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Further searches for Rotating Radio Transients in the Parkes Multi-beam Pulsar Survey

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ABSTRACT
We describe the steps involved in performing searches for sources of transient radio emission such as Rotating Radio Transients (RRATs), and present 10 new transient radio sources discovered in a re-analysis of the Parkes Multi-beam Pulsar Survey. Followup observations of each new source as well as one previously known source are also presented. The new sources suggest that the population of transient radio-emitting neutron stars, and hence the neutron star population in general, may be even larger than initially predicted. We highlight the importance of radio frequency interference excision for single-pulse searches. Also, we discuss some interesting properties of individual sources and consider the difficulties involved in precisely defining a RRAT and determining where they fit in with the other known classes of neutron stars.

Key words: stars: neutron – pulsars: general – Galaxy: stellar content.

1 INTRODUCTION
Rotating Radio Transients (RRATs) were discovered in a search of archival data from the Parkes Multi-beam Pulsar Survey (PMPS) by McLaughlin et al. (2006). These sources exhibit infrequent, short, relatively bright bursts of radio emission. The pulses have peak flux densities (at 1.4 GHz) ranging from $\sim$100 mJy up to 10 Jy and pulse widths in the range 2–30 ms. As we detect pulses only occasionally from RRATs, they are generally not detected in Fourier domain searches (although see the discussion in Section 3) but rather by searching for individual bright pulses (McLaughlin & Cordes 2003; Cordes & McLaughlin 2003). Periodicities can be determined by factorizing the difference between each pair of pulse arrival times (as discussed in Section 2). The underlying periodicities are in the range 0.7–6.7 s. These periodicities are believed to be spin periods and thus RRATs seem to be a new population of neutron stars. Further evidence for this comes from X-ray observations of RRAT J1819$-1458$ (the most prolific, brightest and thus well-studied source) which have revealed thermal emission consistent with that expected from cooling neutron stars as well as an X-ray period identical to that determined from radio observations (Reynolds et al. 2006; McLaughlin et al. 2007).

We see these millisecond bursts as infrequently as once per hour and up to as often as every few minutes. The long periods observed are more comparable to the magnetars (Woods & Thompson 2006) and the isolated neutron stars (INSs, also known as XDINSs; Kaplan 2008) than the radio pulsars, and the relationship between these populations is an open question. The narrow pulse widths are comparable to individual pulses from radio pulsars. Coupled to their longer periods, the duty cycles are apparently much smaller, but including the entire phase range wherein we see emission gives duty cycles comparable to integrated pulsar profiles, e.g. J1819$-1458$ shows emission over $\sim$2.9 per cent phase range (Lyne et al. 2009). There have been many suggested explanations for the ‘bursty’ RRAT behaviour. Some assign it to detection issues with others favouring intrinsically transient emission. Weltevrede et al. (2006) support the former notion and suggest that the RRAT emission may be due to these sources being more-distant analogues of PSR B0656$-14$, i.e. pulsars whose regular emission may be below our detection limit but who show detectable giant pulses or have an amplitude distribution with a long tail at high-flux densities. The alternative models view the emission as truly intermittent with the short duration bursts corresponding to activation times of external excitation events. This is the case in the model of Cordes & Shannon (2006) which considers the re-activation of inactive vacuum gaps due to the presence of circumstellar asteroidal material. Similarly, it has been proposed by Luo & Melrose (2007) that RRATs may be surrounded by a radiation belt which could stimulate transient emission in the magnetosphere behaviour of RRAT.

Apart from these unusual emission properties, RRATs are also of interest due to the predicted size of the population, which is thought to be several times larger than the radio pulsar population (McLaughlin et al. 2006). Previously, Keane & Kramer (2008)
discussed the implications of such a large number of RRATs on the Galactic production rate of neutron stars. It was argued that the many classes of neutron stars now known do not seem to be accounted for by the Galactic core-collapse supernova rate. An evolutionary link between the neutron star classes might eliminate this birthrate problem. An alternative explanation would be that the population estimates for RRATs and other neutron star populations are hugely overestimated.

