

A search for pulsars in supernova remnants

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Abstract. We have carried out a sensitive search for young pulsars associated with supernova remnants using the 76-m Lovell radio telescope at Jodrell Bank. The observations were made at 606 MHz using a system with a bandwidth of 8 MHz and a set noise temperature on cold sky of about 50 K. The survey targeted 33 remnants in the northern hemisphere and achieved a nominal sensitivity of ~ 1 mJy in most cases. Two pulsars were discovered in the course of this survey and the known pulsar PSR B1952+29 was detected. The new pulsars, J0215+6218 and J1957+2831, were found during searches of the supernova remnants G132.7+1.3 and G65.1+0.6 respectively. Based on a statistical analysis of the present sample of proposed pulsar-supernova remnant pairs, we conclude that at most 17 associations are likely to be real. We find no strong evidence for a genuine association between either of the two newly discovered pulsars and their target supernova remnants.

Key words: pulsars: individual (PSRs: J0215+6218, J1957+2831) – supernova remnants: individual G132.7+1.3, G65.1+0.6

1. Introduction

In the standard model for pulsar evolution (Gunn & Ostriker 1970), young rapidly rotating pulsars are expected to be harboured within the remnants of the supernova explosions in which they were formed. The two best-known examples of young pulsars, *viz.* Crab and Vela, were discovered in the early days of pulsar astronomy (Staelin & Reifenstein 1968; Large et al. 1968). The overwhelming evidence in favour of their association with the Crab and Vela supernova remnants helped to establish the basic rotating neutron star model to explain the pulsar phenomenon (Pacini 1968; Gold 1968). In this paper, we describe a survey carried out to find pulsars associated with supernova remnants in the northern hemisphere.

In the past few years, the number of *proposed associations* between pulsars and supernova remnants has risen to around

30 (see Kaspi 1996 for a recent review). This is a result of a number of different approaches: high frequency searches of the Galactic plane (Clifton et al. 1992; Johnston et al. 1992); cross-correlations of the pulsar and supernova remnant catalogues (Caraveo 1993; Fürst et al. 1993; Kulkarni et al. 1993); targeted searches for pulsars in remnants (Frail & Moffett 1993; Gorham et al. 1996; Kaspi et al. 1996) and remnants around young pulsars (Frail et al. 1994).

The number of spurious associations in this sample, *i.e.* those cases where the pulsar and the supernova remnant are merely in chance alignment on the sky, is likely to be significant. Theoretically, the expected number of associations has a complex dependence on a number of factors: the luminosity function and initial spin period of young pulsars (Narayan 1987; Narayan & Schaudt 1988), their beaming fraction (Lyne & Manchester 1988; Biggs 1990), space velocities (Shull et al. 1989; Caraveo 1993; Lyne & Lorimer 1994), the evolution of supernova remnants (Gaensler & Johnston 1995a&b) as well as the fraction of all supernovae that produce pulsars. In a detailed statistical analysis, Gaensler & Johnston (1995b) concluded that fewer than 10 associations are expected to be real.

Statistical studies require accurate flux density upper limits for any pulsars undetected in remnants. Our search complements recent targeted searches on southern supernova remnants at Parkes (Kaspi et al. 1996), on those remnants visible from Arecibo (Gorham et al. 1996), as well as an earlier survey at Jodrell Bank (Biggs & Lyne 1996). The present survey was successful, discovering two new pulsars as well as substantially improving on previous upper limits for the flux density of any pulsars in the target remnants.

The plan for this paper is as follows: In Sect. 2 we describe the survey observations and data reduction techniques. In Sect. 3 we estimate the sensitivity of the survey. We summarise the results of the survey in Sect. 4. In Sect. 5 we discuss the validity of the association between the detected pulsars and their target remnants and comment on the implications of the flux density upper limits for the luminosity of pulsars at birth. In Sect. 6 we carry out a simple model-free statistical analysis to deduce the number of associations that would be expected by chance. Finally in Sect. 7 we present our conclusions.

Table 1. 33 supernova remnants targeted by the survey. From left to right the columns give the remnant name based on its Galactic coordinates, any alias(es) by which the remnant may be called, the equatorial coordinates, the approximate angular size, a classification tag (S – shell remnant, ? – unknown type, F – filled centre). Question marks denote poorly-known observational quantities. All these data are taken from Green’s (1996) catalogue of supernova remnants to which the interested reader is referred for further details. We also list the estimated contribution to the system temperature from the sky background (T_{sky}) and the remnant itself (T_{rem}), the number of telescope pointings used to observe each remnant (N_{pnt}), as well as the estimated minimum flux density at 606 MHz (S_{min}), above which a pulsar would have been detected by the survey (see text).

