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A SEARCH FOR RAPIDLY SPINNING PULSARS AND FAST TRANSIENTS IN UNIDENTIFIED RADIO SOURCES WITH THE NRAO 43 METER TELESCOPE

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ABSTRACT

We have searched 75 unidentified radio sources selected from the NRAO VLA Sky Survey catalog for the presence of rapidly spinning pulsars and short, dispersed radio bursts. The sources are radio bright, have no identifications or optical source coincidences, are more than 5% linearly polarized, and are spatially unresolved in the catalog. If these sources are fast-spinning pulsars (e.g., sub-millisecond pulsars), previous large-scale pulsar surveys may have missed detection due to instrumental and computational limitations, eclipsing effects, or diffractive scintillation. The discovery of a sub-millisecond pulsar would significantly constrain the neutron star equation of state and would have implications for models predicting a rapid slowdown of highly recycled X-ray pulsars to millisecond periods from, e.g., accretion disk decoupling. These same sources were previously searched unsuccessfully for pulsations at 610 MHz with the Lovell Telescope at Jodrell Bank. This new search was conducted at a different epoch with a new 800 MHz backend on the NRAO 43 m Telescope at a center frequency of 1200 MHz. Our search was sensitive to sub-millisecond pulsars in highly accelerated binary systems and to short transient pulses. No periodic or transient signals were detected from any of the target sources. We conclude that diffractive scintillation, dispersive smearing, and binary acceleration are unlikely to have prevented detection of the large majority of the sources if they are pulsars, though we cannot rule out eclipsing, nulling or intermittent emission, or radio interference as possible factors for some non-detections. Other (speculative) possibilities for what these sources might include radio-emitting magnetic cataclysmic variables or older pulsars with aligned magnetic and spin axes.

Key words: pulsars: general – surveys

1. INTRODUCTION

Radio pulsars have a wide range of spin periods, but no pulsar has yet been observed to be rotating faster than PSR J1748−2446ad, which has a spin period of $P = 1.39$ ms (Hessels et al. 2006). Models of the neutron star equation of state (EOS) and the properties of pulsars that have been spun up (recycled) via accretion from a companion suggest that pulsars with spin periods less than a millisecond ("sub-millisecond" pulsars) can exist structurally and could in principle be produced from the recycling process (e.g., Cook et al. 1994; Haensel et al. 1999). A significant population of sub-millisecond pulsars may therefore be present in the Galaxy waiting to be discovered (see, e.g., Possenti et al. 1998). However, some studies have suggested that a spin equilibrium is reached during accretion which limits the neutron star spin to larger (millisecond) periods. In these scenarios, the spin up from accretion is balanced by angular momentum loss through, e.g., an accretion disk/magnetosphere interaction (Patruno et al. 2012) or the emission of gravitational radiation (Wagoner 1984; Bildsten 1998). Ho et al. (2011) provide a brief overview. A more recent model presented by Tauris (2012) suggests that highly recycled neutron stars can be produced as sub-millisecond X-ray sources during the accretion phase, but that they are then rapidly spun down in the Roche lobe decoupling phase. In this case, the magnetosphere expands during the last phase of accretion, a large fraction of the rotational energy is dissipated, and the pulsar is not seen as a sub-millisecond pulsar when the radio emission turns on.

The discovery of a sub-millisecond pulsar would be of particular importance since it would falsify models suggesting that sub-millisecond radio pulsars should not be observed (see above) while also placing significant constraints on the largely unknown EOS of neutron star matter (e.g., Lattimer & Prakash 2004). However, sub-millisecond pulsars are difficult to detect owing to a number of selection effects. These include limitations in observing sensitivity, digital sampling rates, and frequency channel resolution, as well as eclipsing and acceleration effects if the pulsar is in a tight binary system. In fact, very rapidly spinning pulsars may be preferentially located in such eclipsing systems (Hessels et al. 2006; Hessels 2008), making such systems even harder to detect. Large-area surveys having the necessary time and frequency resolution (as well as the required post-observation computational power for data processing) to detect such pulsars have not yet been feasible on the full sky. Therefore, targeting smaller areas likely to harbor pulsars remains one of the most promising avenues for trying to discover a sub-millisecond pulsar. Examples of this approach include the highly successful deep targeted radio searches of *Fermi* γ-ray sources (Ray et al. 2012, 2013) in which an astonishing 44 new millisecond pulsars (MSPs) have recently been discovered.

Some pulsars are also known to exhibit detectable single pulses at irregular intervals. Notable examples of this type include the Crab pulsar (Staelin & Reifenstein 1968) and the MSP PSR B1937+21 (Cognard et al. 1996), both of which are also detectable as periodic sources. Other, more recently discovered sources of sporadic radio emission include rotating radio transients (RRATs; McLaughlin et al. 2006), which are rotating neutron stars that are only detectable as transient burst sources.

In an effort to discover previously undetected millisecond and sub-millisecond pulsars, as well as to find new transient emitters, we have searched a sample of unidentified radio sources from the NRAO VLA Sky Survey (NVSS; Condon et al. 1998). These sources were originally selected by Crawford et al. (2000)

for a similar pulsar search with the 76 m Lovell Telescope at the Jodrell Bank Observatory. We outline the source selection criteria below, which can also be found in Crawford et al. (2000). The NVSS is a large-scale radio survey of the northern sky at 1400 MHz conducted with the Very Large Array (VLA). It covered declinations $\delta > -40^\circ$ in D and DnC configurations with a synthesized beam size of 45″. Position errors in the NVSS catalog are typically $\lesssim 1''$ for strong sources. The catalog contains $\sim 3 \times 10^5$ sources with a flux density greater than 15 mJy, when local sources and unreliable survey regions are excluded (see, e.g., Blake & Wall 2002; Crawford 2009). Many of the sources detected in the NVSS remain unidentified.