The discovery of RRATs has sparked a renewed interest in time-domain searches for transient radio sources—a relatively unexplored parameter space (Cordes, Lazio & McLaughlin 2004b; Lazio et al. 2009) which will be revolutionized with upcoming instruments such as LOFAR (van Leeuwen & Stappers 2007), the ATA (e.g. van Leeuwen & ATA Team 2009), the SKA pathfinders (e.g. Johnston, Feain & Gupta 2009), FAST (Nan et al. 2006; Smits et al. 2009b) and eventually the SKA (Cordes et al. 2004a; Smits et al. 2009a). For now, addressing these questions requires improved population estimates and characterization. In particular, we need to understand which potential selection effects are present during the discovery process and how they impact on the discovered population. With a better understanding of RRAT characteristics and the potential selection effects, an improved population estimate for RRATs will be possible. Motivated by this, we have performed a full reprocessing of the PMPS searching for sources of single pulses of radio emission. In Section 2, we outline the steps involved in our reprocessing. In Section 3, we discuss in some detail the observed characteristics of 10 newly discovered sources as well as the results of follow-up work on one detected, but previously known, source. For the purposes of Sections 2 and 3, we will consider that for a source to be an RRAT at some frequency, it is necessary but not sufficient that it is detected more easily in a single-pulse search than in a periodicity search. In Section 4, we discuss in more detail a refined definition of what a RRAT is as well as the implications for the Galactic neutron star population of these new discoveries before concluding with an outlook towards surveys with LOFAR and the SKA.

2 PMSINGLE

In the original RRAT discovery paper (McLaughlin et al. 2006), it was estimated that approximately half of the RRATs visible in the PMPS had been detected, with the remainder obscured due to the effects of radio frequency interference (RFI). Recently, it has become timely to reprocess the PMPS survey in search of these postulated sources as we have developed a new and effective RFI mitigation scheme (Eatough, Keane & Lyne 2009). Utilizing the Jodrell Bank Pulsar Group’s recently acquired 1400-processor HYDRA supercomputer, the whole PMPS data set was reprocessed. Modified versions of the SIGPROC\(^{1}\) processing tools were used. In the following, we refer to this project as the PMSingle process.

We note that the presence of RFI will make a search somewhat blind to sources with low dispersion measure (DM). The DM of a source at a distance \(L\) from Earth is

\[
DM = \int_0^L n_e(l) \, dl,
\]

where \(n_e(l)\) is the electron density at a distance \(l\). RFI is terrestrial in origin and, not having traversed the interstellar medium, we expect it to have DM = 0.\(^2\) However, as RFI signals are typically very strong, in comparison to the relatively weak astrophysical signals of interest, they are seen with sufficient residual intensity to mask celestial signals to high DM values. Fig. 1 shows an example of this ‘low-DM blindness’ due to the presence of strong terrestrial RFI. This of course means that searches can miss real, low-DM sources. Thus, our sensitivity to the nearby Galactic volume may have been reduced due to the effects of RFI in the initial analysis.

Before proceeding with outlining the PMSingle reprocessing steps, we note some survey and data specifications: the survey covered a strip along the Galactic plane with \(|b| < 5^\circ\) and between \(l = 260^\circ\) and \(50^\circ\). It consists of 3196 \(\times\) 35 min pointings at an observation frequency of 1.4 GHz using the Parkes 21-cm multibeam receiver. This receiver has 13 beams, each receives orthogonal linear polarization so that there are 41 561 dual-polarization beams in total. An analogue filterbank with 96 \(\times\) 3 MHz channels was used with 250-\(\mu s\) sampling. Once the data were received, both polarization signals were added to give total intensity (Stokes I) and the data were 1-bit digitized before recording. Thus, the raw data for each beam can be visualized as a 1-bit digitized data cube (time, frequency and amplitude). The survey specifics are described in more detail in Manchester et al. (2001).

Our PMSingle processing involved the following steps.

(i) Remove all clipping algorithms. In previous analyses of the PMPS, the raw data have been ‘clipped’, i.e. the data were read in 48 KB blocks and those blocks wherein the sum of all the bit values was larger than some (user supplied) threshold above the mean had their values set to the mean level (half 1s and half 0s in the case of 1-bit data). The motivation for such clipping is that RFI signals are typically much stronger than real astrophysical signals, so that the brightest detections are taken to be RFI spikes. This, however, is not optimal in that it removes signals based on strength and the discovery of RRATs and pulsars which show strong single pulses show that such signals may be of astrophysical interest. The threshold used is also arbitrary and usually determined on a trial-and-error basis. We note that the strongest pulses with high dispersion (i.e. dispersed over two or more blocks) can escape being clipped in error so that low-DM sources are the most likely to be clipped in this way. We therefore removed this step from our reprocessing.