Remnant Name	Alias	α_{1950} h m s	δ_{1950} deg m	size arcmin	Type	T_{sky} K	T_{rem} K	N_{pnt}	S_{min} mJy
G65.1+0.6		19 52 30	+28 25	90x50	S	30	1	7	0.8
G65.7+1.2	DA 495	19 50 10	+29 18	18	?	30	7	1	0.9
G67.7+1.8		19 52 34	+31 21	9	S	30	2	1	0.8
G68.6–1.2		20 06 40	+30 28	28x25?	?	31	1	1	0.9
G69.7+1.0		20 00 45	+32 35	16	S	34	2	1	0.9
G73.9+0.9		20 12 20	+36 03	22?	S?	42	10	1	1.1
G74.9+1.2	CTB 87	20 14 10	+37 03	8x6	F	43	11	1	1.1
G76.9+1.0		20 20 30	+38 33	9x12	?	77	3	1	1.3
G78.2+2.1	γ -Cygni	20 19 00	+40 15	60	S	72	110	7	2.4
G82.2+5.3	W63	20 17 30	+45 20	95x65	S	33	15	7	1.0
G84.2–0.8		20 51 30	+43 16	20x16	S	44	14	1	1.1
G84.9+0.5		20 48 45	+44 42	6	S	28	1	1	0.8
G89.0+4.7	HB21	20 43 30	+50 25	120x90	S	26	17	13	1.0
G93.3+6.9	DA530	20 51 00	+55 10	27x20	S	18	12	1	0.8
G93.7–0.2	CTB104A	21 27 45	+50 35	80	S	25	11	7	0.9
G94.0+1.0	3C434.1	21 23 10	+51 40	30x25	S	26	19	1	1.0
G109.1–1.0	CTB109	22 59 30	+58 37	28	S	150	26	1	2.3
G111.7–2.1	Cass-A	23 21 10	+58 32	5	S	300	4000	1	46
G112.0+1.2		23 13 40	+61 30	30?	S?	31	9	1	0.9
G116.5+1.1		23 51 20	+62 58	80x60	S	25	2	7	0.8
G116.9+0.2	CTB1	23 56 40	+62 10	34	S	22	9	1	0.8
G117.4+5.0		23 52 30	+67 30	60x80?	S?	22	5	7	0.8
G119.5+10.2	CTA1	00 04 00	+72 30	90?	S	17	5	7	0.8
G120.1+1.4	Tycho SN1572	00 22 30	+63 52	8	S	25	76	1	1.6
G126.2+1.6		01 18 30	+64 00	70	S?	23	2	7	0.8
G127.1+0.5	R5	01 25 00	+62 55	45	S	23	8	1	0.8
G130.7+3.1	3C58 SN1181	02 01 55	+64 35	9x5	F	21	35	1	1.1
G132.7+1.3	HB3	02 14 00	+62 30	80	S	27	7	7	0.9
G152.2–1.2		04 05 30	+48 24	110?	S?	21	2	7	0.8
G156.2+5.7		04 54 40	+51 47	110	S	16	1	7	0.7
G166.0+4.3	VRO 42.05.01	05 23 00	+42 52	55x35	S	14	3	7	0.7
G166.2+2.5	OA 184	05 15 30	+41 50	90x70	S	14	2	7	0.7
G179.0+2.6		05 50 30	+31 05	70	S?	12	2	7	0.7

2. Survey observations

In order to complement recent searches in the southern hemisphere and from Arecibo, we chose to search primarily those supernova remnants with declinations north of 30 degrees. Our final sample of 33 supernova remnants was selected from Green’s (1996) catalogue and is summarised in Table 1.

The survey observations were made with the 76-m Lovell radio telescope operated by the University of Manchester at Jodrell Bank, on 5 separate observing sessions between 1994 June and 1996 April. The centre frequency for the observations was 606 MHz with a total bandwidth of 8 MHz. For those remnants larger than the telescope beam width (0.5 degrees FWHM) we covered the full area of the remnant using up to 13 individual

telescope pointings (see Table 1). Each telescope pointing was of 35 minutes duration.

The incoming radiation was split by the feed into two orthogonal linear polarisations and amplified by a pair of cryogenically-cooled field effect transistors. The signals then entered wide-band filters and, following a second stage of amplification, were mixed down to an intermediate frequency centred on 8 MHz before entering a pair of 64×0.125 MHz filterbanks. The resulting 64 polarisation pairs were then detected, summed, integrated and one-bit digitised every millisecond. The data were then passed to an on-line VAX computer which wrote the data to a standard Exabyte magnetic tape for off-line processing.

The off-line search for periodic signals in the data consisted of a Fourier analysis of time sequences of dedispersed data in order to search for significant features in the power spectrum. This was followed by a time series analysis to optimise the parameters of the most promising spectral features. The complete search procedure is very similar to that used for the highly successful Parkes southern sky survey described by Manchester et al. (1996). Briefly, the data were de-dispersed and Fourier transformed for 90 trial values of dispersion measure (DM) between zero and $995 \text{ cm}^{-3} \text{ pc}$. For any periodic signal with a small duty cycle (5–10% is typical of most pulsars), the resulting power spectrum from the Fourier transform consists of a family of harmonic spikes with the fundamental corresponding to the signal frequency. To increase the sensitivity to pulsars with narrow pulses, higher order harmonics can be added onto the fundamental (Lyne 1988). For example, to add all 2nd harmonics onto their corresponding fundamentals, we stretch the lower half of the amplitude spectrum by a factor of two and add this to the original unstretched spectrum. While the effect of this harmonic summing process increases the noise by a factor of $\sqrt{2}$, the amplitude of the signal may increase by more than a factor of $\sqrt{2}$ giving a net increase in the signal-to-noise ratio. By repeating this process several times we effect a search in pulse duty cycle. In our analysis the harmonic summing was performed 4 successive times, *i.e.* producing power spectra summed over 1, 2, 4, 8 and 16 harmonics. During this stage periodic signals from known sources of terrestrial interference, *e.g.* the 50 Hz mains power line, were excised from the data by zeroing the appropriate portions of the power spectrum. Due to strong amounts of terrestrial interference in the low-frequency part of the power spectrum, we did not consider signals with frequencies below 0.2 Hz. This degraded our sensitivity only slightly to pulsars with periods greater than 5 seconds which could still be detected in their higher order harmonics.

