A Search for Pulsars in Steep Spectrum Radio Sources

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Abstract

We report on a time-domain search for pulsars in 44 steep spectrum radio sources originally identified from recent imaging surveys. The time-domain search was conducted at 327 MHz using the Ooty radio telescope, and utilized a semicoherent dedispersion scheme, retaining the sensitivity even for submillisecond periods up to reasonably high dispersion measures. No new pulsars were found. We discuss the nature of these steep spectrum sources and argue that the majority of the sources in our sample should either be pulsars or a new category of galactic sources. Several possibilities that could hinder detection of these sources as pulsars, including anomalously high scattering or alignment of the rotation and magnetic axes, are discussed in detail, and we suggest unconventional search methods to further probe these possibilities.

Key words: ISM: general – methods: data analysis – methods: observational – pulsars: general – surveys

1. Introduction

Pulsars are one of the few classes of astronomical sources that have steep radio spectra. In fact, many pulsars have been identified after noticing the steep spectra of their counterparts in continuum images. In many cases, this led to breakthrough discoveries or unearthed especially interesting systems. It was through the unusual, steep spectral properties of the continuum source 4C 21.53W that the first millisecond pulsar (MSP) PSR B1937+21 was discovered (Backer et al. 1982). Similarly, the discovery of the first ever pulsar in a globular cluster (PSR B1821−24 in M28; Hamilton et al. 1985; Lyne et al. 1987) was strongly motivated by its steep spectrum. PSR J0218+4232 was also first detected as a steep spectrum source in continuum imaging using the Westerbork synthesis radio telescope before discovery of the associated radio pulsations (Navarro et al. 1995). It turned out to be the farthest MSP known in the field at that time. Some other notable cases where prior information about the steep spectrum assisted the pulsar discovery are PSR J0220+3842, the central source of supernova remnant G76.9+1.0, concurrently detected in radio imaging and time-domain by Marthi et al. (2011), independently from the X-ray discovery by Arzoumanian et al. (2011); and PSR J0815+4611, which was first identified as a point source in the deep epoch-of-reionization observations of the 3C196 field and turned out to be a highly polarized nearby pulsar (V. Kondratiev et al. 2018, private communication). More recently, image-based searches utilizing the steep spectrum as one of the main criteria have uncovered eight new pulsars from Fermi Large Area Telescope unidentified sources (Bhakta et al. 2017; Frail et al. 2018). These discoveries demonstrate the potential of spectral information based searches for radio pulsars and motivate investigation of the steep spectrum sources for the presence of any pulsations.

There have been not many surveys of steep spectrum sources in the past, partly because a few that were undertaken were not very successful in discovering new pulsars. For example, Damico et al. (1985) searched 18 steep radio sources for the presence of pulsars; however, their sampling time of 0.25 ms would have reduced the sensitivity, particularly for fast pulsars. Kaplan et al. (2000) found 16 compact (typical angular size <0.′2), steep spectrum sources, but suggested that most of those are perhaps high-redshift galaxies. Crawford et al. (2000) did a systematic search for pulsars in 92 significantly polarized, unidentified compact sources but did not find any pulsations. While these surveys were sensitive enough to detect the associated pulsars with high significance, the available observing capabilities (e.g., coarse sampling time as mentioned above, or scintillation-prone narrow bandwidth of 1 MHz in Crawford et al. 2000) at those times could have affected the results for some of the targets. Moreover, techniques to detect exotic sources more effectively (e.g., acceleration searches) and the compute resources to use such techniques at large scales have become available only more recently, and conducting such pulsar surveys now could be more fruitful.

Sensitive all-sky imaging surveys have been uncovering interesting new sources, including ones with steep spectra. A recent 147 MHz survey using the Giant Metrewave Radio Telescope (GMRT), called the TIFR GMRT Sky Survey (TGSS), covers the whole sky north of decl. (δ) =−53° (90% of the total sky; Sirothia et al. 2014). Some of the early results from this survey were presented in Bagchi et al. (2011), Gopal-Krishna et al. (2012), Sirothia et al. (2014), and Krishna et al. (2014). The first alternative data release of this survey (TGSS ADR1; Intema et al. 2017) catalogs 0.62 million radio sources above the 7σ level. TGSS ADR1 in combination with earlier high radio frequency all-sky surveys (e.g., the NRAO VLA Sky Survey, hereafter NVSS, at 1.4 GHz; Condon et al. 1998), presents a wonderful opportunity to study the spectral index distribution of the astronomical sources in general, and find compact, steep spectrum sources that are potential pulsar candidates in particular.

