. 1995, Proc. 24th Int. Cosmic-Ray Conf. (Rome), 2, 528
Edwards, P. G., Thornton, G. J., Patterson, J. R., Roberts, M. D., & Rowell, G. P. 1994, A&A, 291, 468
Fierro, J. M., et al. 1993, ApJ, 413, L27
Fierro, J. M., Michelson, P. F., Nolan, P. L., & Thompson, D. J. 1998, ApJ, 494, 734
Gibson, A. I., et al. 1982, Proc. Int. Workshop on Very High Energy Gamma Ray Astron., ed. P. V. Ramana Murthy & T. C. Weekes (Bombay: Tata Institute), 97
Gould, R. J. 1965, Phys. Rev. Lett., 15, 577
Gotthelf, E. V., & Kaspi, V. M. 1998, ApJ, 497, L29
Grindlay, J. E., Helmken, H. F., Hanbury Brown, R., Davis, J., & Allen, L. R. 1975, ApJ, 201, 82
Halpern, J. P., & Holt, S. S. 1992, Nature, 357, 222
Harding, A. K., & de Jager, O. C. 1997, Towards a Major Atmospheric Čerenkov Detector V, ed. O. C. de Jager (Potchefstroom: Potschefstroom Univ. for CHE), 64
Kanbach, G., et al. 1994, A&A, 289, 855
Kaspi, V. M., et al. 1997, ApJ, 485, 820
———. 2000, ApJ, 528, 448
Kifune, T., et al. 1995, ApJ, 438, L91
Kuiper, L., et al. 1998, A&A, 337, 421
———. 1999, A&A, 351, 119
Manchester, R. N., et al. 1993, ApJ, 403, L29
Markwardt, C. B., & Ögelman, H. B. 1995, Nature, 375, 40
———. 1997, ApJ, 480, L13
Marshall, F. E., Gotthelf, E. V, Zhang, W., Middleditch, J., & Wang, Q. D. 1998, ApJ, 499, L179
Mayer-Hasselwander, H. A., et al. 1994, ApJ, 421, 276
McCulloch, P. M., Hamilton, P. A., Ables, J. G., & Komesaroff, M. M. 1976, MNRAS, 175, 71P
Middleditch, J., & Pennypacker, C. 1985, Nature, 313, 659
Nel, H. I., et al. 1992, ApJ, 398, 602
Nel, H. I., de Jager, O. C., Raubenheimer, B. C., Brink, C., Meintjes, P. J., & North, A. R. 1993, ApJ, 418, 836
Nolan, P. L., et al. 1993, ApJ, 409, 697
Ögelman, H. B., & Finley, J. P. 1993, ApJ, 413, L31
Ramanamurthy, P. V., et al. 1995, ApJ, 447, L109
Ramanamurthy, P. V., Fichtel, C. E., Kniffen, D. A., Sreekumar, P., & Thompson, D. J. 1996, ApJ, 458, 755

Romani, R. W. 1996, ApJ, 470, 469
Seward, F. D., Harnden, F. R., & Helfand, D. J. 1984, ApJ, 470, 469
Standish, E. M. 1982, A&A, 114, 297
Steinberger, J., Kaspi, V. M., & Gotthelf, E. V. 1998, preprint (astro-ph/9809367)
Sturner, S. J., Dermer, C. D., & Michel, F. C. 1995, ApJ, 445, 736
Thompson, D. J., et al. 1992, Nature, 359, 615
———. 1994, ApJ, 436, 229
———. 1996, ApJ, 465, 385
———. 1999, ApJ, 516, 297
Thompson, D. J., Harding, A. K., Hermsen, W., & Ulmer, M. P. 1997, in AIP Conf Proc. 410, Proc. Fourth Compton Symp., ed. C. D. Dermer, M. S. Strickman & J. D. Kurfess (Woodbury: AIP), 39
Ulmer, M. P., et al. 1993, ApJ, 417, 738
Vaughan, A. E., & Large, M. I. 1972, MNRAS, 156, 27P
Vacanti, G., et al. 1992, ApJ, 377, 467
Wang, Q. D., & Gotthelf, E. V. 1998, ApJ, 494, 623
———. 1999, ApJ, 509, L109
Weekes, T. C., et al. 1989, ApJ, 342, 379
Yoshikoshi, T., et al. 1997, ApJ, 487, L65