For each value of DM, the largest features in the power spectra and harmonic sums were then sorted so as to produce a list of “pulsar suspects”. All suspects with spectral signal-to-noise ratios greater than 7 were then folded in the time domain for a range of periods and DMs around the nominal values found in the first stage in an attempt to optimise these parameters and the signal-to-noise ratio. The output from this stage was visually inspected (see also Fig. 5 of Manchester et al. 1996) and the best suspects were stored for re-observation.

3. Search sensitivity

The sensitivity of the survey can be expressed in terms of the minimum detectable flux density S_{\min} which is a function of a number of parameters. Following Dewey et al. (1984), we write:

$$S_{\min} = \frac{\sigma \eta T_{\text{sys}}}{G \sqrt{n \Delta \nu \tau}} \left(\frac{W}{P - W} \right)^{1/2}. \quad (1)$$

In this expression σ is the threshold signal-to-noise ratio above which a detection is considered significant (7 in our case), η is a constant ~ 1.3 which reflects losses to hardware limitations, G is the gain of the telescope (1.0 K Jy^{-1} for the Lovell telescope

operating at 606 MHz), n is the number of polarisations used, $\Delta \nu$ is the observing bandwidth, T_{sys} is the system temperature, τ is the integration time, P is the period of the pulsar and W is the observed width of the pulse. With the parameters for this survey, the above expression simplifies to

$$S_{\min} \simeq 0.05 T_{\text{sys}} \left(\frac{W}{P - W} \right)^{1/2} \text{ mJy}. \quad (2)$$

The system temperature T_{sys} is the sum of separate components: the set noise of the receiver T_{set} ; the sky background noise T_{sky} and the contribution T_{rem} from continuum flux of the supernova remnant. Regular calibration measurements made during the survey indicated T_{set} to be typically 50 K. The contribution to T_{sys} from the Galactic background and the supernova remnant covers a large range. This is shown in Table 1 where we list the estimated sky background temperatures from a machine-readable version of the Haslam et al. (1982) all-sky survey, scaled to 606 MHz assuming a spectral index of -2.7 (Lawson et al. 1987) together with the expected contribution from each supernova remnant. To calculate the latter values, we estimated the flux density of the remnant at 606 MHz from spectral information in Green’s (1996) catalogue and multiplied this by the beam filling factor, defined as the lesser of unity and $(\text{FWHM}/D_{\text{SNR}})^2$, where D_{SNR} is the angular diameter of the supernova remnant. Using these values in Eq. 2, we have estimated the minimum flux density required to detect a 0.1 s pulsar with a duty cycle of 4% in each remnant. These limiting flux densities are listed in Table 1 for reference. With typical values of $\sim 1 \text{ mJy}$ at 606 MHz, they demonstrate the excellent sensitivity of the survey. We note from Table 1 that T_{rem} is a significant factor for only 3 of the 33 SNRs searched.

The observed pulse width W in Eqs. 1 and 2 is likely to be greater than the intrinsic width W_{int} emitted at the pulsar because of the scattering and dispersion of pulses by free electrons in the interstellar medium, and by the post-detection integration performed in the receiver. The observed sampled pulse profile will therefore be the convolution of the intrinsic pulse width and broadening functions due to dispersion, scattering and integration and can be estimated approximately from the following quadrature sum:

$$W^2 = W_{\text{int}}^2 + t_{\text{samp}}^2 + t_{\text{DM}}^2 + t_{\text{scatt}}^2, \quad (3)$$

where t_{samp} is the data sampling interval, t_{DM} is the dispersion broadening across one filterbank channel and t_{scatt} is the interstellar scatter broadening. Pulse scattering becomes particularly important when observing distant pulsars towards the inner Galaxy at frequencies $\lesssim 1 \text{ GHz}$. Many of the supernova remnants in our sample are relatively nearby $\lesssim 5 \text{ kpc}$ so that we do not expect a significant effect on our sensitivity due to scattering.