de Gasperin et al. (2018) used TGSS ADR1 and NVSS to make a spectral index catalog for nearly 80% of the whole sky and confirmed an intriguing excess of compact and steep source.
spectrum (with the spectral index $\alpha < -1.5$) sources in the galactic plane first indicated by de Breuck et al. (2000). Since pulsars are well known for their steep spectra and there is no other known category of compact and steep spectrum sources in the Galaxy, the above excess makes a compelling case to search for radio pulsations from the galactic steep spectrum sources. While some of these sources are bright enough that pulsations should have been detected in earlier high frequency pulsar surveys, many are faint and some are detected only in TGSS. In any case, deep and well designed pulsation searches are needed to detect or rule out exotic classes of pulsars (e.g., highly relativistic binaries, submillisecond pulsars, etc.) possibly harboring these sources, before considering a new class of galactic steep spectrum sources. With these motivations, we have selected two groups of steep spectrum sources as potential pulsar candidates and searched for any pulsations from them. To minimize the effects of interstellar scattering as well as use the advantage of intrinsically larger flux density at lower frequencies, we have used a frequency of 327 MHz as an optimal choice for our survey.

Details of the sample selection, observations, and our data reduction and search methods are presented in the next section. Section 3 presents the results of our search, Section 4 comprises a detailed discussion on the nature of sources in our sample, followed by a summary in the last section.

2. Target Sources and Methods

2.1. Sample Selection

Tiwari (2016) and de Gasperin et al. (2018) have combined data at 147 MHz and 1.4 GHz from TGSS and NVSS, respectively, to make spectral index maps as well as source catalogs for nearly 80% of the whole sky (assuming no variability between the epochs of the two surveys). These catalogs have provided useful starting points for our selection of compact, steep spectrum sources. Specifically, we have chosen two samples: sources within galactic plane and targets with steepest known spectra. More details of these samples are given below.

2.1.1. The Galactic-plane (GP) Sample

We first chose all the sources from Tiwari (2016) that are detected with a significance of more than 10$\sigma$ (\textgreater 35 mJy) in TGSS, and have spectral indices ($\alpha$) steeper than $-1.4$, decl. in the range of $-45^\circ$ to $+45^\circ$ (a constraint from the observing setup, see the next subsection), and angular sizes less than $50^\prime$. Intema et al. (2017) also define the observed multiplicity of the source structure in terms of Gaussian components. To increase the chance of retaining only point-like sources, we also discarded the ones with complex structures (i.e., the ones that need multiple or overlapping Gaussians to fit) or whose fitted positions differ by more than $20^\prime$ in TGSS and NVSS. The sample was then filtered out for any already known identifications using the NASA/IPAC extragalactic database (NED). The remaining sources were (again) cross-matched with NVSS and their spectral indices were verified. Toward the end of data reduction for this sample, de Gasperin et al. (2018) published their spectral index catalog. We also cross-matched with their catalog and found our spectral indices to be consistent.

Apart from pulsars, high-redshift radio galaxies (HzRGs) constitute another class of astronomical sources that exhibit steep radio spectra and compact angular sizes (Miley & De Breuck 2008). Some HzRGs and quasars also tend to be bright in infrared. In our “Galactic-plane sample,” we try to minimize the probability that the chosen source is a HzRG by confining the selection to a narrow galactic latitude ($b$) range of $-2$ to $+2$ and looking at the infrared properties of the sources. We cross-matched the sources with the ALLWISE source catalog$^7$ and examined the ALLWISE image atlas to exclude the targets with any obvious infrared counterparts. Then, the remaining sources were cross-matched with the ATNF pulsar catalog (Manchester et al. 2005) to identify any known pulsar. A total of three known pulsars, including one in a Globular cluster, were identified at various filtering stages mentioned above. Using the spectral index catalog by de Gasperin et al. (2018), we note that there are 16 more known pulsars that are identifiable in TGSS ADR1 within the galactic latitude range of $-2$ to $+2$ and which have spectral indices steeper than $-1.4$. However, their high frequency counterparts are not detected in NVSS. Since our GP sample has considered only the sources that have counterparts detected in both the surveys, these 16 pulsars naturally did not get selected. Finally, TGSS ADR1 cut-out images$^8$ around each of the source were examined to exclude any candidates due to imaging artifacts. The final galactic-plane sample consists of 25 sources with spectral indices in the range of $-1.80$ to $-1.44$, and are listed in Table 1.