Owing to the large number of extended, resolved sources in the catalog, it was necessary to explicitly check for the point-like nature of those objects. Sources were checked for corresponding detections in the Faint Images of the Radio Sky at Twenty Centimeters (FIRST) survey (Becker et al. 1995). The FIRST survey covered the north and south Galactic caps using VLA in B configuration with a synthesized beam size of 5.″4. For sources found in both the NVSS and FIRST catalogs, the corresponding flux densities were compared. If a source was extended, the better resolution of the FIRST survey would result in a lower flux density than the NVSS survey, since some of the flux would be resolved out. Therefore, sources were only included if their FIRST and NVSS flux densities agreed to within a few percent (indicating an unresolved, non-variable source) or if the FIRST flux density exceeded the NVSS flux density (indicating an unresolved scintillating source). For those sources outside of the FIRST survey region, observations were performed using VLA in B configuration to achieve the same angular resolution as the FIRST survey. The flux densities of the sources observed in these pointings were then compared with their NVSS values to eliminate any additional extended sources.

The target list was further reduced by requiring that the sources have no identifications with known sources (and no optical source coincidences), be radio bright (with a 1400 MHz flux density $\geqslant$15 mJy), be spatially unresolved in the NVSS catalog, and be more than 5% linearly polarized. The polarization criterion was used since pulsars often have a high degree of linear polarization (Lyne & Manchester 1988), which makes polarized point radio sources good candidates to search. Although there is not a clear polarization cutoff separating the pulsar and extragalactic populations, a polarization threshold of 5% excludes about 90% of the identified non-pulsar population while retaining about 90% of the identified pulsar population (Han & Tian 1999; Crawford et al. 2000).

Using these criteria, a list of 92 target sources was compiled and searched by Crawford et al. (2000) for radio pulsations using the 76 m Lovell Telescope. No pulsations were detected from any of the target sources in that search, but no search for single pulses was done at that time. A recent re-analysis of these data using a search for single pulses revealed no new detections. Since the completion of the Crawford et al. (2000) survey, 16 of the 92 target sources have been identified as extragalactic objects in SIMBAD[4] (see Table 1). Some of the targets have also been detected in other radio surveys (listed in Table 1) at different frequencies. In these cases we measured spectral indices for them (see Table 1). All of the measured spectral index values are shallower than the average pulsar spectral index of $\alpha = -1.6$ (Lorimer et al. 1995), where α is defined according to $S \sim \nu^\alpha$ (S is flux density and ν is the observing frequency). This does not preclude these sources being pulsars, but they are not as steep as expected.

For our search, we have used the same set of selection criteria but have excluded the 16 sources that now have secure extragalactic identifications. One remaining source was not observed owing to telescope scheduling limitations, leaving 75 unidentified targets that we observed and searched. We checked the *Fermi* LAT 2 yr Point Source Catalog (2FGL; Nolan et al. 2012) for coincidences with our targets and found that none lie within the 95% error ellipses of any of the *Fermi* sources. Table 1 presents the full list of 92 sources from Table 1 of Crawford et al. (2000). The 16 secure extragalactic identifications are indicated, as are the measured radio spectral index values (where available). This list represents just a small fraction (<0.1%) of the total number of sources in the NVSS catalog with flux densities greater than 15 mJy. Note that the flux densities and polarization fractions listed were obtained from revision 2.18 of the NVSS catalog[5] and in some cases are slightly different from the earlier catalog values presented in Table 1 of Crawford et al. (2000).

2. MOTIVATION FOR NEW OBSERVATIONS

Starting in 2010 February, we conducted new observations of the 75 unidentified sources with the NRAO 43 m Telescope[6] at the Green Bank Observatory. Several factors motivated this. The first was the availability of the PRESTO[7] and SIGPROC[8] software packages, which are now widely used for pulsar data analysis (Ransom 2001; Ransom et al. 2002). PRESTO and the single pulse search capability of SIGPROC were not available at the time of the search of Crawford et al. (2000). The development of the Fourier-based search code in PRESTO for acceleration searches was also a major advancement for detecting binary pulsar systems in our search. The ability to conduct acceleration searches of the survey data is especially important for the detection of millisecond and sub-millisecond pulsars since approximately 80% of MSPs are known to be in binaries (e.g., Lorimer 2008). Second, in the time that has passed since the original search, greatly increased computational power for acceleration searches has become feasible at a reasonable cost. Finally, a new high bandwidth (800 MHz) backend with fast sampling capability became available at the telescope (the West Virginia Ultimate Pulsar Processing Instrument (WUPPI); see, e.g., Mickaliger et al. 2012). Sub-millisecond pulsars are in principle detectable with this instrument, and the wide bandwidth and many narrow frequency channels allow radio frequency interference (RFI) to be more easily recognized and excised. The 8 bit sampling and polyphase filterbank of WUPPI also mitigated RFI and reduced digitization loss compared to the 1 bit sampling in the Crawford et al. (2000) search. The higher central observing frequency (1200 MHz versus 610 MHz for the previous survey) also helped reduce pulse broadening from interstellar dispersion and scattering. Table 2 summarizes the different observing parameters for the two surveys. For our observing system, the dispersion broadening within channels was $\sim$0.1 ms for DM = 100 pc cm^{-3}. This value is comparable to the previous Jodrell Bank search observations which had narrower channels but also a lower central observing frequency (Crawford

4 http://simbad.u-strabg.fr/simbad

5 http://www.cv.nrao.edu/nvss/NVSSlist.shtml
6 http://www.gb.nrao.edu/43m/
7 http://www.cv.nrao.edu/~sransom/presto
8 http://sigproc.sourceforge.net