The effects of sampling and dispersion do, however, significantly affect the search sensitivity at short pulse periods. This is shown in Fig. 1, where S_{\min} is plotted against P for a pulsar with a dispersion measure of $150 \text{ cm}^{-3} \text{ pc}$, a typical value for a pulsar at the distance of one of the remnants in our sample (see

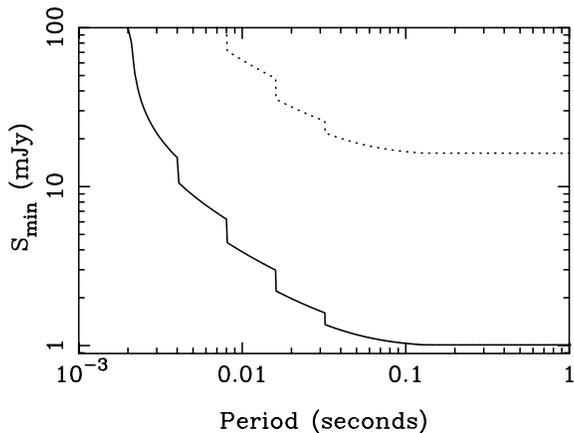


Fig. 1. The limiting sensitivity of the survey as a function of pulse period for a pulsar with a DM of $150 \text{ cm}^{-3} \text{ pc}$ and a duty cycle of 4% is shown by the solid curve. The calculation assumes a total system temperature of $\sim 95 \text{ K}$, a typical value for supernova remnants observed during the survey. The dotted curve shows the approximate sensitivity to a pulsar lying 0.25 degrees outside the boundary of the remnant (see text).

Sect. 5.2). We have also calculated the reduction in sensitivity at short periods due to the loss of higher order harmonics in the power spectrum – shown by the abrupt jumps in the sensitivity curve shown in Fig. 1.

It is worth noting that our search had only limited sensitivity to any high-velocity pulsars that may have moved outside the projected boundaries of their parent supernova remnants. The dotted curve in Fig. 1 gives the approximate sensitivity to a pulsar lying 0.25 degrees outside the remnant boundary and indicates a limiting 600 MHz flux density $\gtrsim 20 \text{ mJy}$. Such bright pulsars should have been found in previous large scale surveys of the northern sky. Future surveys targeted specifically outside the periphery of the remnants will substantially improve the sensitivity to fainter pulsars.

4. Results and follow-up observations

Twenty-five of the most promising pulsar candidates were re-observed in April 1996 and the detection of three pulsars was confirmed, B1952+29 and two that were previously unknown: PSRs J0215+6218 and J1957+2831. No further previously known pulsars were expected to be above our detection threshold. The new pulsars lie within the boundaries but towards the outer regions of the target supernova remnants G132.7+1.3 and G65.1+0.6 respectively. No further pulsars were discovered during these observations.

In order to accurately determine the astrometric and spin parameters of the two newly discovered pulsars, regular follow-up observations at 606 and 1400 MHz have been made ever since their discovery as part of the Jodrell Bank pulsar timing programme (see for example Shemar & Lyne 1996). We have been able to model the pulse arrival times for both pulsars using standard pulsar timing techniques (Manchester & Taylor 1977). Timing solutions obtained from these data are given in Table 2.

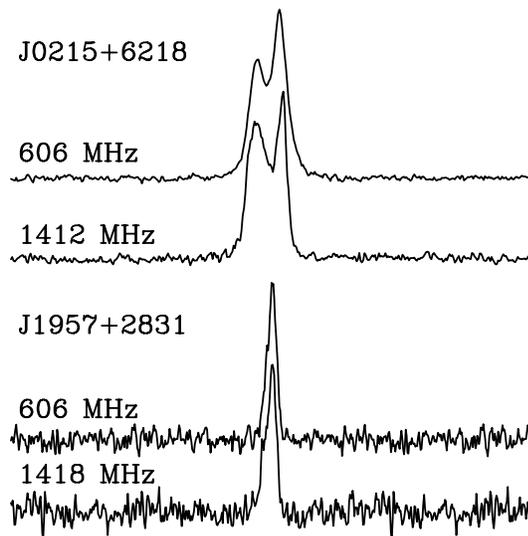


Fig. 2. Total intensity integrated pulse profiles for PSRs J0215+6218 and J1957+2831. In each case the whole of the pulsar period is displayed. These profiles are freely available at the on-line database of pulse profiles – <http://www.mpifr-bonn.mpg.de/pulsar/data>.

Table 2. Observed and derived parameters of the two newly discovered pulsars. Quoted errors refer to the last significant digit.

PSR	J0215+6218	J1957+2831
R. A. (J2000)	02 15 56.61(1)	19 57 19.36(3)
Decl. (J2000)	62 18 33.36(6)	28 31 44.1(2)
Period (sec)	0.548879759260(4)	0.30768255585(6)
$\dot{P}(10^{-15})$	0.661(6)	3.124(7)
Epoch (MJD)	50295.0	50278.0
DM ($\text{cm}^{-3} \text{ pc}$)	84.22(2)	139.08(2)
S_{600} (mJy)	10.6(4)	2.1(5)
S_{1400} (mJy)	3.7(7)	1.0(2)
α	-1.3(2)	-0.9(4)
τ_c (Myr)	13	1.6
B (10^{12} G)	0.61	0.99

Total intensity pulse profiles of the newly discovered pulsars at 606 and 1412/1418 MHz are shown in Fig. 2. Mean flux densities at both frequencies were determined in an identical fashion to that described by Lorimer et al. (1995). We also list the characteristic age $\tau_c = P/2\dot{P}$ and the surface magnetic field $B \approx 3.2 \times 10^{19} (P\dot{P})^{1/2}$ Gauss which assume a constant dipolar magnetic field and short initial period (Manchester & Taylor 1977).