2.1.2. The Ultra-steep Spectrum (USS) Sample

For this sample, we used catalogs from Tiwari (2016) and de Gasperin et al. (2018) to select all sources with spectral indices steeper than $-2.5$ and decl. in the range of $-45^\circ$ to $+45^\circ$. This sample consists of 21 sources, including two known pulsars (see Table 2). We retained the two known pulsars in our sample to use them as additional control pulsars, but do not consider them in our discussion on the steep spectrum sources later. Many of these sources do not have an identifiable counterpart in NVSS implying that the deduced spectral indices are in fact upper limits and actual spectra could be even steeper. We note that the targets in this sample were not scrutinized using many of the criteria detailed above for the GP sample, including examining the TGSS ADR1 cut-out images to rule out any artifacts.

2.2. Observations

Observations were conducted at 327 MHz using the Ooty radio telescope (ORT; Swarup et al. 1971). The telescope has an offset, long parabolic cylindrical reflector mounted equatorially, with a physical area of 15,900 m$^2$ and on-skym beam width of 1$^\circ.75$ and 6$^{\prime}$ in east–west and north–south, respectively. While the steering in the east–west direction is mechanical, the beam is steered electronically in the north–south direction. The effective collecting area is estimated to be 55% of the projected physical area in the declination range of $-45^\circ$ to $+45^\circ$. Outside this range, the sensitivity drops rapidly.

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$^6$ Spectral index $\alpha$ is defined via the conventional power-law representation of the spectrum: $S \propto \nu^{\alpha}$, where $S$ and $\nu$ are the flux density and observing frequency, respectively.

$^7$ http://wise2.ipac.caltech.edu/docs/release/allwise/

$^8$ http://tgssadr.strw.leidenuniv.nl
with declination. The telescope is receptive to only a single linear polarization (in the north–south direction).

Each of the sources in the above two samples was observed twice. The first round of observations of the GP sample sources were typically 5 or 10 minutes long. The durations were estimated using the expected flux densities at 327 MHz such that the pulsed signals from any associated pulsars would be detectable with a high significance of $25\sigma$. The second round of observations of this sample were typically 30 or 45 minutes long. Observing durations of the the USS sample sources in two rounds were 5 and 10 minutes, respectively. In each observing session, a raw voltage sequence was recorded at the Nyquist rate (with 8 bit sampling) for a 16 MHz wide band, centered at 326.5 MHz using the new pulsar receiver PONDER (Naidu et al. 2015).

### 2.3. Search Processing

The pulsar population is known to have a fairly steep radio spectrum with an average $\alpha$ of $-1.4 \pm 1.0$ (Bates et al. 2013), and the ones with the steepest spectra ($\alpha < -2.5$) tend to be the fastest rotating MSPs (Kuniyoshi et al. 2015; Frail et al. 2016; Kondratiev et al. 2016; Bassa et al. 2017b; Pleunis et al. 2017). To minimize dispersion smearing across individual frequency channels and retain full sensitivity for MSPs (and even submillisecond pulsars), we have employed a semicoherent dedispersion scheme implemented in cdmt (Bassa et al. 2017a). This search scheme is detailed in Bassa et al. (2017b) and uses the GPU accelerated cdmt software to coherently dedisperse the raw voltage input data, GPU accelerated incoherent dedispersion based on the DEDISP library (Barsdell et al. 2012) and tools from the PRESTO pulsar search package (Ransom 2001), including a GPU accelerated version of the frequency-domain acceleration search technique (Ransom et al. 2002).