Table 1
NVSS Radio Source Targets

NVSS Source	α (J2000.0) (h m s)	δ (J2000.0) (d m s)	S_{1400}[a] (mJy)	Lin. Poln[b] (%)	Source ID[c]	α[d]	Survey[e]
J000240−195252	00 02 40.96	−19 52 52.3	60	9			
J000404−114858	00 04 04.90	−11 48 58.4	459	6	B		
J001109−225458	00 11 09.91	−22 54 58.5	38	10			
J001444−280047	00 14 44.06	−28 00 47.3	54	14			
J002330−215537	00 23 30.21	−21 55 37.6	137	8		−0.32(11)	PMN
J002449+030834	00 24 49.37	+03 08 34.7	69	9			
J002651−111252	00 26 51.45	−11 12 52.4	169	8	Q		
J002702−303032	00 27 02.07	−30 30 32.0	24	14			
J003233−264917	00 32 33.03	−26 49 17.6	135	7	Q		
J003708−232340	00 37 08.81	−23 23 40.5	67	6			
J004021+132937	00 40 21.80	+13 29 37.9	34	10			
J005151+022944	00 51 51.30	+02 29 44.2	15	21			
J005410−175413	00 54 10.78	−17 54 13.0	30	11			
J005736+134145	00 57 36.44	+13 41 45.4	65	9	G		
J010711−121123	01 07 11.79	−12 11 23.6	60	6			
J011448−321951	01 14 48.89	−32 19 51.7	124	16		−0.37(13)	PMN
J013840−295445	01 38 40.50	−29 54 45.9	46	10			
J014614+022208	01 46 14.62	+02 22 08.2	138	8		−0.13(9)	PMN
J014727+071502	01 47 27.77	+07 15 02.9	241	6		−0.72(6)	TXS
J015456−242233	01 54 56.90	−24 22 33.5	45	11			
J021459+102748	02 14 59.23	+10 27 48.8	29	13			
J021750−235456	02 17 50.76	−23 54 56.3	90	11			
J022333+073219	02 23 33.94	+07 32 19.6	125	13	G		
J022340+115910	02 23 40.83	+11 59 10.2	34	10			
J022441+135733	02 24 41.85	+13 57 33.1	95	10		−0.17(13)	87GB
J023855−303202	02 38 55.19	−30 32 02.6	165	5			
J024944+123706	02 49 44.50	+12 37 06.3	261	6		−0.65(12)	87GB
J025106−174239	02 51 06.22	−17 42 39.5	69	13		−0.09(15)	PMN
J025805−314627	02 58 05.95	−31 46 27.8	247	8	Q		
J025927+074739	02 59 27.06	+07 47 39.2	834	5	Q		
J025904+470840	02 59 04.20	+47 08 40.4	108	9		−0.58(7)	TXS
J031726+060614	03 17 26.85	+06 06 14.7	200	8		−0.89(14)	PMN
J032213−345833	03 22 13.10	−34 58 33.2	49	7			
J032615−324324	03 26 15.12	−32 43 24.3	95	5			
J034914+035445	03 49 14.31	+03 54 45.4	150	8		+0.30(16)	PMN
J040342+644556	04 03 42.80	+64 45 56.1	74	5		−0.22(10)	87GB
J042119+351115	04 21 19.72	+35 11 15.6	68	10			
J045828+495355	04 58 28.75	+49 53 55.8	19	13			
J050554+260625	05 05 54.20	+26 06 25.1	23	11			
J051843+643958	05 18 43.68	+64 39 58.0	28	13			
J060650+440140	06 06 50.20	+44 01 40.9	147	8		−0.24(5)	7C
J060718+291527	06 07 18.95	+29 15 27.7	25	16			
J062052+733441	06 20 52.10	+73 34 41.2	85	10		−0.69(11)	87GB
J070120+263157	07 01 20.74	+26 31 57.1	32	12			
J071923+293551	07 19 23.05	+29 35 51.8	18	13			
J073313+333151	07 33 13.31	+33 31 51.8	19	14			
J075501+301347	07 55 01.81	+30 13 47.4	51	12		−1.13(9)	TXS
J075536+334159	07 55 36.71	+33 41 59.2	82	7			
J075752+272111	07 57 52.82	+27 21 11.3	45	7			
J075808+392928	07 58 08.84	+39 29 28.7	545	8	G		
J080212+312240	08 02 12.78	+31 22 40.7	86	10			
J080519+273736	08 05 19.02	+27 37 36.1	42	10			
J080601+331010	08 06 01.70	+33 10 10.3	44	6			
J081040+303433	08 10 40.30	+30 34 33.7	154	6			
J084030+292336	08 40 30.72	+29 23 36.8	18	14			
J084308+373816	08 43 08.76	+37 38 16.2	111	12			
J084456+362927	08 44 56.27	+36 29 27.5	50	7			
J084647+374615[f]	08 46 47.43	+37 46 15.1	22	16			
J090305+352316	09 03 05.50	+35 23 16.2	58	6			
J091147+334917	09 11 47.77	+33 49 17.1	380	7	B		
J092329+301106	09 23 29.97	+30 11 06.7	36	6	Q		
J092822+414221	09 28 22.18	+41 42 21.9	98	12		−0.95(15)	TXS
J094459+380317	09 44 59.21	+38 03 17.6	43	12			
J100022+371844	10 00 22.29	+37 18 44.4	35	10			
J100357+324403	10 03 57.63	+32 44 03.7	429	8	Q		

Table 1
(Continued)