5. Discussion

5.1. Are the detected pulsars really associated with their target supernova remnants?

The previously known pulsar PSR B1952+29 was detected during observations of G65.1+0.6. The pulsar lies outside the boundary of the remnant and is clearly not associated with

G65.1+0.6 because of its extremely large characteristic age (4×10^9 yr) and the proper motion measurement (Lyne et al. 1982), which shows that it is moving towards rather than away from the remnant centre as is required for a genuine association.

The evidence that the newly discovered pulsars are associated with their target remnants is not clear. PSR J0215+6218 has a period of 549 ms and a DM of $84 \text{ cm}^{-3} \text{ pc}$. The distance to this pulsar estimated from its DM and Galactic coordinates using the Taylor & Cordes (1993) electron density model is 3.2 ± 1.0 kpc, consistent with the distance to G132.7+1.3 of 2.2 ± 0.2 kpc (Routledge et al. 1991). Timing measurements show that the characteristic age of PSR J0215+6218 is 13 Myr, anomalously large by comparison with the age of G132.7+1.3, estimated to be between 30,000 and 50,000 yr (Leahy et al. 1985).

In the case of the 308 ms pulsar J1957+2831, there is unfortunately no independent distance estimate to the target remnant, G65.1+0.6. However the angular size of the remnant (~ 1 degree) indicates that it is likely to be closer than the distance of 7.0 ± 2.3 kpc inferred from the dispersion measure of PSR J1957+2831 ($139 \text{ cm}^{-3} \text{ pc}$). Whilst the age of G65.1+0.6 is also not known, it is likely to be much smaller than the characteristic age of PSR J1957+2831 (1.6 Myr).

Thus, in both cases, the pulsar characteristic age is anomalously large by comparison with the expected ages of the supernova remnants. This suggests that they are either not associated with the remnant, or the characteristic ages are anomalously large, due perhaps to the initial spin period of the pulsar being similar to its presently observed value. We note in passing that the spectral index of PSRs J0215+6218 and J1957+2831 are -1.2 and -0.9 respectively, typical of many other young pulsars (Lorimer et al. 1995) and suggesting that these pulsars may indeed be younger than their characteristic ages would suggest. Although this remains a possibility, as we shall show in Sect. 6, on statistical grounds, neither of the newly discovered pulsars are likely to be associated with the target supernova remnants.

5.2. The luminosity of pulsars at birth

In a study of pulsar population statistics Lorimer et al. (1993) suggested that there may be no need for a significant number of pulsars to be born with 400 MHz radio luminosities below 30 mJy kpc^2 . Deep surveys of supernova remnants, like the present one, can in principle be used to test this hypothesis by combining the flux density upper limit (S_{\min}) given in Table 1 with the distance to each remnant (d_{SNR}) to estimate the minimum luminosity (L_{\min}) that a young pulsar would need in order to be detectable. In Table 3 we list the 17 supernova remnants in our sample which have reliable distance estimates. Note that we have chosen not to use the surface brightness-angular size ($\Sigma - D$) relationship (Clark & Caswell 1976) as a means of estimating d_{SNR} since it has subsequently been shown to be unreliable (Berkhuijsen 1987; Green 1991).

For each supernova remnant in Table 3, we list the minimum detectable luminosity $L_{\min} = 2S_{\min}d_{\text{SNR}}^2$, where the factor of 2 in this expression scales S_{\min} defined for this survey at 606 MHz

Table 3. The supernova remnants targeted by the survey with published distance estimates. From left to right the columns give the remnant name based on its Galactic coordinates, alias(es) by which the remnant may be called, the distance and reference tag, and the corresponding minimum 400 MHz luminosity for a pulsar to be detectable in our survey (see text). The references are: a. Lozinskaya et al. (1993); b. Green & Gull (1989); c. Landecker et al. (1980); d. Green (1989); e. Feldt & Green (1993); f. Tatematsu et al. (1990); g. van den Bergh (1971); h. Reich & Braunsfurth (1981); i. Hailey & Craig (1994); j. Pineault et al. (1993); k. Albinson et al. (1986); l. Green (1996); m. Roberts et al. (1993); n. Routledge et al. (1991); o. Reich et al. (1992); p. Landecker et al. (1989); q. Routledge et al. (1986)

