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O'Brien, J. T., et al. (2008). PSR J1410-6132: a young, energetic pulsar associated with the EGRET source 3EG J1410-6147.

Originally published in *Monthly Notices of the Royal Astronomical Society*, 388(1), L1–L5.

Available from: <http://dx.doi.org/10.1111/j.1365-2966.2010.16717.x>

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# PSR J1410–6132: A young, energetic pulsar associated with EGRET source 3EG J1410-6147

J. T. O’Brien,<sup>1\*</sup> S. Johnston,<sup>2</sup> M. Kramer,<sup>1</sup> A. G. Lyne,<sup>1</sup> M. Bailes,<sup>3</sup> A. Possenti,<sup>4</sup> M. Burgay,<sup>4</sup> D. R. Lorimer,<sup>5</sup> M. A. McLaughlin,<sup>5</sup> G. Hobbs,<sup>2</sup> D. Parent<sup>6</sup> and L. Guillemot<sup>6</sup>

<sup>1</sup>University of Manchester, Jodrell Bank Centre for Astrophysics, Alan-Turin Building, Manchester M13 9PL, UK

<sup>2</sup>Australia Telescope National Facility, CSIRO, P.O. Box 76, Epping NSW 1710, Australia

<sup>3</sup>Swinburne Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Hawthorn, VIC 3122, Australia

<sup>4</sup>INAF - Osservatorio Astronomica di Cagliari, 09012 Capoterra, Italy

<sup>5</sup>Department of Physics, West Virginia University, Morgantown, WV 26506, USA

<sup>6</sup>Centre d’Etudes Nucleaires de Bordeaux Gradignan, Chemin du Solarium, Le Haut Vigneau, BP 120, F-33175 GRADIGNAN Cedex, France

3 June 2008

## ABSTRACT

We present the discovery of PSR J1410–6132, a 50-ms pulsar found during a high-frequency survey of the Galactic plane, using a 7-beam 6.3-GHz receiver on the 64-m Parkes radio telescope. The pulsar lies within the error box of the unidentified EGRET source 3EG J1410–6147, has a characteristic age of 26 kyr and a spin-down energy of  $10^{37}$  erg s<sup>−1</sup>. It has a very high dispersion measure of  $960 \pm 10$  cm<sup>−3</sup> pc and the largest rotation measure of any pulsar,  $RM = +2400 \pm 30$  rad m<sup>−2</sup>. The pulsar is very scatter-broadened at frequencies of 1.4 GHz and below, making pulsed emission almost impossible to detect. Assuming a distance of 15 kpc, the pulsar’s spin-down energy and a  $\gamma$ -ray efficiency factor of  $\sim 10$  per cent is sufficient to power the  $\gamma$ -ray source. We therefore believe we have identified the nature of 3EG J1410–6147. This new discovery suggests that deep targeted high-frequency surveys of inner-galaxy EGRET sources could uncover further young, energetic pulsars.

**Key words:** methods: observational — pulsars: general — pulsars: individual: J1410–6132 — pulsars: searches — pulsars: timing

## 1 INTRODUCTION

The Galactic population of pulsars is still poorly known in the inner parts of our Galaxy. Studies of the Galactic structure (e.g. Bahcall 1986, Gilmore et al. 1989) and studies of the radial distribution of pulsars (e.g. Lyne et al. 1985) however, suggest that a large number of pulsars await discovery in the inner spiral arms. Unfortunately, selection effects imposed by the interstellar medium make the discovery of such pulsars difficult. First, the interaction of the broadband pulsed radio signal with the ionised component of the interstellar medium causes the effect of dispersion, delaying signals observed at lower frequencies relative to their higher frequency counterparts (Hewish et al. 1968). The dispersive delay is inversely proportional to the square of the observing frequency, the constant of proportionality being the column density of the free electrons between Earth and the pulsar, known as the dispersion measure (DM). Without a cor-

rection for this effect, the recorded pulse becomes smeared and eventually undetectable. Secondly, the pulse also becomes broadened due to interstellar multi-path scattering as the free electron distribution in the turbulent interstellar medium is inhomogeneous (Rickett 1977). Scattering is especially severe at low frequencies, since the scattering time is proportional to  $\nu^\beta$  where  $\nu$  is the observational frequency and  $\beta \gtrsim -4$  (Löhmer et al. 2004). Unlike dispersion, scattering cannot be removed by instrumental means. Both effects are particularly severe for high DM pulsars. Another factor that mitigates against low frequency surveys is that at low Galactic latitudes, the background (synchrotron) radiation has an effective temperature,  $T_{sky}$ , which dominates  $T_{sys}$  at low frequencies with a dependence which varies approximately  $\nu^{-2.6}$ .