NVSS Source	α (J2000.0) (h m s)	δ (J2000.0) (d m s)	S_{1400}[a] (mJy)	Lin. Poln[b] (%)	Source ID[c]	α[d]	Survey[e]
J101349+344550	10 13 49.59	+34 45 50.7	356	6	Q		
J103319+285121	10 33 19.66	+28 51 21.0	29	10		0.00(17)	87GB
J112612+341818	11 26 12.32	+34 18 18.2	40	7			
J112951+362217	11 29 51.56	+36 22 17.1	122	7			
J114523+314515	11 45 23.20	+31 45 15.3	83	10			
J114608+260105	11 46 08.52	+26 01 05.3	116	7		−0.62(14)	87GB
J115043+302018	11 50 43.89	+30 20 18.3	32	14			
J120125+255006	12 01 25.63	+25 50 06.9	25	26			
J120144+312904	12 01 44.50	+31 29 04.1	91	6			
J122004+311149	12 20 04.37	+31 11 49.0	29	10	Q		
J123454+291744	12 34 54.36	+29 17 44.2	446	9		−0.52(9)	7C
J123650+370603	12 36 50.94	+37 06 03.8	63	10			
J124219+272156	12 42 19.75	+27 21 56.2	70	10		−0.65(8)	7C
J125124+364354	12 51 24.28	+36 43 54.9	30	8			
J133426+343425	13 34 26.94	+34 34 25.8	49	8			
J134324+290358	13 43 24.38	+29 03 58.6	24	18			
J141440+402229	14 14 40.46	+40 22 29.7	44	6			
J142658+403539	14 26 58.42	+40 35 39.6	29	9	Q		
J143447+380514	14 34 47.05	+38 05 14.4	153	9	A		
J145844+372022	14 58 44.77	+37 20 22.0	215	6	B		
J150808+281811	15 08 08.32	+28 18 11.2	77	7			
J154740+395438	15 47 40.19	+39 54 38.4	131	15			
J160616+270930	16 06 16.20	+27 09 30.6	29	8			
J160950+262839	16 09 50.12	+26 28 39.4	20	17			
J161827+293118	16 18 27.05	+29 31 18.3	30	9			
J163552+375159	16 35 52.59	+37 51 59.5	48	7			
J232102−175822	23 21 02.41	−17 58 22.0	18	15			

Notes. The original set of 92 NVSS target sources from Table 1 of Crawford et al. (2000) is presented here, including 16 sources that have been more recently identified as extragalactic objects. The flux densities and polarization fractions listed were taken from the NVSS catalog browser (revision 2.18, 2004 February 3; http://www.cv.nrao.edu/nvss/NVSSlist.shtml).
[a] Nominal 1400 MHz flux density from the NVSS catalog.
[b] Linearly polarized intensity as a percentage of total source intensity, derived from the NVSS catalog.
[c] Source identifications from SIMBAD. The identification codes are: A = AGN; B = BL Lac object; G = Galaxy; Q = Quasar.
[d] Spectral index α defined according to $S \sim \nu^{\alpha}$. The figure in parentheses represents the uncertainty in the last digit quoted in the measured value.
[e] Radio survey used with the NVSS to determine the spectral index, where possible. The survey codes are: 7C = Seventh Cambridge Catalog at 151 MHz (Hales et al. 2007); TXS = The Texas Survey at 365 MHz (Douglas et al. 1996); 87GB = 87 Green Bank Catalog at 4850 MHz (Gregory & Condon 1991); PMN = Parkes–MIT–NRAO Survey at 4850 MHz (Griffith & Wright 1993).
[f] Source not observed owing to telescope scheduling limitations.

Table 2
Observing Parameters for Jodrell Bank and NRAO 43 m Surveys

Survey	Crawford et al. (2000)	This Survey
Number of Targets	92	75
Telescope	Lovell (Jodrell Bank)	NRAO
Telescope diameter (m)	76	43
Central observing frequency, ν_c (MHz)	610	1200
Observing bandwidth (MHz)	1	800
Number of frequency channels	32	4096
Number of bits per sample	1	8
Integration time per source (s)	420	900
Sampling time (μs)	50	61.44

et al. 2000). As seen in Figure 1, dispersion broadening does not significantly reduce the sensitivity of our search even at very low periods ($P \lesssim 1$ ms). Our survey maintains good sensitivity to sub-millisecond pulsars for dispersion measures (DMs) between 0 and 100 pc cm^{-3}, the range which is most relevant for our survey.

Apart from the effects of acceleration, the presence of orbital companions can significantly affect detectability through eclipsing by the companion. Material blown off of a companion star by the pulsar wind can obscure the pulsar signal in such cases (Tavani 1991; Hessels et al. 2006). This has been observed for a number of MSPs with non-degenerate companions, including PSR J1748−2446ad (Hessels et al. 2006) and PSR J1740−5340 (D'Amico et al. 2001), both of which are located in globular clusters and are eclipsed for ∼40% of their orbit. The number of "black widow" (Fruchter et al. 1988) and "redback" (Archibald et al. 2009) eclipsing pulsar systems in the Galaxy has also recently grown (see Roberts 2012 for a summary). These pulsars are in tight binary systems with eclipse fractions that can vary with frequency and which can be quite large. As mentioned above, eclipsing systems may preferentially harbor very rapidly spinning pulsars (Hessels 2008), making sub-millisecond pulsar systems even more likely to be missed. Such systems might be discovered by re-observing them at a different epoch when they are not in eclipse. Time-dependent effects such as diffractive scintillation or sporadic radio emission from the neutron star may also have previously prevented detection of some of our