For each of the observations, we coherently dedispersed the raw voltage sequence to 40 evenly spaced trial dispersion measures (DMs) in the range of $2.5-197.5$ pc cm$^{-3}$ (both values inclusive) using cdmt and recorded coherently dedispersed data with 256 spectral channels (i.e., with channel widths of 62.5 kHz) and 16 $\mu$s sampling time to disk. These channelized data were then incoherently dedispersed around the corresponding coherent DM trials in steps of 0.01 pc cm$^{-3}$, providing a uniform coverage of the DM range of 0–200 pc cm$^{-3}$ in 20,000 incoherent trial DMs. Similarly, data were coherently dedispersed to another 40 evenly spaced trial DMs spanning the range from 210 to 990 pc cm$^{-3}$ with a step size of 20 pc cm$^{-3}$, and the coherently dedispersed data were recorded with 256 channels and 64 $\mu$s time resolution. The incoherent trial DMs were chosen in steps of 0.04 pc cm$^{-3}$, covering the range of 200–1000 pc cm$^{-3}$ in another 20,000 steps. The above configurations limit the dispersive smearing to a maximum of about 40 $\mu$s and 150 $\mu$s in the lower and higher DM ranges, respectively, retaining the sensitivity to even submillisecond pulsars subject to the un-correctable smearing due to interstellar scattering.

Each dedispersed time series was searched for periodic signals using accelsearch from the pulsar search and analysis software PRESTO (Ransom et al. 2002). For 5 and 10

### Table 1

| Sr. No. | Target-ID | $\alpha$ | $S_{325\,\text{MHz}}$ (mJy) | $S_{\text{pulsed}}$ (mJy) | $S_{\text{aligned–pulsed}}$ limit (mJy) [%] |
|---------|-----------|----------|-------------------------------|--------------------------|----------------------------------|
| 1       | J050416+413334 | $-1.74 \pm 0.08$ | 41.8 | 5.5 | 14.5 [34.7] |
| 2       | J051322+413839 | $-1.80 \pm 0.07$ | 57.5 | 5.5 | 14.5 [25.2] |
| 3       | J054154+285045 | $-1.62 \pm 0.10$ | 27.4 | 5.7 | 15.1 [55.4] |
| 4       | J054238+273955 | $-1.48 \pm 0.10$ | 23.5 | 5.7 | 15.1 [64.6] |
| 5       | J054751+244742 | $-1.50 \pm 0.08$ | 33.6 | 5.5 | 14.5 [43.2] |
| 6       | J055426+232641 | $-1.39 \pm 0.09$ | 81.7 | 5.7 | 15.1 [18.5] |
| 7       | J055751+242623 | $-1.51 \pm 0.08$ | 35.1 | 5.5 | 14.5 [41.3] |
| 8       | J060126+221705 | $-1.52 \pm 0.05$ | 153.7 | 5.5 | 14.5 [9.4] |
| 9       | J060633+240947 | $-1.49 \pm 0.06$ | 60.2 | 5.5 | 14.5 [24.1] |
| 10      | J061644+122121 | $-1.49 \pm 0.07$ | 43.9 | 5.5 | 14.5 [33.0] |
| 11      | J061726+181632 | $-1.72 \pm 0.07$ | 56.5 | 5.5 | 14.5 [25.7] |
| 12      | J061919+140306 | $-1.44 \pm 0.09$ | 34.1 | 5.7 | 15.1 [44.4] |
| 13      | J062043+114313 | $-1.62 \pm 0.08$ | 37.3 | 5.5 | 14.5 [38.9] |
| 14      | J062257+121518 | $-1.49 \pm 0.07$ | 42.2 | 5.5 | 14.5 [34.4] |
| 15      | J063148+102416 | $-1.70 \pm 0.09$ | 34.4 | 5.2 | 13.9 [40.3] |
| 16      | J064124+014858 | $-1.60 \pm 0.07$ | 49.2 | 5.5 | 14.5 [29.5] |
| 17      | J064801+032706 | $-1.52 \pm 0.07$ | 44.8 | 5.5 | 14.5 [32.4] |
| 18      | J185321+050802 | $-1.54 \pm 0.05$ | 91.9 | 10.7 | 28.4 [30.9] |
| 19      | J191120+073531 | $-1.51 \pm 0.06$ | 105.0 | 13.1 | 34.7 [33.0] |
| 20      | J191350+083553 | $-1.49 \pm 0.06$ | 69.6 | 10.7 | 28.4 [40.8] |
| 21      | J192014+111338 | $-1.55 \pm 0.06$ | 89.9 | 10.7 | 28.4 [31.6] |
| 22      | J200130+331242 | $-1.73 \pm 0.09$ | 43.2 | 7.2 | 18.9 [43.9] |
| 23      | J201759+363016 | $-1.52 \pm 0.10$ | 39.3 | 9.5 | 25.2 [64.2] |
| 24      | J202134+332733 | $-1.77 \pm 0.08$ | 53.8 | 7.2 | 18.9 [35.2] |
| 25      | J211746+470956 | $-1.70 \pm 0.07$ | 49.8 | 6.4 | 17.0 [34.2] |