(ii) Dedisperse the raw filterbank data using the zero-DM filter. We searched for dispersed signals in a DM range of 0–2200 cm\(^{-3}\) pc. For the Galactic longitudes covered by the PMPS, this corresponds, at \(|b| = 0^\circ\), to typical distances of \(\geq 40\) kpc at \(l = 260^\circ\) and \(50^\circ\) to 8.5 kpc towards the Galactic Centre. The zero-DM filtering technique can be simply stated: for each time sample \(t\), we average all \(N_{\text{chans}}\) frequency channels and subtract this average from each channel. The value of a frequency channel \(f_i\) at time \(t\) is \(S(f_i, t)\) and after applying the zero-DM filter function will become

\[
S(f_i, t) \rightarrow S'(f_i, t) = S(f_i, t) - \frac{1}{N_{\text{chans}}} \sum_{i=1}^{N_{\text{chans}}} S(f_i, t).
\]

This has the effect of removing short-duration broad-band RFI but real dispersed pulses will be convolved with a particular function. After applying this filter, we dedisperse the data. A dispersed input

\(^{1}\)http://sigproc.sourceforge.net/

\(^{2}\)RFI signals emerging from air-traffic control radar, a particular problem at frequencies near 1400 MHz, are sometimes observed to also show signals sweeping in frequency.
RRAT searches of the PMPS

Figure 1. The ordinate in the large left-hand plots is trial DM over the range 0–500 cm$^{-3}$ pc and the abscissa is time over a 35-min PMPS observation. To the right-hand side are plots of trial DM versus peak S/N. Significant detected events are plotted as circles with radius proportional to S/N.

(a) The strong vertical stripes across wide DM ranges are instances of extremely strong RFI. Inspection of the plot for the presence of a celestial source is impossible due to the presence of this RFI. (b) The same beam after the zero-DM filter has been applied [see Section 2(ii)]. We can see that the RFI has not been completely removed, especially at higher DMs. However, the RFI has been removed much more effectively at low DMs and a source at DM $\sim 20$ cm$^{-3}$ pc is beginning to become visible. (c) The same beam after application of the zero-DM filter and the removal of multiple-beam events. We can see that the diagnostic plot is cleaned up even further and, although there is still remnant RFI, it is clear that there is a real source in this beam at DM $\sim 20$ cm$^{-3}$ pc. This is the first detection of J1841$-$14 in the PMPS, the lowest DM source found so far in the survey.

Square pulse $\pi(t, \text{DM}, w, \text{BW}, f_0)$ at time $t$, with pulse width $w$, observed with a bandwidth (BW) at a central frequency $f_0$ will become

$\pi(t, \text{DM}, w, \text{BW}, f_0) \rightarrow 2\pi(t, \text{DM}, w, \text{BW}, f_0)$

$= \pi(t, \text{DM}, w, \text{BW}, f_0) - \nabla(t, \text{DM}, w, \text{BW}, f_0)$.

The peak of the pulse is reduced with the addition of triangular ‘dips’ on either side of the pulse with the exact shape dependent on the pulse’s DM and width, as well as on $f_0$ and BW. Examples of this are given in Fig. 2 which shows single pulses detected from J1841$-$14. We note that the zero-DM filter acts as a more natural RFI mitigation tool than standard clipping as it removes signals based on their dispersion properties as opposed to sheer strength. Details of the zero-DM filter including assumptions, uses and limitations are discussed in detail in Eatough et al. (2009).

(iii) Search for bright single pulses. This is an exercise in matched filtering using box-cars of various sizes. However, instead of rectangular box-cars, the zero-DM filtering means it is optimal to search with box-cars of the form $2\pi(t, \text{DM}, w, \text{BW}, f_0)$ for various trial widths. That this is the optimal strategy is evident from examining the pulse in Fig. 2 which clearly shows the characteristic dips from the zero-DM filtering procedure. In PMSingle, we search for pulse widths as narrow as 250 $\mu$s to as wide as 128 ms at the lowest DMs. As we increase the DM trial value, we get dispersive smearing of pulses to widths much longer than their intrinsic widths, so at these DMs we search for even wider pulses. The widest pulse widths searched for are a factor of 16 larger than in the original PMPS single-pulse search analysis of McLaughlin (2009a).

(iv) Perform a beam comparison to remove multibeam events. The zero-DM filtering is effective at removing short-duration broadband RFI. The more persistent or narrow-band that RFI is the less likely it will be completely removed. However, as the PMPS used a 13-beam receiver, we have extra information to help with RFI mitigation. Pulsar signals are very weak and typically are seen in
only one beam. The strongest pulsars (e.g. Vela) can be seen in a few beams but normally no more than three. Even the extremely bright 30-Jy 5-ms single burst (from an unknown source possibly at a cosmological distance), reported by Lorimer et al. (2007), was seen in just three beams. We can thus apply a rejection criteria for detected events like: for each detected event – (DM, time) point, if we have detections in the range (DM ± εDM, time ± εtime) for, e.g. ≥5, beams in that pointing then ignore this detection as it is most likely RFI. We conservatively took ε to be one bin in each case (i.e. one DM trial step and one time sample step). In addition, for all beams, a check is made against the known pulsars (from the ATNF pulsar data base; 3 Manchester et al. 2005) which fall within the beam.