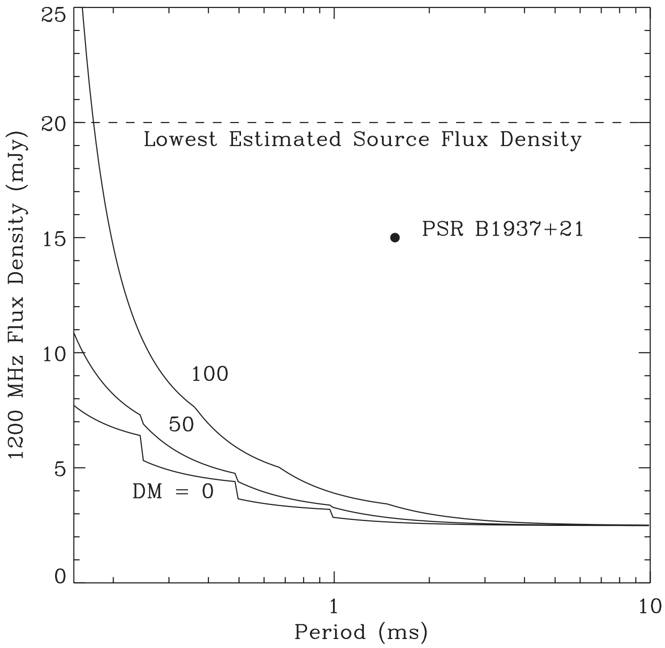

Figure 1. Sensitivity curves for our pulsar survey for assumed DMs of 0, 50, and 100 pc cm^{-3}, and a 5% intrinsic pulsed duty cycle. Each curve represents the flux density as a function of spin period that would result in an S/N of 7 in the Fourier spectrum in the search. The dashed line at 20 mJy indicates the lowest estimated flux density of the 75 sources at 1200 MHz. The sensitivity baseline was empirically determined by scaling an S/N = 33 blind detection of PSR B1937+21, which has a DM of 71 pc cm^{-3} and an estimated 1200 MHz flux density of 15 mJy. Not included here is the additional selection criterion that Fourier candidates must have $P \geqslant 0.5$ ms to be considered, which effectively restricts our sensitivity to $P \geqslant 0.5$ ms.

sources. The much larger observing bandwidth in the search described here helps mitigate diffractive scintillation effects (see Section 5 for more details).

For these reasons we re-performed a search of these targets using the 43 m Telescope and WUPPI backend. Details of our observational method are provided in Section 3, followed by a description of our data reduction techniques for both the periodicity search and the single pulse search in Section 4. The results of our search are discussed in Section 5, and our conclusions are presented in Section 6.

3. OBSERVATIONS

Observations of the 75 sources were conducted with the 43 m Telescope and WUPPI backend between 2010 February and 2011 August. We observed each source at a center frequency of 1200 MHz in two orthogonal linear polarizations for a total of 900 s per source. A bandwidth of 800 MHz was split into 4096 frequency channels, and each channel was 8 bit sampled every 61.44 μs. Data were recorded directly to disk in PSRFITS format (Hotan et al. 2004). We determined an empirical flux density limit to pulsed emission for the search using a 900 s test observation of the bright MSP PSR B1937+21. With a DM of 71 pc cm^{-3} and a period of 1.56 ms, PSR B1937+21 is similar to the rapidly spinning pulsars we hoped to detect. According to the ATNF catalog (Manchester et al. 2005),[9] PSR B1937+21 has a flux density of 10 mJy at 1400 MHz and a spectral index of $\alpha = -2.6$. This corresponds to a flux density of 15 mJy at 1200 MHz, our central observing frequency. The weakest of our 75 target sources had a flux density of 15 mJy at 1400 MHz

[9] http://www.atnf.csiro.au/people/pulsar/psrcat

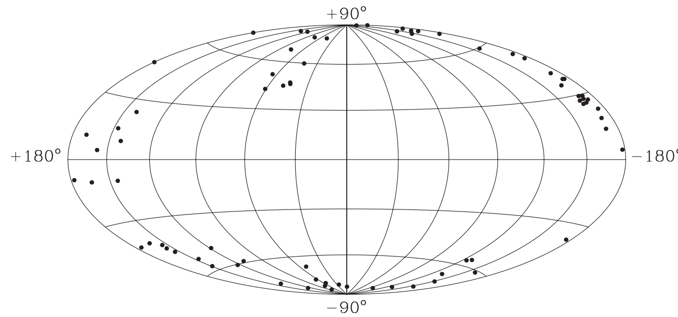

Figure 2. Aitoff projection plot of the sky positions of the 75 unidentified sources surveyed plotted in Galactic coordinates. The Galactic plane runs horizontally and bisects the plot. Most of the sources are located far from the Galactic plane, where there is less interstellar medium plasma, and subsequently the maximum expected DMs are smaller. From the NE2001 model of Cordes & Lazio (2002), the estimated maximum DM along the line of sight for all but 8 of the 75 sources is expected to be less than 100 pc cm^{-3} (Cordes & Lazio 2002).

(see Table 1). Assuming a typical value of $\alpha = -1.6$ for pulsars (Lorimer et al. 1995), this scales to 20 mJy at 1200 MHz. A 900 s observation of PSR B1937+21 yielded a clear detection of the pulsed emission in the Fourier search with a signal-to-noise ratio (S/N) of 33 in the spectrum. Given the same observing configuration and integration time, the S/N of our weakest source would be expected to have an S/N of 44 in the absence of time-dependent variability in intensity or Fourier bin drift due to acceleration (see Section 4.1). Assuming an S/N threshold of 7 for detectability, it is clear that even our weakest source should be well above the limiting flux density of our observations if it is a pulsar (see Figure 1).

Each set of observations in an observing session was preceded by an approximately 90 s observation of a known bright pulsar in order to ensure that the telescope and observing software were functioning properly.

4. DATA REDUCTION AND ANALYSIS

We searched each data set for both fast periodic signals and single dispersed pulses at a range of DMs. The single pulse search was employed specifically to detect transient objects that would not appear in the periodicity search, and the periodicity search included a search for accelerated signals to account for binary motion. We describe these searches below.

4.1. Periodicity Search

We performed the periodicity search using PRESTO. Each observation was first checked for bright narrowband and undispersed short-duration signals, indicative of terrestrial RFI. Corrupted samples in the time-frequency array were replaced by median value powers. Additionally, we flagged several bands in the frequency range in which RFI was known to be persistent. On average, we masked approximately 10% of the total data in each beam. We dedispersed the data at 401 evenly spaced trial DMs between 0 and 100 pc cm^{-3}, corresponding to a step size of 0.25 pc cm^{-3}. We chose this DM range since the NE2001 model of the Galactic electron distribution (Cordes & Lazio 2002) indicates that all but 8 of the 75 sources observed are expected to have a maximum possible DM contribution along the line of sight of less than 100 pc cm^{-3}, while the remaining eight sources are not anticipated to have maximum DMs much greater than this. This is due to their location at relatively large Galactic latitudes away from the Galactic plane (see Figure 2), where there is generally less Galactic plasma. The DM spacing