Any pulsar survey therefore needs to balance the above effects against the fact that pulsars are intrinsically brighter at low frequencies and the larger telescope beam at lower frequencies reduces the survey time for a given area. Population studies take these selection effects into account and

\* Email: Jennifer.O’Brien@manchester.ac.uk

a recent population study by Lorimer et al. (2006) suggests that, using the electron density model of Cordes & Lazio (2002), a dearth of pulsars exist in the inner Galaxy. As uncertainties in the electron model remain (cf. Kramer et al. 2003, Lorimer et al. 2006) a high-frequency survey is the only direct way to shed light on the population of pulsars in the inner Galaxy, as was previously demonstrated by the pioneering use of high frequencies in pulsar surveys by Clifton & Lyne (1986). This is particularly true for the studies of young pulsars which are especially important for our understanding of birthrates derived in these population studies. Indeed, for young pulsars still residing near their birth place in the Galactic plane, the aforementioned selection effects are extremely severe as they are typically spinning fast. These considerations were the motivation to conduct a survey of the inner Galactic plane at an unusually high frequency of 6.3 GHz, of which the first results are presented here.

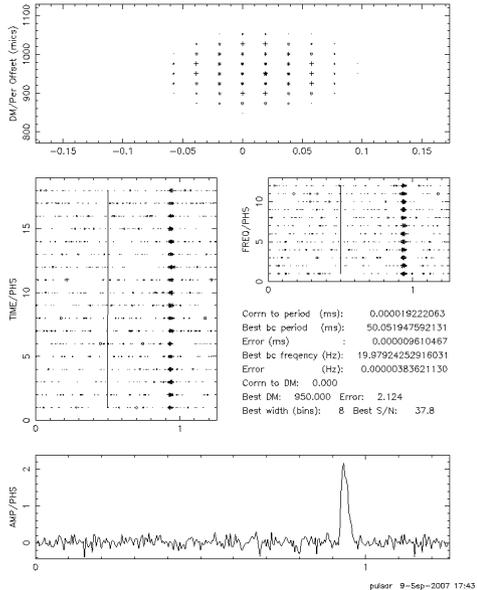
The new survey utilises a seven beam receiver that was built in collaboration between Jodrell Bank Observatory and the Australia Telescope National Facility, operating at a wavelength around 5 cm, to search the Galaxy for emission of methanol masers. Exploiting this “methanol multi-beam” (MMB) receiver (each beam with a width of 0.11 deg) allows us to rapidly cover the inner Galactic plane at a central observing frequency of 6306 MHz, with a bandwidth of 576 MHz, which is indeed much higher than for usual pulsar surveys. As a result, we expect the survey to discover a sample of new pulsars that is dominated by young objects.

We report here the first discovery of the MMB survey which, in accordance with the expectations, is a young, energetic pulsar. In Section 2 we briefly outline the parameters of the MMB survey and in Section 3 discuss the pulsar’s parameters and its discovery. Section 4 discuss the likely association between the pulsar and the unidentified  $\gamma$ -ray point source, 3EG J1410–6147.

## 2 THE METHANOL MULTIBEAM SURVEY

The survey of the Galactic plane for pulsars using the MMB receiver on the Parkes radio telescope commenced in February 2006. Full details will be given elsewhere, therefore we will only summarise its basic characteristics now.

The survey used a **192-channel filterbank, with a channel width of 3 MHz for a total of 576 MHz centred at 6306 MHz, to cover an area of 40 square degrees, ranging from a longitude of  $-60^\circ < l < +20^\circ$  and a latitude range of  $|b| < 0.25^\circ$ . The integration time of 1055 s is modest and a compromise between survey speed and sensitivity. Assuming a duty cycle of 5% and with a system noise of 60 Jy, the average limiting detectable flux density is 0.1 mJy.** All data are 1-bit sampled at 0.125 ms, written to tape and analysed off-line using standard algorithms which search for short- and long-period pulsars, as well as for short radio bursts and bright single pulses (see Lorimer & Kramer 2005 for details). Currently, 94% of all survey pointings have been observed; their full analysis will be presented elsewhere.