Note. (1) Target-ID denotes the source name based on the J2000 coordinates following the convention Jhhmms+ddmss. (2) $S_{325\,\text{MHz}}$ is the expected continuum flux-density at 325 MHz derived using the TGSS flux density and the spectral index. $S_{\text{pulsed}}$ is the formal upper limit on pulsed flux-density averaged over the period, assuming 10% pulse duty cycle. (3) $S_{\text{aligned–pulsed}}$ is the upper limit on pulsed flux density assuming a large pulse duty cycle (e.g., due to scattering or for nearly aligned rotators) of 70% of the rotation period and presented in milliJansky as well as a percentage of $S_{325\,\text{MHz}}$.
minute long observations, we fixed the parameter \( z_{\text{max}} \) to 256, while for 30 and 45 minute long observations we used a value of 1024. These values imply that we have searched for average accelerations of about 213 and 42 m s\(^{-2}\) of a 1000 Hz signal, for observing durations of 10 and 45 minutes, respectively. For each observation, 400 best pulsar candidates (200 each from the two DM ranges) were folded and the diagnostic plots were examined by eye. The search pipeline was successfully validated using several control pulsars.

We also examined the faint candidates that were found to have consistent periods (within 0.01% of each other) and DMs in multiple observations of the same target fields. For such candidates, the data were folded and the corresponding diagnostic plots for all observing sessions of a particular target field were examined together.

### 3. Results

Our survey did not yield any new pulsars. Several faint candidates (6–8σ) that appeared to be potential pulsars turned out to be false alarms in follow-up observations. In addition to the control pulsars that were observed to validate the pipeline (PSRs B1937+21, B1820–30A, B1820–30B, and B2002+31), we also detected several known pulsars that happened to be in the beam or primary side lobes (PSRs J1908+0734, B2111+46, B1844–04, and B1919+21) by chance or design. We have used the control pulsar detections to make a realistic estimate of the achievable sensitivity during our observations. The expected signal-to-noise ratios (S/N) for the detections of the above known pulsars are plotted against the observed ones in Figure 1. For estimating the expected S/N, we have assumed an aperture efficiency of 55% for the projected physical collecting area and a receiver temperature of 150 K. We also took into account the observed pulse widths as well as any offset in position from the beam center (a detection from a side lobe is not included). We also estimated the direction dependent sky temperature using an all-sky map extrapolated to 325 MHz (for details, see Maan et al. 2017; though, here we use the value at the beam center unlike the weighted average across the elongated beam therein). The observed S/N is generally affected by interstellar scintillation; however, we assume that observations of different pulsars as well as multiple observations of individual pulsars provide us with an average trend between expected and observed S/N that is decided by the achievable sensitivity. A straight line fit (see Figure 1) suggests that the achievable sensitivity is about 70% of what is suggested by the radiometer equation. It is worth emphasizing here that the above sensitivity degradation factor (70% or 0.7) includes the aspects such as the effective bandwidth, which is typically smaller due to the effect of filter roll-off on the band edges, and reduction in sensitivity due to low-level radio frequency interference.
The 10σ upper limits on flux densities of a periodic signal with 10% duty cycles from the target fields are listed in Tables 1 and 2 (see the parameter $S_{\text{lim},\text{obs}}^\text{m}$. These upper limits have taken into account the above deduced sensitivity degradation factor. While scintillation could have prohibited detection of a few of these sources, our tight upper limits suggest that these sources, as a population, are not observable radio pulsars at 327 MHz.