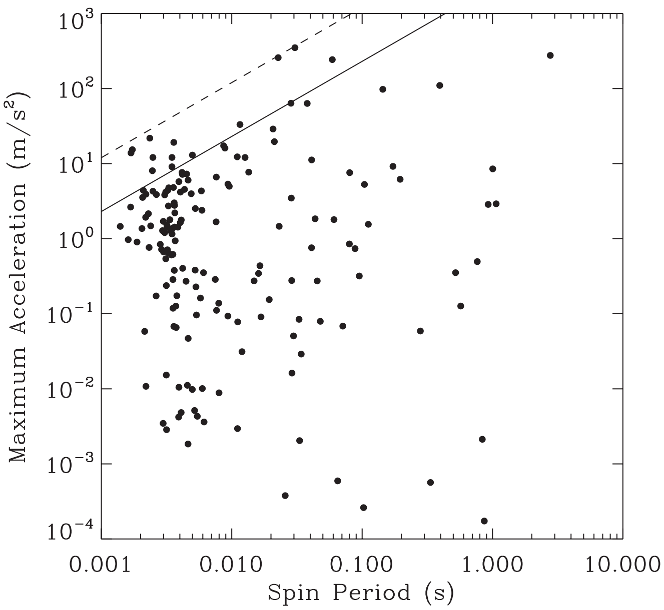

Figure 3. Maximum line-of-sight acceleration vs. spin period for 167 known binary radio pulsars in the ATNF catalog with measured projected semi-major axis values and binary orbital periods. The maximum acceleration was calculated using the method described by Freire et al. (2001). The solid line represents the acceleration search range ± 2.3 m s^{-2}(P/1 ms), for which full sensitivity was maintained in our search. All but 13 of the pulsars fall below this cutoff, indicating that our search range would be sufficient to detect most known pulsars in binary systems even if they were observed while undergoing maximum acceleration in their orbits. The dashed line indicates the acceleration search range ± 12 m s^{-2}(P/1 ms). This acceleration search range would provide full sensitivity to all 167 pulsars shown in the plot. Our search was not performed out to this range owing to computational limitations. However, given the large flux densities of our sources compared to our sensitivity limit, even such extremely accelerated pulsars would still be expected to be detectable with an S/N above 7 in our search in the absence of flux variability (see Section 4.1).

was slightly larger than the ideal spacing of $\leqslant 0.18$ pc cm^{-3} (see the single pulse search described in Section 4.2), but it still maintained sensitivity to sub-millisecond pulsars while making the Fourier search computationally feasible.

Each dedispersed time series was Fourier transformed to produce a power spectrum, and each spectrum was subsequently high-pass filtered in order to remove any slowly varying noise contribution (red noise). Each spectrum was also harmonically summed in order to enhance signals with significant integer harmonic content (e.g., Taylor & Huguenin 1969). We performed a search on each harmonically summed spectrum, with an S/N threshold of 7 and a searchable modulation frequency range between 1600 Hz (100 Hz $\times$ 16 integer harmonics, corresponding to pulsars with fundamental periods of 10 ms) and 10,000 Hz. This restricted our full search sensitivity to pulsars with $P < 10$ ms, which encompassed our period range of interest. However, pulsars with periods greater than this may still have been detectable if they had harmonics present above 100 Hz.

We conducted an acceleration search to account for any binary acceleration, which causes a drift of the signal in phase over time and a decrease in S/N. Our search resulted in no sensitivity loss for the acceleration range ± 2.3 m s^{-2}(P/1 ms), where P is the candidate spin period. For comparison, this search would have ensured full sensitivity to most (154 out of 167) known binary radio pulsars while they were undergoing maximum line-of-sight acceleration in their orbits (see Figure 3). This set of 167 pulsars was taken from entries in the ATNF catalog which had measured values for the projected semi-major axis and binary orbital period (see below), but it did not include any binary systems recently discovered in the High Time Resolution Universe (Keith et al. 2010) or Pulsar Arecibo L-Band Feed Array (Cordes et al. 2006) surveys.

To calculate the maximum line-of-sight accelerations for these 167 pulsars, we used an expression derived by Freire et al. (2001) in which the acceleration of a pulsar in a binary system is described as a function of observable parameters. From this equation, the maximum possible acceleration $A_{\rm max}$ is

$$A_{\rm max} = \frac{4\pi^2\, a\,(1+e)^2}{P_b^2\,(1-e^2)^2}, \qquad (1)$$

where a is the projected semi-major axis of the pulsar's orbit, P_b is the orbital period, and e is the orbital eccentricity.

For the sample of 167 binary radio pulsars, if no eccentricity e was measured in the ATNF catalog, we assumed $e = 0$ (a perfectly circular orbit) for the calculation. As seen in Figure 3, an acceleration search range of ± 12 m s^{-2} (P/1 ms) would ensure full sensitivity to all known binary radio pulsars in the sample undergoing maximum acceleration. However, the computational time required to perform a search of our 75 sources with this full acceleration range was excessive. Furthermore, the relatively large flux densities of our sources ensured that pulsars with accelerations near the highest values in this sample of 167 would probably still have been detectable even if the S/N were reduced by acceleration bin drift. The amount of Fourier bin drift of a pulse depends linearly on the acceleration. For a acceleration of ± 12 m s^{-2}(P/1 ms), the S/N would be reduced by a factor of 5.2 when searching only out to an acceleration of ± 2.3 m s^{-2}(P/1 ms). Since we expect our weakest source to have an S/N of 44 in the absence of time-dependent variability in intensity (see Section 3), the smallest S/N we would expect from an extremely accelerated pulsar is $\geqslant 8$, which is still above our survey detection limit of 7 (see Figure 1).