**Figure 1.** The confirmation observation of PSR J1410–6132. Top panel shows the search range in DM and period space, middle panels show the folded sub-integrations of the time series (left) and frequency bands (right), bottom panel shows the folded pulsar profile.

## 3 PSR J1410–6132

Wide survey observations at the pulsar’s location were carried out on 2007 April 18 and subsequent processing revealed a promising candidate with a pulse period of 50 ms and a DM of  $\sim 800 \text{ cm}^{-3} \text{ pc}$  with a signal-to-noise ratio of 12.6. Observations were made of the same area of sky using the same observing setup on 2007 September 9 and the pulsations were confirmed (see Figure 1). In the following days, observations were made at 1.4 and 3.1 GHz using a digital backend capable of recording full Stokes parameters. Further timing observations have been carried out since, and additional polarimetric observations were made at 6.4 GHz.

The top part of Table 1 gives the measured pulsar parameters obtained from a coherent timing solution using 24 independent measurements made over a time span of 98 days. The DM is measured from the time delay and the RM obtained from the position angle variation with frequency across the 1 GHz band at 3.1 GHz. Errors given in parentheses refer to the last quoted digit and are twice the formal standard error. The bottom part of the Table gives the derived parameters where the distance has been computed from the DM and the Cordes & Lazio (2002) electron density model and the other parameters using standard equations (Lorimer & Kramer 2005).

This pulsar is a young, highly energetic pulsar buried deep in the Galactic plane. As a young object, it is the sixth shortest period non-recycled pulsar, is one of only 12 pulsars with  $\dot{E} > 10^{37} \text{ ergs}^{-1}$  and ranks in the top 50 when sorted by age. Its DM, refined from the initial survey estimate, is also very large, especially considering its displacement of  $48^\circ$  from the Galactic centre. Furthermore, the magnitude of the Rotation Measure (RM) of  $+2400 \pm 30 \text{ rad m}^{-2}$  is

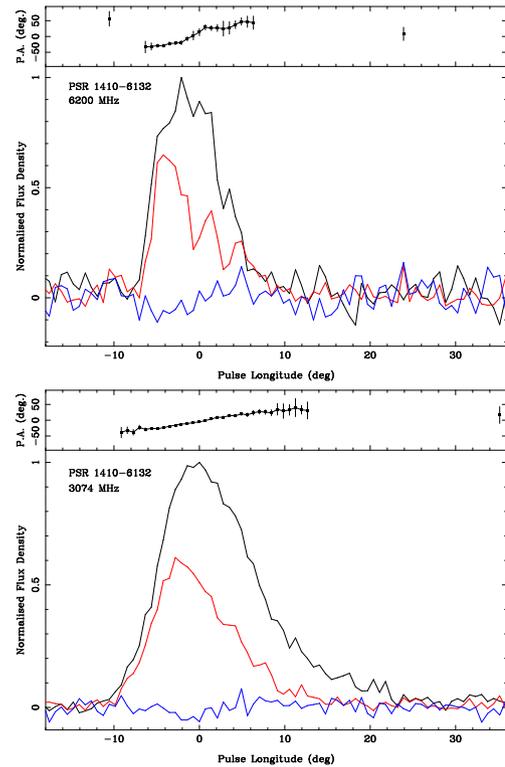
**Table 1.** Measured and derived parameters for PSR J1410–6132

Right Ascension (J2000)	14 <sup>h</sup> 10 <sup>m</sup> 24 <sup>s</sup> (4)
Declination (J2000)	−61°32′(1)
Galactic Longitude (degrees)	312.19
Galactic Latitude (degrees)	−0.09
Period (s)	0.0500519462
Period Derivative	$32 \times 10^{-15}$
Frequency (s <sup>−1</sup> )	19.979
Frequency Derivative	$-1.267 \times 10^{-11}$
Epoch of Period (MJD)	54357.3
Dispersion Measure (cm <sup>−3</sup> pc)	960(10)
Rotation Measure (rad m <sup>−2</sup> )	2400(30)
Flux density at 1.5/3.0/6.5 GHz (mJy)	<b>6(1)/2.0(2)/0.60(6)</b>
Spectral index	−1.3(2)
Distance (kpc)	15.3
Characteristic Age (yr)	$26 \times 10^3$
Surface Magnetic Field (G)	$1.3 \times 10^{12}$
Spin down energy (erg s <sup>−1</sup> )	$1.0 \times 10^{37}$

also unusually large for this longitude, and in fact, it is the largest for any known pulsar; nearly all other pulsars in the vicinity have large negative RMs and extragalactic sources also have large negative RMs in this area of sky (Brown et al. 2007). The RM in conjunction with the DM gives the mean value of the magnetic field parallel to the line of sight as 3.1  $\mu$ G.