4. Discussion

The natural question follows: if not pulsars, what could these sources be? Many of the earlier pulsation surveys of image-based targets, e.g., Damico et al. (1985), Crawford et al. (2000), and Kaplan et al. (2000), concluded that most of their target sources were possibly extragalactic. Only a few categories of extragalactic sources (e.g., extended emission from radio halos and relics in merging galaxy clusters, HzRGs) are known to exhibit spectral indices as steep as $-1.5$. Within our galaxy, only pulsars are known to have such steep radio spectra. As noted earlier, de Breuck et al. (2000) and de Gasperin et al. (2018) reported an excess of steep spectrum, compact sources in the galactic plane. For galactic latitudes $|b| < 10^\circ$, de Gasperin et al. (2018) quantify the excess at 28%. For the galactic latitude range of our GP sample, i.e., $|b| < 2^\circ$, the excess is even higher and appears to be as much as 50% (de Gasperin et al. 2018, see their Figure 15), and these are clearly of galactic origin. If we assume that half of the remaining 50% steep spectrum sources in this galactic latitude range are extragalactic, 75% of the targets in our GP samples can be expected to be extragalactic. Unless we are looking at a previously unknown class of steep spectrum sources in our Galaxy, the majority of sources in our GP sample should still be pulsars but somehow missed in our searches. A few, specific scenarios explaining such nondetections of presumably associated pulsars have been considered by many authors, including Crawford et al. (2000) and de Gasperin et al. (2018). Below we discuss if, particularly in the context of our survey, these scenarios could possibly lead to nondetection of the underlying pulsar population in these steep spectrum sources.

4.1. Pulsars in Very Tight Binary Systems

Signals from pulsars in tight and relativistic binary systems experience varying Doppler shifts as a function of orbital phase that could make their detection difficult. However, we have searched for accelerations up to more than 200 m s $^{-2}$ in our shorter duration observations. That should be sufficient to detect all currently known relativistic double neutron-star binaries. Even the accelerations of the top four such binaries are within our search range. PSR J1906+0746 (van Leeuwen et al. 2015) achieves a maximum acceleration of $\sim 95$ m s $^{-2}$; the MSP in the double pulsar, PSR J0737$-$3039A, was detected at 99 m s $^{-2}$ and reaches up to 250 m s $^{-2}$ (Eatough 2007); the 1.88 hr orbit of PSR J1946+2052 (Stovall et al. 2018) imparts a maximum acceleration over 300 m s $^{-2}$. These three systems are all relatively circular. The highly eccentric orbit of PSR J1757$-$1854 (Cameron et al. 2018) means that while it was detected at 32 m s $^{-2}$, its maximum encountered acceleration is in excess of 600 m s $^{-2}$.

The acceleration search methods (like the one employed by accelsearch) are most efficient when the duration of the signal is less than or around one-tenth of the orbital period

Figure 2. The worst-case scatter broadening: The blue dots are the scatter-broadening measurements for 148 known pulsars. The open squares and circles indicate the maximum DMs (i.e., assuming the sources to be at the outer edges of the Galaxy) and corresponding characteristic scatter broadening at 1 GHz for the targets in our GP and USS samples, respectively. The corresponding scatter broadening at 325 MHz is indicated by the right-hand side vertical axis assuming a $\tau \propto \nu^{-4}$ relationship. The red and blue colored symbols indicate that the quantities are estimated using the YMW16 and NE2001 models, respectively.

(Ransom et al. 2001). It might imply that our search was not very sensitive to orbital periods shorter than an hour or so. However, we note that our upper limits are nearly an order of magnitude better than the expected flux densities, and we would have easily detected the signals in much smaller temporal sections at appropriate acceleration values. Hence, such a scenario is unlikely to have hindered detections of any underlying pulsars.

4.2. Highly Scattered Pulsars

Scattering in the ionized interstellar medium results in broadening of pulsed periodic signals from pulsars. Scattering-induced broadening generally has steep dependence on the observing frequency and DM of the source, with the effect becoming highly pronounced at lower frequencies and higher DMs. Depending on the observing frequency and DM, the scatter-broadened pulse-width could become comparable, or even larger than the pulse period, in which case detection of the periodic signals becomes very difficult or even impossible.