The acceleration search produced a list of candidate signals for each trial DM with periods and spectral S/N values. These candidate files from different DM trials for a source were combined into a master list. We subsequently removed candidates if they were deemed unlikely to be pulsars (see below) and also removed duplicates and harmonically related signals. The heuristics used in keeping good candidates included the requirements that the candidate have its maximum signal at a DM greater than 1 pc cm^{-3} and that it have a period $P \geqslant 0.5$ ms. The result was a list of the best pulsar candidates for a source ranked by S/N. We then dedispersed and folded the raw data at periods and DMs near the candidate values. We inspected the resulting plots by eye to see if promising features were present, indicating that a confirmation observation was warranted.

We tested this method with a 900 s observation of PSR B1937+21 using the same observing system as was used for the 75 survey sources. We successfully detected the pulsar in the search with a DM and period consistent with its catalog values.

4.2. Single Pulse Search

We performed a search for single pulses in the data using SIGPROC. Data from each source were dedispersed using 713 trial DMs with variable spacing, with the DMs ranging between 0 and 100 pc cm^{-3}. The maximum spacing between DM trials in this range was 0.18 pc cm^{-3}. We chose the spacing to ensure that the dispersion smearing due to an offset in DM did not greatly exceed the dispersion smearing within the frequency channels at that DM. We checked each dedispersed time series for pulses having a range of widths using a boxcar smoothing technique described by Cordes & McLaughlin (2003). We tested this technique on a 900 s observation of the Crab pulsar (PSR B0531+21), and we detected single pulses from the Crab easily. The method was also tested on the same 900 s observation of PSR B1937+21 that was used to test the periodicity search technique. No single pulses were detected in that search, which had a minimum S/N threshold of 5. While PSR B1937+21 and the Crab pulsar have similar giant pulse emission rates (Cognard et al. 1996) as well as comparable 1400 MHz flux densities, the giant pulses emitted by PSR B1937+21 are much narrower than the survey's sampling time of 61.44 μs (the pulse widths are on the order of a few microseconds; see Figure 1 of Cognard et al. 1996). These narrow pulses are smeared out within each time sample, leading to a significant reduction in the S/N. Thus, it is unlikely that such narrow pulses would be detected in our single pulse search. This also indicates that our search is not sensitive to extremely narrow single pulses or bursts (a few μs or less in width) from our target sources.

4.3. Follow-up Observations

One candidate from the periodicity search showed merit and warranted re-observation at the telescope. We conducted a confirmation observation using the same observing system and integration time (900 s) as the original observation. The data were dedispersed and folded at a range of DMs and periods near the candidate period and DM to see if the same signal was re-detected. We also performed a blind periodicity search and single pulse search on the confirmation data. The signal was not confirmed.

5. RESULTS AND DISCUSSION

We confirmed no dispersed pulsations or transient bursts from any of the target sources in either the periodicity search or the single pulse search. Below we consider possible factors that could have led to the non-detections if these sources were pulsars.

It is unlikely that diffractive scintillation caused us to miss detections in most cases. This can be shown using several different assumptions to calculate the expected scintillation bandwidths for these sources. First, an expression given by Cordes et al. (1985) gives an estimated typical scintillation bandwidth $\Delta\nu_{\rm scint}$ in MHz (see also Equation (2) in Crawford et al. 2000):

$$\Delta\nu_{\rm scint} \simeq 11\, \nu_c^{4.4}\, d^{-2.2}. \quad (2)$$

Here ν_c is the central observing frequency in GHz and d is the source distance in kiloparsecs. For $d = 0.2$ kpc and $\nu_c = 1.2$ GHz, $\Delta\nu_{\rm scint}$ is comparable to our observing bandwidth of 800 MHz. Thus, sources with $d < 0.2$ kpc would be expected to occasionally be undetectable in our search owing to diffractive scintillation. Note that this does not take into account the large degree of variability in $\Delta\nu_{\rm scint}$ that exists as a function of sky position. A calculation of scintillation bandwidths for the 75 sky positions of our sources using the NE2001 model (Cordes & Lazio 2002) gives similar results: for a frequency of 1200 MHz and an assumed distance $d = 0.2$ kpc, we find that only 3 of the 75 sources have $\Delta\nu_{\rm scint} < 800$ MHz (where we have assumed a Kolmogorov scaling dependence of $\nu^{4.4}$ for $\Delta\nu_{\rm scint}$). This number increases to 58 and 75 for $d = 0.5$ and 1.0 kpc, respectively. Thus, it appears that the range 0.2–0.5 kpc represents a critical distance below which scintillation bandwidths rapidly increase for these sources and where they can exceed the 800 MHz observing bandwidth. We can also estimate a typical source distance using several assumptions. The median 1400 MHz flux density of our 75 target sources is $S = 51$ mJy, and the median value of the 1400 MHz pseudo-luminosity for known recycled radio pulsars in the ATNF pulsar catalog (Manchester et al. 2005) is $L \sim 2$ mJy kpc^2. The pseudo-luminosity L is defined according to $L = S\,d^2$ (Lorimer & Kramer 2004). Using these values for L and S, we obtain a characteristic source distance of $d \sim 0.2$ kpc, which is close to the critical distance described above. The observed median L value used here may be overestimated if the luminosity distribution of the underlying population of recycled pulsars extends well below the observed lower limit. In this case, the derived characteristic source distance d would be reduced as well. In any case, even if $\Delta\nu_{\rm scint}$ were to exceed 800 MHz for every source, this would still not prevent the detection of the majority of our sources. The likelihood of detection of a source in this case is an exponential function dependent on the source flux density and flux density limit of the search observation. The total number of sources n expected to be detectable is the sum of these individual detection likelihoods over all sources (see Crawford et al. (2000) for a description and similar calculation),

$$n = \sum_{i=1}^{75} e^{-S_i/S_{\rm min}}, \quad (3)$$

where $S_{\rm min}$ is the 1200 MHz flux density limit of the survey (~3 mJy; see Figure 1) and the sum is taken over all 75 sources having 1200 MHz flux densities S_i (which we estimated using the cataloged 1400 MHz values and a typical pulsar spectral index of $\alpha = -1.6$ in those cases where α could not be measured). This calculation shows that $n = 71$ (out of 75) sources should still be detectable in our survey. Therefore, diffractive scintillation is not expected to be a dominant reason for the non-detection of these sources if they are pulsars.