(v) Produce diagnostic plots for inspection and classification. Along the lines of Cordes & McLaughlin (2003), a series of diagnostic plots are created for each beam. An example of this is shown in Fig. 3. The plots include beam information (beam and pointing number, sky position etc.) as well as information on the number of multiple beam detections which were removed. Each beam was inspected and classified as containing either noise, known pulsars, known RRATs or new candidates – divided into Classes 1, 2 and 3. Examples of each of these classes are given in Fig. 4. Class 1 candidates are all thought to be real sources, either yet-to-be confirmed RRATs or known pulsars detected in the telescope’s far-side lobes. Class 3 candidates are weak and no confirmations are expected. Class 2 sources are intermediate between these classes. Beams could also be classified as being too adversely affected with remnant RFI (not removed by zero-DM filtering or beam comparisons) so as to make inspection impossible. In these beams, a real source, unless it was very strong, would not have been detectable. The results of the classifications are given in Table 1.

(vi) Cross-check with known sources. For each candidate, we confirm that it is not a known pulsar (or RRAT). Even if there is no pulsar within the pulse, the pulses could still be from a known (strong) pulsar perhaps several beams away on the sky (e.g. PSRs B0835—41, B0833—45 and B1601—52 are detected many times like this). To do this, we can compare the position (with a larger tolerance) and DM of the candidate to that of known sources.

\[ \text{http://www.atnf.csiro.au/research/pulsar/psrcat/} \]

3. Examples of each of these classes are given in Fig. 4. Class 1 candidates are all thought to be real sources, either yet-to-be confirmed RRATs or known pulsars detected in the telescope’s far-side lobes. Class 3 candidates are weak and no confirmations are expected. Class 2 sources are intermediate between these classes. Beams could also be classified as being too adversely affected with remnant RFI (not removed by zero-DM filtering or beam comparisons) so as to make inspection impossible. In these beams, a real source, unless it was very strong, would not have been detectable. The results of the classifications are given in Table 1.

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(vii) Determine a period for the candidate. As RRATs are not seen in Fast Fourier Transform (FFT) searches (although see the discussion in Section 3), we use a method of factorizing the pulse time of arrival (TOA) differences to determine the period. For N TOAs, there are at most \( \binom{N}{2} \) unique TOA differences which we can use. For some small increment, we step through a large range of period trials. The correct period will fit all of the TOA differences with a small error and rms residual. Harmonics of the true period will also match many of the TOA differences but at a less significant level. If the most significantly matching period does not match all of the TOA differences then progressively removing the TOAs with the largest uncertainty will increase the significance of the match on to the true period. As a rule of thumb, approximately eight pulses (i.e. 28 TOA differences) in an observation allow a reliable period estimate, i.e. at the correct harmonic. We note that for a TOA difference to be usable in this method both pulses must not be far separated so as not to lose coherence, e.g. eight pulses in a single observation yields 28 usable TOA differences for period determination, but two separated observations each of four pulses yields just 12 TOA differences. Some example output plots from this method are shown in Fig. 5. If a period determination is possible, it can be used with position and DM to further confirm whether or not the candidate is a previously known source. We note one difficulty with this method is that it is possible that the range of emitting pulse longitudes is wide (e.g. for an aligned rotator) so that sharp peaks like those shown in Fig. 5 will be smeared out across a wider trial period range.

3.1 Detection of known sources

Currently, we have confirmed 11 sources, 10 of which are new. These are listed in Table 2 with some observed properties. We note that these confirmed sources are amongst the better Class 1 candidates. The detection statistics for these sources are given in Table 3. Coherent timing solutions have been obtained for all the sources that have determined periods, but spanning only a few months, so that accurate position and period derivative determinations are not yet possible. In this section, we discuss the individual sources discovered in more detail.

3.1 Detection of known sources

In addition to the newly discovered sources, the analysis has made many detections of previously known sources. These include detections of 300 previously known pulsars. Many of these were detected multiple times so that there were 606 known pulsar detections in total. Up to 2006, the PMPS detected 976 pulsars (of which, at the time, 742 were new sources; see e.g. Lorimer et al. 2006). Since then new analyses of results have given rise to more sources such that the ATNF pulsar data base now lists 1030 pulsars as detected in the PMPS. The 300 known pulsar detections here then correspond to ~ 30 per cent of pulsars detected just from single-pulse searches. This is an increase on the 250 pulsars detected in the original single-pulse search (McLaughlin 2009a) with extra detections made across the entire DM range.