Remnant Name	Alias	Dist. kpc	Ref.	L_{\min} mJy kpc ²
G73.9+0.9		1.3	a	4
G74.9+1.2	CTB 87	12	b	320
G78.2+2.1	γ -Cygni	1.5	c,d	11
G84.2-0.8		4.5	e	44
G89.0+4.7	HB21	0.8	f	1
G109.1-1.0	CTB109	4.0	d	74
G111.7-2.1	Cass-A	2.8	g	720
G116.5+1.1		4.4	h	30
G116.9+0.2	CTB1	3.1	i	15
G119.5+10.2	CTA1	1.4	j	3
G120.1+1.4	Tycho SN1572	2.7	k	22
G127.1+0.5	R5	1.3	l	3
G130.7+3.1	3C58 SN1181	3.2	m	22
G132.7+1.3	HB3	2.2	n	9
G156.2+5.7		2.0	o	6
G166.0+4.3	VRO 42.05.01	4.5	p	28
G166.2+2.5	OA 184	8.0	q	90

to 400 MHz assuming a typical pulsar spectral index of -1.6 (Lorimer et al. 1995). We find the median value of L_{\min} to be 22 mJy kpc^2 , with 12 of these values lying between 1 and 30 mJy kpc^2 . In this sample of 12 supernova remnants with well defined distances, we detected one pulsar (PSR J0215+6218) which has a 400 MHz luminosity $\sim 80 \text{ mJy kpc}^2$. If we assume that each of these remnants contains a radio pulsar born with a luminosity above 30 mJy kpc^2 , then we expect to see $12f$ pulsars, where f is the mean beaming fraction. A consensus on the beaming fraction of young pulsars has yet to be established. Frail & Moffet (1993) obtained a value $f \sim 0.6$ based on a deep imaging search at the VLA. In this case we would expect to see ~ 7 pulsars. On the other hand, Tauris & Manchester (1997) recently claim f to be as low as ~ 0.1 implying a detection of only one pulsar. Thus, although our results are consistent with few pulsars being born with luminosities below 30 mJy kpc^2 , they are still hampered by small number statistics and we conclude that yet deeper searches are required to provide a larger sample with which to test this hypothesis (see also Kaspi et al. 1996).

5.3. Radio-quiet neutron stars

The above discussion does not, of course, exclude the possibility that neutron stars exist in the remnants which do not produce significant radio emission. One classic example is the 6.9 s X-ray pulsar 1E 2259+586 which has long been postulated to be associated with CTB 109 (Fahlman & Gregory 1981). Despite extensive efforts, no radio counterpart to the pulsar has ever been detected. Coe et al. (1994) used the VLA at 1489 MHz to set a 3σ upper limit to continuum emission of $50\ \mu\text{Jy}$. Our limit to *pulsed* emission from CTB 109 2.3 mJy at 600 MHz corresponds to about $500\ \mu\text{Jy}$ when scaled to 1489 MHz, again assuming spectral index of -1.6 . Another example is 3C 58, a Crab-like plerion containing an X-ray point source which is highly suggestive of a young pulsar (Helfand et al. 1995 and references therein). Our limit of 1.1 mJy to pulsed emission at 600 MHz corresponds, after scaling, to about a factor of two larger than the present best upper limit of 0.15 mJy at 1400 MHz (Frail & Moffet 1993).

One of the supernova remnants observed during this survey, G78.2+2.1, also known as γ -Cygni, contains the bright γ -ray source 2EG J2020+4026. Brazier et al. (1996) have recently discovered an X-ray source within the error box of 2EG J2020+4026. Assuming this to be the X-ray counterpart, they propose, on the basis of the γ -ray to X-ray flux ratio, that this source is most probably a Geminga-like neutron star. No significant radio pulsations were detected during our search of this remnant and our estimated 400 MHz lower luminosity limit of $11\ \text{mJy kpc}^2$ certainly rules out the presence of a bright, favourably beamed, Crab-like radio pulsar associated with this source of emission.

6. Pulsar-Supernova remnant pair statistics

In this section, we address the question: How many pulsar-supernova remnant pairs (which we shall hereafter refer to simply as pairs) are likely to occur by chance in the present sample? As mentioned previously, this question has been tackled in some detail by Gaensler & Johnston (1995a&b) who concluded that the majority of claimed associations are likely to be chance alignments. The main motivation for the present analysis is partly to approach the question from a different direction than the modelling of Gaensler & Johnston (1995b). Our analysis has the main advantage that it is somewhat simpler and more model-free than the method described by Gaensler & Johnston (1995b).

For the purposes of the analysis it is useful to characterise each pair by the dimensionless parameter β which is independent of distance, defined as the ratio of the angular separation between the pulsar and the remnant centroid to the angular radius of the remnant. Thus pairs in which the pulsar is within the boundary of the remnant occur if $\beta \leq 1$, whereas $\beta > 1$ indicates that the pulsar lies outside the remnant (see also Shull et al. 1989; Frail et al. 1994; Gaensler & Johnston 1995 a&b).