To investigate if scattering could have affected detection of some of the potential pulsars in our survey, we have estimated the maximum galactic DM toward each of the target fields using the electron density models by Yao et al. (2017, hereafter YMW16) and Cordes & Lazio (2002, hereafter NE2001). These maximum DMs and the corresponding estimates of the characteristic scatter broadening ($\tau$) at 1 GHz and 325 MHz are shown in Figure 2, along with the available measurements from 148 known pulsars (Löhmer et al. 2001, 2004; Lewandowski et al. 2015; Geyer et al. 2017; Krishnakumar et al. 2017, 2018; M. A. Krishnakumar et al. in preparation, measurements at different frequencies are scaled to 1 GHz). NE2001 seems to underestimate the scatter broadening for the majority of the targets, while YMW16 estimates use the empirical relationship from Krishnakumar et al. (2015) and naturally follow the average trend when compared with the available measurements. Considering the YMW16 estimates, for the majority of the
targets in our GP sample the maximum galactic contribution to DMs is around 300 pc cm$^{-3}$, and for the others its in the range of 500–700 pc cm$^{-3}$. For the USS sample, the maximum DMs for the majority of the targets are below 100 pc cm$^{-3}$, and those for the rest are between 200 and 300 pc cm$^{-3}$. The right vertical axis of Figure 2 indicates the scatter broadening at 325 MHz assuming a $\tau \propto \nu^{-4}$ relationship. We note that the distances corresponding to the maximum galactic DMs are about 20–25 kpc for each of the sources in our GP sample. So, if all the targets are really at the extreme outer edges of the Galaxy in their respective directions, then indeed our survey would not be sensitive to many of the GP-sample sources for rotations periods shorter than about 50–100 ms. However, the DM estimates from YMW16 model could easily have uncertainties of the order of 50% or even more. If we assume the DMs to be half of those suggested by YMW16, then 19 of the 25 sources in our GP sample would have scatter broadening less than or around 10 ms. Furthermore, if these sources are only a few kiloparsecs away, say 3 kpc, then the scatter broadening would be much less than or around 10 ms for all of the sources in the GP sample. Moreover, at this distance, considering the 50% uncertainties on the DMs, the scatter broadening could be potentially less than a millisecond for the majority of the GP sample targets. On the other hand, if we consider the DMs to be underestimated by a factor of two, then more than 50% of the GP sample sources would not be detectable even from a distance of 3 kpc if their spinning periods are shorter than 100 ms.

Most of the targets in the USS sample are still expected to have scatter broadening much less than 1 ms, even if they happen to be at the outer edges of the Galaxy, implying no loss of sensitivity due to scattering for these sources even for submillisecond rotation periods.

Measurements from known pulsars show more than two orders of magnitude scatter of pulse broadening around a power-law trend (see Figure 2), and even anomalously higher scattering for some. If all of these steep spectrum sources happen to exhibit anomalously high scatter broadening, then signals with short periods would not be detectable even at 1.4 GHz.

4.3. Aligned or Nearly Aligned Rotators

The misaligned rotation and magnetic axes and the beaming of radio emission around the latter, gives rise to the observed pulsed periodic signals from pulsars. However, there is some evidence that the two axes approach toward alignment with age, on typical timescales of 10$^7$ years (Tauris & Manchester 1998). In a scenario where the magnetic inclination angle approaches the half opening angle of the radio beam, the primary observable effect would be the increased pulse duty cycle. Detection of periodic signals with large duty cycles requires more sensitive observations than that of narrow duty-cycle signals, since the overall flux is smeared out over more bins, and harmonic summing in the Fourier domain search becomes less effective. In fact, less than 1% of known pulsars have pulse widths wider than half the rotation period. For rotation periods longer than 100 ms, only a few pulsars are known for which the intrinsic radio emission spans a significant fraction of the period (e.g., PSR B0826–34, PSR J1732–3131; Ashworth & Lyne 1981; Maan et al. 2012). However, our observations were of such sensitivity that even if the pulsed emission spanned 90% of the period, signals from a majority the periodicities would have been detected. So, our target sources, as a population, are unlikely to be just large duty-cycle pulsars.