The true PMPS single detection rate for known pulsar detections may even be better than 30 per cent if we consider whether any of the pulsars detected in the PMPS would actually be removed by the
zero-DM filter. This could be the case for low-DM pulsars. However, if we assume zero-DM must remove the amplitude spectrum up to a fluctuation frequency which is $\delta^{-1}$ harmonics in order to remove all information of the pulsar, where $\delta = w/P$ is the pulsar duty cycle, then just four of the PMPS pulsars would be removed. Assuming we need to remove just $P/2w$ harmonics would see 16 sources (or 1.6 per cent) removed by the zero-DM filter which leaves the detection rate at $\sim 30$ per cent. In addition, some of the sources classified as candidates may turn out to be (far side-lobe detections of) known pulsars which could potentially boost the number of single-pulse detections by a few per cent.

The original 11 RRATs were all redetected. RRAT J1819−1458 is observed three times in the survey. The third PMPS detection, revealed in this analysis, was previously unknown. This is very helpful for timing and for attempts in connecting over a long $\sim 1800$ d gap in timing data (between survey observations and the initial single-pulse search of the data). This enables a conclusion that RRAT J1819−1458 does not seem to have suffered a large glitch during this gap in observations (Lyne et al. 2009).

### 3.2 Discussion of interesting individual sources

J1047−58 was found within the same beam as the known pulsar J1048−5832. This allowed for a rapid confirmation of the source by examining archival Parkes data of the known pulsar. In the discovery observations, all of the six detected pulses were clustered within a $\sim 100$ s window. In the followup observations of this source, there is a suggestion of such ‘on’ times in which pulses are clustered together in windows of up to $\sim 500$ s. This enables a conclusion that RRAT J1819−1458 does not seem to have suffered a large glitch during this gap in observations (Lyne et al. 2009).

J1514−59 is detected in all observations with a period of $1.046$ s and a large average burst rate of $\dot{\chi} \sim 20$ h$^{-1}$. It is not seen in FFT searches of entire observations which have all been $\sim 30$ min in duration. However, its pulses are seen to come in approximately minute-long clumps separated by $\sim 800$–$1000$ s. Fig. 3 shows an example of this. Performing FFT searches focused on a small ‘on’ region (albeit with quite poor spectral resolution of $\sim 10$ mHz) gives a period which agrees with that obtained from examining the differences in pulse pair arrival times. Folding the ‘on’ regions at the nominal period gives us a pulse profile which shows a single narrow peaked pulse.

Analysing the intervals between the bursts shows that they do not obey a Poissonian distribution. The KS test probability that the distribution is Poissonian is $< 10^{-8}$. In fact, it seems the distribution is bimodal with a peak at short burst intervals (of a few periods) and another at long intervals (several hundred periods). We find that the short intervals are consistent with a Poissonian distribution with average expected interval of $\lambda = 7$ periods. More observations are needed to determine the ‘peak’ of the longer interval distribution.

The long $\sim 15$ min intervals do not seem to be due to the effects of interstellar scintillation. For this observation frequency and DM, we are in the strong scintillation regime (Lorimer & Kramer 2005) and so must consider diffractive and refractive scintillation as possibilities. Assuming the NE2001 model (Cordes & Lazio 2002, 2003) of the Galactic free electron density, we find a diffractive time-scale $\Delta t_{\text{Diss}}$ of $\sim 30$ s which is much too short to explain this modulation. Similarly, the diffractive scintillation bandwidth $\Delta f_{\text{Diss}}$ is just $\sim 10$ kHz, much narrower than the bandwidth of a single channel in any of these observations. Thus, every channel averages many scintles and observing this modulation is not possible. The refractive scintillation time-scale is related to the diffractive time-scale by $\Delta t_{\text{Riss}} = (f/\Delta f_{\text{Diss}})\Delta t_{\text{Diss}}$ which in this case is $\sim 10$ s of days which is much too long to account for this modulation.

It would seem then that this modulation may be something intrinsic to the neutron star. The situation seems somewhat consistent with a nulling pulsar where the majority of the pulses emitted during the non-nulling phase are below our sensitivity threshold. This would imply a nulling length of $\sim 14$ min and a nulling cycle of $\sim 1$ min, i.e. a nulling fraction of more than 90 per cent. In studies
Table 1. The classifications of the PMPS beams in the PMSSingle single-pulse search. For the known sources, the number of unique sources detected are given in parentheses.