Figure 2 shows the polarisation profiles of the pulsar at 3.1 and 6.2 GHz. The first point to notice is the scatter broadening at the lower frequency and indeed at 1.4 GHz (not shown) the profile is exceedingly broadened by interstellar scattering. Under the assumption of Kolmogorov turbulence, the time constant of the scatter broadening should vary with frequency like  $\nu^\beta$  with a scattering power law index  $\beta = -4.4$ . Following Löhmer et al. (2001), fits were made to the scattering tails of the pulses of PSR J1410–6132 as a function of frequency, at 1.4 GHz and across the 3.1 GHz band. The result shown in Figure 3 leads to a scattering power law index of  $\beta = -3.2 \pm 0.5$ , significantly flatter than expected but in line with values seen in other high DM pulsars (Löhmer et al. 2004). We only obtain an upper limit for the seemingly unscattered profile at 6.2 GHz which is rather narrow with a full width of only 14°. The linear polarisation is relatively high, especially across the leading part of the profile. The position angle of the linear polarisation swings through  $\sim 80^\circ$  across the profile. The narrow pulse width and the relatively flat gradient of position angle swing preclude any determination of the geometry of the star.

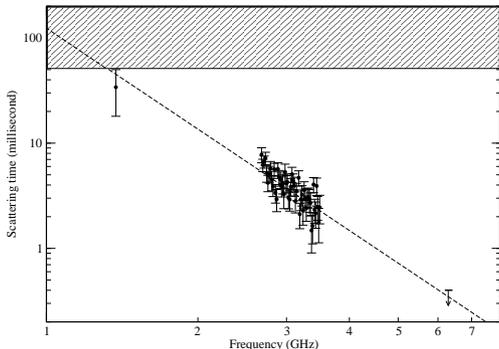
**The flux densities at 1.5, 3.0 and 6.5 GHz are listed in Table 1. At 1.5 GHz, the large scattering tail leads to a significant fraction of the flux density being present as a DC term which is normally removed during baseline subtraction. We have therefore corrected the measured flux density of 4 mJy to 6 mJy to compensate for this effect.** The flux density spectrum,  $S \propto \nu^\alpha$ , at 1.5, 3.0 and 6.3 GHz, has a power law index of  $\alpha = -1.3 \pm 0.2$  which is somewhat flatter than the mean power law index of  $-1.7$  derived from a large sample of pulsars (Maron et al. 2000).

**Figure 2.** Polarisation profiles of PSR J1410–6132 at 6.7 GHz (top) and 3.1 GHz (bottom). The total intensity (black), linear polarisation (red) and circular polarisation (green) traces are shown in the lower panel of each plot. The upper panels show the position angles of the linear polarisation.

## 4 DISCUSSION

PSR J1410–6132 is a young, highly energetic pulsar and it is located within the positional error box of a previously unidentified  $\gamma$ -ray point source, 3EG J1410–6147. There are currently over 100 unidentified  $\gamma$ -ray sources resulting from the  $\gamma$ -ray sky survey with the Energetic Gamma Ray Experiment Telescope (EGRET), aboard the Compton Gamma-Ray Observatory, which was performed from 1991 until 1999 in the energy range 100 MeV to 10 GeV (Hartman et al. 1999). The nature of these unidentified point sources has been debated for some time and many attempts have been made to find corresponding counterparts at other parts of the electromagnetic spectrum. Those that have been identified include solar flares,  $\gamma$ -ray bursts, normal galaxies, active galactic nuclei and pulsars.

Pulsars are of particular interest because they have a similar spatial distribution as the unidentified EGRET point sources and have been positively identified as being  $\gamma$ -ray emitters, e.g. the Crab and Vela pulsars. Indeed, emission theories for pulsars predict  $\gamma$ -ray emission in particular for young pulsars in either so called “outer gap” or “polar cap” models (see e.g. Harding 2005 for a recent review). In addition to seven pulsars clearly identified as  $\gamma$ -ray sources due to their detected *pulsed* emission, several more possible pulsar associations have been made with EGRET sources, often motivated by positional coincidences (e.g. Camilo et al. 2001; Kramer et al. 2003). However, due to the large positional errors of most  $\gamma$ -ray sources (of the order of  $1^\circ$ ), it



**Figure 3.** Measurement of the scattering broadening time of the pulses of PSR J1410–6132 as a function of frequency at 1.4 GHz and across the 3.1 GHz band and at 6.3 GHz. The derived scattering power law index is  $-3.2 \pm 0.5$ . The shaded area marks the region where the scatter broadening time exceeds the pulse period, preventing a detection of the pulsar.

is often difficult to be certain if the association is real and final confirmation may need the detection of corresponding pulsed emission using the new  $\gamma$ -ray satellites like AGILE or the Gamma-Ray Large Area Space Telescope (GLAST).