We are interested in deriving the distribution of β that occurs by chance and comparing this directly with the observed distri-

bution. For completely unrelated sets of pulsars and supernova remnants, the number of pairs occupying an annulus between β and $\beta + d\beta$ is proportional to β , regardless of the relative densities of pulsars and supernova remnants over the plane of the sky. To demonstrate this, we decoupled the respective pulsar and supernova remnant samples by applying a systematic shift to the Galactic longitude of each pulsar and then calculating the distribution of β . To improve the statistics, we performed this procedure for shifts of ± 4 and ± 8 degrees in the Galactic longitudes of the pulsars. The shift sizes were chosen so that they are small compared to changes in the density of both types of objects on the sky, whilst being larger than the angular size of any supernova remnant in Green's (1996) catalogue. The shifted samples therefore contain only pairs which are truly unrelated, allowing us to deduce the expected distribution of chance remnants. This distribution is shown in Fig. 3 and is in excellent agreement with the theoretical prediction $dN \propto \beta d\beta$ shown by the straight line fit through the origin. The slope of the best-fit straight line shown in Fig. 3 is 47 ± 3 .

We are now in a position to apply this relationship, which is based on a superposition of four longitude-shifted samples, to the observed distribution of β shown in Fig. 4. The straight line shown in this case thus has a slope which is one quarter the value derived above. Comparing the observed distribution with this straight line we see a clear excess of pairs with $\beta \leq 1$ in the observed sample, whilst the distribution with $\beta > 1$ is in good agreement with the theoretical prediction. The pair excess is clearly due to the fact that many of these are genuine associations, not chance line-of-sight alignments. From Fig. 4, we infer that 12 ± 5 pairs are likely to be genuinely associated.

The difference between the shifted and observed samples can also be seen in the lower panels of Figs. 3 and 4, where we have plotted the median characteristic age of the pulsars as a function of β . The shifted samples show no significant deviation from a flat distribution with respect to β , and have a median age of $\gtrsim 1$ Myr. The observed sample however is clearly more youthful for $\beta \leq 1$ than for $\beta > 1$ for which the median characteristic age is again $\gtrsim 1$ Myr.

From an inspection of the observed sample and the available literature, we have compiled a list of the most likely associations in Table 4. A critical appraisal of each of these and other proposed associations can be found in the original references and see also Gaensler & Johnston (1995b) and Kaspi (1996). Note that this list is concerned only with Galactic associations and therefore does not include PSR B0540–69 associated with the supernova remnant in the LMC (Seward et al. 1984). Based on the above analysis and the available statistics, which suggested a total of 12 ± 5 pairs, we expect anything from zero to nine further pairs to represent genuine associations. Examples of further candidates include recently discovered remnants around PSRs B1643–43 and B1706–44 (Frail et al. 1994), PSR B1930+22 and G57.3–1.2 (Routledge & Vaneldik 1988) and PSR J0538+2817 and G180.0–1.7 (Anderson et al. 1996). In the absence of further information to validate these associations, we list the 8 sources in Table 4.

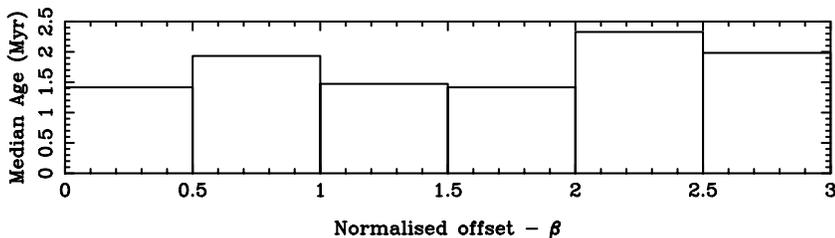
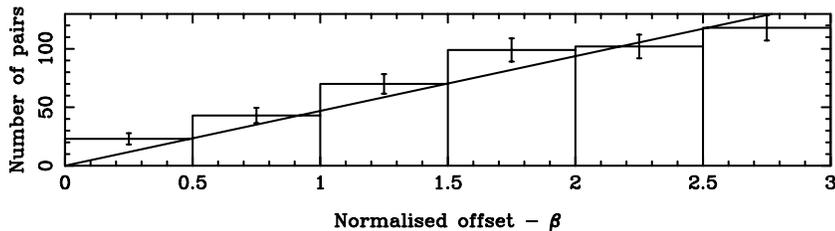


Fig. 3. Top panel: The distribution of β for the sample of pulsar and supernova remnants *after* applying shifts in Galactic longitude to the pulsar sample; this is in excellent agreement with the distribution $dN \propto \beta d\beta$ shown by the solid line. The lower panel shows the median characteristic age of the pulsars in the pairs as a function of β (see text).

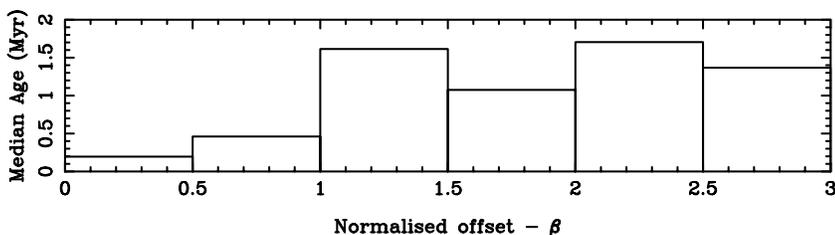
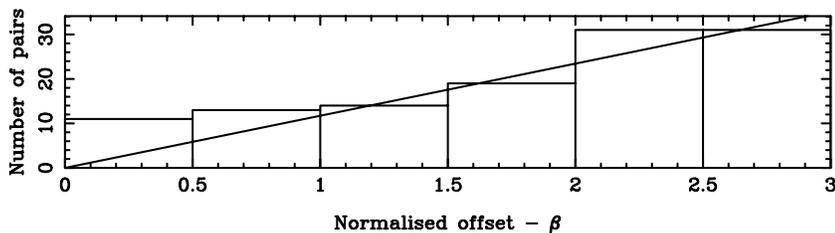