<table>
<thead>
<tr>
<th>Classification</th>
<th>$N_{\text{detections}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Candidate:Class 1</td>
<td>162</td>
</tr>
<tr>
<td>Candidate:Class 2</td>
<td>204</td>
</tr>
<tr>
<td>Candidate:Class 3</td>
<td>319</td>
</tr>
<tr>
<td>Known PSR</td>
<td>606 (300)</td>
</tr>
<tr>
<td>Known RRAT</td>
<td>13 (11)</td>
</tr>
<tr>
<td>Noise</td>
<td>27493</td>
</tr>
<tr>
<td>Noise + some remnant RFI</td>
<td>12061</td>
</tr>
<tr>
<td>Large remnant RFI</td>
<td>693</td>
</tr>
</tbody>
</table>

of 23 nulling pulsars detected in the PMPS. Wang, Manchester & Johnston (2007) observed nulling fractions from as low as 1 per cent to as high as 93 per cent. One source showed a similar nulling cycle of $\sim 515$ s although most were lower. This is not inconsistent, however, due to the obvious difficulty of detecting long-duration nullers. Their results also showed large nulling fraction to be related to large characteristic age, $\tau = P/2\dot{P}$, rather than long periods, a relationship which can be tested for this source once a full timing solution has been obtained. We do note the similarity between J1514$-$59 (and J1047$-$58) and the class of ‘intermittent pulsars’ (Kramer et al. 2006). However, the time-scales for the ‘on’ and ‘off’ states in these sources can be $10$ s of d which is much longer than what is seen in these RRATs. The possibility remains though that RRATs may fit into a continuum of nulling behaviour which could range from those sources which null for a few periods at a time to the intermittent pulsars at the other extreme. As the numbers of known RRATs and intermittent pulsars increases, timing observations can be used to investigate what properties (if any, e.g., period and age) correlate with nulling fraction.

J1554$-$52 is a strong single-pulse emitter showing 35 pulses in its discovery observation. It is also weakly detectable in FFT searches of most observations but with much higher significance in single-pulse searches. The weakness in the FFT detection is one reason for the previous non-detection of this source. However, it
Figure 5. Trial period differences for J1841−14. The top panel shows the rms residuals for each trial period. The middle panel shows the number of rms residuals below 10 per cent and the bottom panel shows the number with rms residuals below 2 per cent.

is likely that this source would have been removed by previously applied algorithms designed to remove RFI signals. For instance, frequency domain ‘zapping’ would have removed this source, i.e. setting certain frequencies in the fluctuation spectrum (of a dedispersed time series) to zero. This is done at known RFI frequencies (e.g. 50 Hz) and their harmonics. With a period of 125 ms, this pulsar falls exactly into one of these zapped regions. The pulses are also seen to fall into two main phase windows, reminiscent of the three such windows observed in RRAT J1819−1458 (Lyne et al. 2009).

J1724−35 was the first source to be discovered in this reprocessing (Eatough et al. 2009). Since the two survey observations of this source, it has been re-observed 15 times and detected in 10 of those. Despite having a fairly high DM, its discovery is helped immensely by the removal of very strong RFI by the zero-DM filter. In all but two observations, it is not detected in an FFT search. In one observation, it can be detected from focused FFT searches of times when strong single pulses are seen, as for J1514−59. In another observation, it is detected with FFT signal-to-noise ratio (S/N) of 15 which is evidence that there is underlying weak emission in addition to the detected single pulses. During these times when the source is detectable in periodicity searches, a folded profile can be obtained which is quite wide and double peaked. We note that this variation is not due to scintillation as the scintillation time-scale of 2 s is too short and the bandwidth of ∼20 Hz is too narrow to explain this. The burst rate is insufficient for analysis of the intervals between bursts at present.

J1727−29 is detected once in the PMPS with just one strong single pulse. It was re-observed in a followup observation where we again detected just one pulse. Further followup observations have not revealed anything further from this source. This source is obviously too weak to time and without even two pulses in a single
observation a period estimate is not possible. We expect a number of candidates like this to be confirmed while proving impractical to be engaged when such facilities become available.