It is possible that some of these sources could be binary pulsars that are being eclipsed and that the pulsar signal was masked at the time of observation by material ablated from the companion by the pulsar wind (e.g., black widows or redbacks). As mentioned previously, very rapidly spinning pulsars may exist more commonly in eclipsing systems (Hessels 2008). Since the obscuration is frequency dependent, with detectability decreasing at lower observing frequencies, this effect could be mitigated by conducting higher-frequency observations in the future. It is not likely that binary acceleration is a significant factor in any of our non-detections. Our range of trial accelerations in the periodicity search was sufficient to maintain sensitivity to even the most highly accelerated radio pulsar systems currently known (see Figure 3).

Only 8 of our 75 sources had maximum estimated DMs from the NE2001 model that were greater than 100 pc cm^{-3} (Cordes & Lazio 2002). Since we searched DMs up to 100 pc cm^{-3}, it is possible that dispersive smearing rendered pulsations from some of these sources undetectable. However, since the sources in our sample are very bright relative to our survey detection limit, they are also likely to be relatively close (see the estimated distance discussion above), with corresponding DMs that are much smaller than the maximum DM. Thus, dispersive smearing is unlikely to be a significant factor. Using the known recycled pulsar population as a guide, the estimated characteristic distance to the sources is small ($d \sim 0.2$ kpc;

see above). For this distance, the NE2001 model indicates that the corresponding DMs are between about 1 and 5 pc cm^{-3} for all 75 sources. Our candidate selection criteria in the search included keeping Fourier candidates having DM $>$ 1 pc cm^{-3}. Nevertheless, pulsar signals at such low DMs are at risk of being flagged as RFI in the processing. For several of our sources for which there was a significant amount of RFI present in the data, removal of a low-DM pulsar signal during the RFI excision process is a possibility. RFI in these beams also affected the single pulse search, and any low-DM transient signals from the target sources may have been removed along with RFI.

If some of these sources are transient objects, such as RRATs (McLaughlin et al. 2006) or intermittent or nulling pulsars (e.g., Kramer et al. 2006; Wang et al. 2007), it is possible that they were simply not active at the time of observation. The discovery of the intermittent emission behavior of the supposedly ordinary pulsar PSR B1931+24 by Kramer et al. (2006) suggests that many more such objects could have been missed in previous pulsar searches. In this case, the chances of detecting pulsations from our target sources would increase with additional observations, preferably with longer observing times.

6. CONCLUSIONS

No new pulsars or transient objects were discovered in the survey, and the question of what the unidentified target sources are remains unanswered. Below we outline some speculative possibilities.

Some of these sources may be active galactic nuclei (AGN) that will be identified in the future. While only $\sim$10% of known quasars and BL Lac objects are more than 5% linearly polarized (Han & Tian 1999), this does not completely discount extragalactic sources as a possibility. In fact, as seen in Table 1, 16 of the 92 previously unidentified sources searched by Crawford et al. (2000) have been identified as extragalactic objects and are no longer candidate pulsars. The generally shallower spectral indices seen for our target sources in Table 1 relative to the steeper average observed for the radio pulsar population also suggests this as a possibility.

Another possibility is that some of these sources might be radio-emitting white dwarfs (WDs). Persistent radio emission has been observed from several WD systems. Chanmugam & Dulk (1982) were the first to observe radio emission from AM Her, a magnetic cataclysmic variable (MCV). AM Her is in a short-period binary orbit and has a strong magnetic field. Radio emission was subsequently observed from two other MCVs: AE Aqr (Bookbinder & Lamb 1987; Bastian et al. 1988) and AR UMa (Mason & Gray 2007). However, radio searches of a range of CV subclasses indicates that they are not generally radio detected (Cordova et al. 1983; Chanmugam 1987; Mason & Gray 2007). It is worth noting that Mason & Gray (2007) observed the FIRST source J1023+0038 to search for radio emission. At the time, this source was tentatively identified as a CV associated with a FIRST radio source (Bond et al. 2002). Mason & Gray (2007) found no radio emission from J1023+0038, but the source was subsequently detected and identified as the first redback radio pulsar system discovered in the Galactic field (Archibald et al. 2009). This highlights the importance of repeated observations of undetected radio sources.

The observed radio sources might also be radio pulsars having closely aligned spin and magnetic axes. A study by Tauris & Manchester (1998) found that there is a tendency for the magnetic and spin axes to become aligned as pulsars age. Using pulsar polarization data sets from Rankin (1993) and Gould (1994), they found that this alignment occurs on a timescale of $\sim 10^7$ yr. More recent work by Young et al. (2010) using Candy–Blair evolution models (Candy & Blair 1983, 1986; Jones 1976) also shows progressive alignment occurring, but on a timescale of $\sim 10^6$ yr. Such aligned rotators would be hard or impossible to detect in traditional pulsar searches owing to their decreased (or non-existent) modulation (Tauris & Manchester 1998). This is illustrated in Figure 1 of Young et al. (2010), which shows that in cases where the emission cone encompasses the spin axis, one would not expect to see a modulated signal. If our target sources are indeed unmodulated radio pulsars with aligned magnetic and spin axes, then these models indicate that they are likely to be old pulsars. In this case, the shallower spectral indices of these older pulsars (see Table 1) relative to the general radio pulsar population would need to be explained.

If these unidentified sources are rapidly rotating pulsars with modulated radio emission, the effects of diffractive scintillation, dispersive smearing, and binary acceleration are unlikely to have prevented the detection of a large majority of the targets in our search. However, we cannot rule out eclipsing, intermittent emission, nulling, or RFI as possibly important factors. Just as *Fermi* sources must be searched multiple times before declaring that no radio pulsar is present (Ray et al. 2012), repeated observations of our targets may be required to reach the same conclusion.

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