The true nature of EGRET source 3EG J1410–6147 has been long debated in the literature (Sturmer & Dermer 1995; Case & Bhattacharya 1999; Doherty et al. 2003; Kramer et al. 2003). The error box of 3EG J1410–6147 contains the supernova remnant (SNR) G312.4–0.4 and two young energetic pulsars, PSRs J1412–6145 and J1413–6141. It is possible that the SNR itself is responsible for the  $\gamma$ -rays (Case & Bhattacharya 1999) but the two pulsars almost certainly are not, unless they have unusually high  $\gamma$ -ray efficiencies or grossly underestimated distances (Doherty et al. 2003; Kramer et al. 2003). Doherty et al. (2003) speculated that the most likely source powering 3EG J1410–6147 was a still hidden energetic pulsar. We will show here that our newly discovered pulsar is a very strong candidate for the long sought after counterpart of this well studied EGRET source.

Table 2 shows a comparison of the properties of the three energetic pulsars coincident with the error box of 3EG J1410–6147, along with the seven confirmed  $\gamma$ -ray pulsars. The variability index  $V$  for each is shown in column 2 (McLaughlin et al. 1996) and is  $V < 1$  for all pulsars and proposed pulsar associations, indicative of non-variable flux. 3EG J1410–6147 has a value of 0.72, highly indicative of a pulsar. **Column 4 shows the pulsar’s position relative to the size of the EGRET 95% confidence error ellipse.** The newly discovered pulsar is **the closest to the centroid of the error ellipse of 3EG J1410–6147 than the other two putative candidates.** The spin-down luminosity  $\dot{E}$  is shown in column 5 and the “spin-down flux”  $\dot{E}/d^2$ , which generally gives an indication of the detectability of  $\gamma$ -ray pulsars, is shown in column 6. The observed efficiency for the conversion of spin-down luminosity ( $\dot{E}$ ) into  $\gamma$ -ray luminosity ( $L_\gamma$ ) is shown in column 7. This value,  $\eta$ , was derived as in Kramer et al. (2003), using:  $\eta = L_\gamma/\dot{E} =$

$f4\pi d^2 \bar{F}/\dot{E}$ , where  $\bar{F}$  is the observed  $\gamma$ -ray flux and  $f$  is the  $\gamma$ -ray beaming fraction which we assumed to be  $f \equiv 1/4\pi$ .

The values in Table 2 show it very unlikely, from an efficiency point of view, that either PSR J1412–6145 or J1413–6141 are associated with the EGRET source unless their distances are overestimated by a factor of at least 3. In contrast, PSR J1410–6132 even at a distance of 15 kpc has an efficiency similar to that of the known  $\gamma$ -ray pulsars and is located much closer to the centroid of the  $\gamma$ -ray position than the other two pulsars within the error box. The efficiency would be identical to that of PSR B1055–52 if the real distance of PSR J1410–6132 were about 50% less than that predicted from the value of the DM. **Conversely, we could place the pulsar at a distance which is 50% further than that derived from its DM and it would still have an efficiency no greater than the upper limit of 20% considered plausible by Torres et al. (2001).** Such uncertainties in distances based on the DM are not uncommon (Kramer et al. 2003), **and we therefore claim that the new pulsar is the likely source of the  $\gamma$ -rays in 3EG J1410–6147.**

Searching seven viewing periods of archival EGRET data, we performed an analysis to detect pulsed  $\gamma$ -ray emission from the source, which was limited by the low statistics and also possible timing noise and glitches. In addition, large time intervals between viewing periods rendered optimal  $\nu$  and  $\dot{\nu}$  pairs for one viewing period inappropriate for studying others. No evidence for a signal with a fluctuation detection probability below 1% was found in the seven data sets. However, with improved sensitivity, observations with AGILE and GLAST will provide the opportunity to search for periodic  $\gamma$ -ray emission with contemporaneous radio ephemerides to confirm our claim.