J1841−14 was observed twice in the PMPS where, as we can see from Fig. 1, its detection was hindered by the presence of strong RFI in the initial analysis. The source has been re-observed 11 times and detected in all cases. It has the lowest DM of any RRAT found in the PMPS (and lower than 95 per cent of normal radio pulsars). It has a very high burst rate of ˙\( \chi \) ~ 10 h\(^{-1} \). It is undetectable in FFT searches and has a long period of 4.558 s. However, this more distant source (it is approximately six times further away than J1841\(^{-1} \)) shows weak pulses. Typical peak flux densities (at 1.4 GHz) of ~1 Jy and a maximum peak flux density observed of 1.7 Jy. While most of the pulses are narrow at ~2 ms, there are few pulses detected with pulse widths of as wide as 20 ms. The high burst rate means that obtaining a sufficiently large number of TOAs at regular intervals to obtain a coherent timing solution should be straightforward. Obtaining an accurate timing position will be useful for a detection of this source at X-rays which appears very promising as the source is nearby at a distance of ~800 pc.

J1854+03 was observed once in the PMPS and has since been re-observed eight times and detected in all cases. This source is one previously identified by the 1.4-GHz PALFA survey (Deneva et al. 2009). As the PALFA position is much more accurate than one previously identified by the 1.4-GHz PALFA survey (Deneva et al. 2009). As the PALFA position is much more accurate than which we were able to obtain with the Parkes telescope (due to the much smaller beam size of the Arecibo telescope), it may be possible to determine a period derivative for this source on a shorter time-scale than for the other sources. This is because, typically, determining a period derivative takes a year of timing observations so that the effects of positional uncertainty (which shows year-long sinusoidal patterns in timing residuals) and the slowdown rate of the star can be disentangled. This source has a high burst rate which is ˙\( \chi \) ~ 10 h\(^{-1} \). It is undetectable in FFT searches and has a long period of 4.558 s. However, this more distant source (it is approximately six times further away than J1841−14) shows weak pulses. Typical peak flux densities (at 1.4 GHz) are ~100 mJy but the brightest observed pulse is ~540 mJy. The pulse widths are typically ~15 ms and there are no indications of clumps of emission on which to focus FFT searches.

### Table 3. Detection statistics for the confirmed sources from the PMSingle analysis. \( \chi \) refers to the detected burst rate.

<table>
<thead>
<tr>
<th>Source</th>
<th>( N_{\text{det}}/N_{\text{obs}} )</th>
<th>( N_{\text{pulses}} )</th>
<th>( T_{\text{obs}} (\text{h}) )</th>
<th>˙( \chi ) (h(^{-1} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1047−58</td>
<td>8/15</td>
<td>54</td>
<td>8.96</td>
<td>6.0</td>
</tr>
<tr>
<td>J1423−56</td>
<td>9/12</td>
<td>35</td>
<td>10.01</td>
<td>3.4</td>
</tr>
<tr>
<td>J1514−59</td>
<td>9/9</td>
<td>92</td>
<td>4.58</td>
<td>20.0</td>
</tr>
<tr>
<td>J1554−52</td>
<td>8/8</td>
<td>214</td>
<td>4.25</td>
<td>50.3</td>
</tr>
<tr>
<td>J1703−38</td>
<td>5/6</td>
<td>10</td>
<td>3.08</td>
<td>3.2</td>
</tr>
<tr>
<td>J1707−44</td>
<td>5/5</td>
<td>22</td>
<td>2.58</td>
<td>8.5</td>
</tr>
<tr>
<td>J1724−35</td>
<td>12/17</td>
<td>34</td>
<td>9.95</td>
<td>3.4</td>
</tr>
<tr>
<td>J1727−29</td>
<td>2/5</td>
<td>2</td>
<td>2.11</td>
<td>0.9</td>
</tr>
<tr>
<td>J1807−25</td>
<td>7/7</td>
<td>25</td>
<td>3.97</td>
<td>6.2</td>
</tr>
<tr>
<td>J1841−14</td>
<td>13/13</td>
<td>231</td>
<td>5.01</td>
<td>46.0</td>
</tr>
<tr>
<td>J1854+03</td>
<td>9/9</td>
<td>42</td>
<td>4.52</td>
<td>9.2</td>
</tr>
</tbody>
</table>

This is due to red-noise, and in the case of the zero-DM filter a suppressed fluctuation spectrum at low frequencies.

### 4 DISCUSSION

The motivation for this reprocessing of the PMPS is to find more RRAT sources. The reason for this is that the RRATs seem to represent a very large population of Galactic neutron stars, likely larger than the regular radio pulsar population. It is therefore important to clearly describe differences between RRATs and pulsars, leading to a meaningful definition of RRATs. Having discovered the existence...
of RRATs by their bursty emission, our ongoing studies of their emission properties suggests that a useful definition will go beyond a simple description of this burst behaviour.