Once the magnetic inclination angle becomes comparable or smaller than the half opening angle of the radio beam, a good fraction of the radio emission would appear as continuous emission (cf. top and middle panels of Figure 3). As the typical pulse shape from most pulsars is far from a “top-hat,” these intrinsic variations would cause some modulation in the observed intensity over the pulsar period, even for a nearly aligned rotator. However, only a fraction of the total flux density would be apparent as pulsed, and that too with large duty cycles. One known example of such a system is PSR J0218+4232, where only about half of the total radio flux is pulsed (Navarro et al. 1995). The increased baseline does not, by its own right, make pulsar searching harder. A successful detection in such a search is determined only by the signal-to-noise of the pulsed signal. And given our sensitive observations, in a number of cases we could have measured such small variations. Assuming a duty cycle of 70%, in the last columns of Tables 1 and 2, we place upper limits on pulsed fractions of the target-source flux density. We can generally rule out pulsed flux densities higher than a few tens of percents. Probing a scenario where the pulsed flux is only a few percent of the total observed emission would require significantly deeper observations.

A perfect alignment suggests a cessation of any “pulsar” action as an observable phenomenon. However, for an
asymmetric emission beam, which pulsars are generally known to have (cf. the beam mapped for PSR J1906+0746; Desvignes et al. 2013), the observable implications are identical to those described for nearly aligned rotators above.

While the total intensity in an aligned rotator may be steady, other properties of the emission do vary with pulse phase. Throughout the pulse period, the line of sight will steadily traverse 360° in azimuth, around the magnetic pole. In the rotating vector model (Radhakrishnan & Cooke 1969), this translates to a full rotation of the angle of linear polarization. Even under invariant total intensity, position-angle sweep may be visible in sources with some fractional linear polarization (Figure 3). The same interstellar medium that inflicts the frequency dispersion to the pulsar signal will also Faraday rotate. The magnitude of both effects is unknown but could be dealt with similarly; through a search in both DM (this work) and rotation measure (RM). Using the RM–DM relation (Lyne & Smith 1989) would help limit the range of trial RMs per trial DM. From the polarization-angle swings found after applying a fast folding algorithm, aligned rotators could be disentangled from background sources. Alternatively, a time series formed from the values of the polarization angle in each sample could be searched in a Fourier transform. With the period, DM and RM known, deep follow-up at higher frequencies, where the narrowing beam may no longer cover the entire pulse period, could provide insights into the pulsar geometry.

Since ORT is receptive to only a single linear polarization, the differential Faraday rotation of a linearly polarized signal manifests itself in the form of spectral intensity modulation within the observation bandwidth. This spectral modulation can be exploited to deduce RM and linear polarization properties (Ramkumar & Deshpande 1999; Maan 2015). However, this is possible only for reasonably high RMs and significantly linearly polarized sources, and the abovementioned search involving RM would require computing time several orders of magnitude longer than that spent in the current search limited to DM, period, and acceleration domains.

In very specific cases, the observation bandwidth might sample only a small and near-bottom fraction of the above Faraday rotation induced spectral intensity modulation, which could potentially lead to a nondetection. However, such a nondetection would essentially need the signal to exhibit nearly 100% linear polarization, appropriately low RM, and a near constant polarization position angle (PPA). For most of the sources in our GP sample, the upper limits on linearly polarized components are 20%–30% of the total flux density (NVSS). The small linear polarization fraction may be intrinsic to the sources or might be indicating depolarization due to well known large PPA swings exhibited by pulsars or scattering. In either of the cases, ORT’s reception to only a single linear polarization is unlikely to affect the potential detection.

5. Summary

Summarizing, we have presented a search for pulsars in 44 steep spectrum sources, employing a semicoherent dedispersion scheme. While our survey did not yield any new pulsars, we argue that the majority of the sources in our samples should actually be pulsars or a new category of Galactic sources. Nondetection of any pulsars from our GP sample of 25 sources suggests that even at 327 MHz the excess of steep spectrum sources in the Galactic plane cannot be accounted for by a conventionally observable pulsar population. Interstellar scattering could have affected our searches only if the majority of the sources in our sample happen to be pulsars with millisecond or a few tens of millisecond rotation periods and they are either located at extreme outer edges of the Galaxy or exhibit anomalous scattering. A fraction of the MSPs located a few kiloparsecs away could also have been missed. We have also discussed in detail the scenario that these sources are in fact aligned or nearly aligned rotators and propose methods to probe such a situation further. Deep searches at higher frequencies (a few gigahertz) will, in general, be helpful in uncovering interesting pulsars, in case these steep spectrum sources harbor anomalously scattered or (nearly) aligned rotators.

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Software: PRESTO (Ransom et al. 2002), cdmtp (Bassa et al. 2017a), DEDISP library (Barsdell et al. 2012).

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