The detection of this pulsar, in a region of the Galactic plane surveyed many times before, re-opens the question as to the nature of the unidentified sources found by EGRET in the plane. The low variability index of many sources is typical of the known pulsar/EGRET source associations. It seems possible therefore, that a high frequency search for pulsars in the EGRET error boxes could uncover more distant, highly scattered pulsars previously missed in low frequency surveys. Such a survey would be timely prior to the launch of GLAST.

## 5 CONCLUSIONS

A survey with the Parkes telescope at the high frequency of 6.3 GHz has been carried out along a thin strip of the Galactic plane. We report here on the discovery of a young, highly energetic pulsar located in the error box of the  $\gamma$ -ray source 3EG J1410–6147. The parameters of the pulsar indicate that the association is highly likely, although confirmation awaits the reduction of the  $\gamma$ -error box and/or the detection of pulsations with AGILE or GLAST.

## ACKNOWLEDGEMENTS

This research was partly funded by grants from the Australian Research Council and the Science & Technology Facilities Council, UK. The Australia Telescope is funded by

**Table 2.** Comparison of the parameters of the three possible pulsar associations with the EGRET source 3EG J1410–6147 and the seven confirmed  $\gamma$ -ray pulsars. Column 1 shows the pulsar name and EGRET source. The variability index ( $V$ ) according to McLaughlin (2001) is shown in column 2 with the distance to the pulsar in column 3. This distance is based on the electron density model by Cordes & Lazio (2002) unless other information was available. The offset between the pulsar position and the EGRET centroid is listed in column 4, where  $\Delta\Phi$  is the separation between the EGRET source and the pulsar listed in column 1 and  $\Theta_{95}$  is the size of the 95 per cent error-box. Column 5 gives the pulsar’s  $\dot{E}$  and the spin-down flux  $\dot{E}/d^2$  is shown in column 6. The efficiency  $\eta$  of the conversion of spin-down energy to  $\gamma$ -ray flux measured in the band 100 MeV–10 GeV is given in the final column. The parameters were derived using standard equations (see Lorimer & Kramer 2005 for details).

Pulsar/3EG Source	$V$	$d$ (kpc)	$\Delta\Phi/\Theta_{95}$	$\dot{E}$ (erg s $^{-1}$ )	$\dot{E}/d^2$ (erg s $^{-1}$ kpc $^{-2}$ )	$\eta$ (per cent)
J1410–6132/J1410–6147	0.72	15.3	0.14	$1.0 \times 10^{37}$	$4.3 \times 10^{34}$	10
J1412–6145/ ...	0.72	7.8	0.41	$1.2 \times 10^{35}$	$1.4 \times 10^{33}$	230
J1413–6141/ ...	0.72	10.1	0.75	$5.6 \times 10^{35}$	$1.6 \times 10^{33}$	84
Crab/J0534+2200	0.50	2.0	1.23	$4.6 \times 10^{38}$	$1.2 \times 10^{38}$	0.02
Vela/J0835–4511	0.01	0.3	3.72	$6.9 \times 10^{36}$	$8.2 \times 10^{37}$	0.07
Geminga/J0633+1751	0.59	0.2	–	$3.2 \times 10^{34}$	$1.3 \times 10^{36}$	2
B1055–52/J1058–5234	0.04	0.7	0.66	$3.0 \times 10^{34}$	$5.8 \times 10^{34}$	4
B1509–58/(2EG 1443–6040)*	0.99	4.2	–	$1.8 \times 10^{37}$	$1.0 \times 10^{36}$	0.8
B1706–44/J1710–4439	0.17	2.3	2.26	$3.4 \times 10^{36}$	$6.4 \times 10^{35}$	1
B1951+32/†	??	3.2	–	$3.7 \times 10^{36}$	$3.6 \times 10^{35}$	0.6

\* COMPTEL detection. The weak 2EG source J1443–6040 associated by Kuipers et al.(1999) does not appear in the 3EG catalogue.

† While clearly detected as pulsed  $\gamma$ -ray emission by Ramanamurthy et al. (1995), no associated sources appears in the 3EG catalogue.

the Commonwealth of Australia for operation as a National Facility managed by the CSIRO. We thank A. Corogniu, R. Eatough and R. Smits for helping with the observations and to M. Keith for helping to set up the software applications. We are grateful to D. A. Smith for useful discussions.

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