Fig. 4. Top panel: The *observed* distribution of β for the sample of pulsar and supernova remnants. When compared to the distribution expected by chance shown by the solid line, this shows a clear excess of pairs with $\beta \leq 1$. The lower panel shows the median characteristic age of the pulsars in the pairs as a function of β (see text).

As discussed in Sect. 5.1, both of the newly discovered pulsars in this survey, PSRs J0215+6218 and J1957+2831, have characteristic ages much larger than that expected for their target remnants. If they were to be genuinely associated with these remnants, then both the pulsars would have had to have been born with periods similar to the presently observed values, 0.5 and 0.3 seconds, in order to explain the large characteristic ages. In addition, the respective observed value of β for these pulsars 0.7 and 0.8 does *not* place them in the group of pairs most likely to be genuinely associated. Based on the results of the above analysis, there is no strong statistical requirement for either of these pulsars to be associated with the remnants although they cannot be entirely ruled out.

Whether a significant number of radio pulsars were born with such long periods is controversial. Several authors, notably Vivekanand & Narayan (1981), Narayan (1987), Narayan & Ostriker (1990) and Deshpande et al. (1995) have found evi-

dence for “injection” of pulsars into the population with periods ~ 500 ms, however other authors (Lyne et al. 1985; Stollman 1987; Lorimer et al. 1993) find no requirement for it. From an inspection of the pulse periods listed in Table 4, with the possible exception of PSR B2334+61, none of the pulsars listed in Table 4 are likely to have had such long periods at birth. Indeed Kulkarni et al. (1993) argue that PSR B2334+61 is the energy source to G114.3+0.3, which appears to be a Crab-like nebula. In this case, the initial period of B2334+61 must have been $\lesssim 100$ ms. Thus the simplest, and most likely conclusion, to be drawn from the present sample of pulsar-supernova remnant pairs is that they support the notion that all pulsars are born with initial spin periods $\lesssim 100$ ms.

Finally we wish to point out that, whilst our method is in principle sensitive to pairs over a large range in β , the sample that we have used for our analysis is far from homogeneous. Therefore any real pairs with $\beta \gtrsim 1$ are most likely to be un-

Table 4. A compilation of the most likely genuine pulsar-supernova remnant pairs with $\beta \leq 1$. Our statistical analysis suggests that, at most, a further nine pairs may be real (see text).

Pulsar Name	Period ms	Age kyr	β	Supernova Remnant
B0531+21	33	1.3	0.10	G184.6–5.8
B0833–45	89	11.4	0.29	G263.9–3.3
B1338–62	193	12.1	0.39	G308.8–0.1
B1757–24	125	15.5	~ 1	G5.4–1.2
B1853+01	267	20.3	0.51	G34.7+0.1
B1509–58	151	1.6	0.24	G320.4–1.2
B1951+32	40	107.3	0.14	G69.0+2.7
B2334+61	495	40.9	0.08	G114.3+0.3

derestimated in the present sample in comparison with those with $\beta \lesssim 1$ since many of the targeted searches for pulsars in remnants have concentrated mainly close to the remnant centre. Indeed, together with the searches by Gorham et al. (1996) and Kaspi et al. (1996), our search represents the first major effort to search the entire area, rather than just the centroid, of many of the more extended supernova remnants. Further searches with improved sensitivity to pulsars with $\beta \gtrsim 1$ will improve the situation. New multibeam searches of the Galactic plane, presently underway at Parkes and Jodrell Bank, should provide a more homogeneous sample for further statistical studies.

7. Conclusions

We have conducted a sensitive search for pulsars in supernova remnants. The search detected a total of three pulsars, two of which were previously unknown. The new pulsars, J0215+6218 and J1957+2831, were found during searches of the supernova remnants G132.7+1.3 and G65.1+0.6 respectively. The case for associations between the new pulsars and their target remnants is presently unclear. From an analysis of the present sample of radio pulsars and supernova remnants, we reach two main conclusions: (i) The number of real associations in the present sample is at most 12 ± 5 . (ii) These are most likely to occur for pairs with $\beta \lesssim 1$ for which we see a clear excess in the observed distribution compared with that expected by chance.

Based on this analysis, neither of the two newly discovered pulsars seem likely to be genuinely associated. In order to unambiguously confirm/refute both these candidate associations, measurements of the pulsar proper motions are required. Such measurements would determine in each case whether the pulsar velocity is of the correct magnitude and direction to carry them to their presently position with respect to the remnant centre. Interferometric measurements to determine the proper motion of both pulsars using MERLIN, the Multi-Element Radio Linked Interferometer network operated by the University of Manchester have recently been initiated.

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