### 4.1 What is an RRAT?

From a detection point of view it is difficult to define a RRAT. One possible definition is that of a source only detectable in single-pulse searches and not in periodicity searches. As the RRATs seem to have intrinsically longer periods, one might think this is a selection effect. For equal amplitude distributions, one might indeed expect less periodicity search detections as the number of pulse periods in a given observation time is less. However, McLaughlin et al. (2009) show that the period distributions are different with high significance and that the single-pulse search sensitivity does not select against low-period RRATs, should they exist. It seems therefore that the RRATs have intrinsically longer periods than most radio pulsars.

One might extend the definition to be that of a source more easily detected in single-pulse searches than periodicity searches. The so-called ‘intermittency ratio’, $R$, is defined as the ratio of the single-pulse and periodicity search S/N. Thus, a RRAT would be considered to be a source that has $R > 1$ but this immediately has several problems as the intermittency ratio varies between observations and some kind of arbitrarily averaged value of $R$ would be needed. Also, as far as detectability is concerned, several single-pulses with, say, S/N of 10 are much more easily detectable than a periodicity search with a similar S/N of 10 due to the different false-positive noise levels for each method. Thus, the same value of $R$ can describe very different scenarios and its usefulness as a measure of detectability is limited. Another problem is that our current data suggest that a RRAT detected at 1.4 GHz can behave differently at a different observing frequency. Corresponding studies of the yet unknown spectra through multifrequency observations of RRATs are underway (Keane et al., in preparation; Miller et al., in preparation).

A detailed definition of RRATs therefore needs to include all of this information – intermittency, amplitude and spectral distributions, multifrequency behaviour as well as period and period derivative properties and the derived quantities related to these in particular. For example, the inferred magnetic fields distribution in RRATs has been shown to be different to that of the pulsars with a high significance (McLaughlin et al. 2009). In addition, one source has also shown anomalous glitch activity (Eatough et al. 2009), although it is unknown whether this is characteristic of the entire population of RRATs. In Table 4, we summarize the observed properties of pulsars, magnetars and the RRATs. The INSs are also likely related but are not included here for lack of information on their radio properties. Further observations will constrain the ranges of these properties further for RRATs which will allow us to refine the classification of RRAT sources.

### 4.2 Distant pulsars?

Closely related to the question of the nature of a RRATs are, of course, models that explain RRATs as distant analogues of pulsars with a pulse amplitude distribution with a long tail. Weltevrede et al. (2006) have shown that the nearby PSR B0656+14 (at a distance of 288 pc) would appear RRAT-like if moved to typical RRAT distances. The amplitude distribution of the pulses from this source are lognormal but can be described by a power law with index of between $-2$ and $-3$ at the high-flux density end. We can test this scenario if we assume that RRATs emit pulses according
pulses will provide a powerful discriminator between sources that can be explained as distant pulsars and those which cannot.

Fig. 6 shows the amplitude distributions for J1514−59, J1554−52 and J1841−14, the three sources discussed here with the highest number of detected pulses. These distributions are found not to be consistent with a power-law distribution but instead are well fitted by lognormal distributions, the parameters of which are given in Table 6. The best-fitting curves are overplotted on the observed distributions in Fig. 6. For these three sources, there is a low-flux density turnover. It is not clear whether this is an intrinsic turnover or simply due to the sensitivity threshold. The flux density threshold for a single pulse depends on the pulse width. Plugging in the known observing parameters for Parkes into the radiometer equation gives a single-pulse peak flux of $S_{\text{peak}} \approx 245 \, \text{mJy (w/ms)}^{-1/2}$; assuming a 5σ detection threshold. Although the widths of the pulses vary from pulse to pulse, we can take the average widths from Table 2 to get sensitivity estimates of 135, 250 and 150 mJy for J1514−59, J1554−52 and J1841−14, respectively. If the turnovers were intrinsic to the sources then it would suggest that we are not just seeing the brightest pulses from a continuously emitting source but rather that we are seeing most pulses which are emitted. If this is the case, the bursty behaviour is indeed due to the lack of continuous emission and an innate property of the sources. For the remaining sources, the number of pulses detected is as yet still too low for such an analysis. Continued observations will allow accurate determination of amplitude distributions of all the sources as more observations are made.

### 4.3 The emerging RRAT population

We note that the scope of any definition can and should be wary of those radio pulsars which are sufficiently weak and/or distant not to be detected by periodicity searches. Such sources are automatically accounted for by the predicted Galactic pulsar population. For instance, there are estimated to be $\sim 150\,000$ radio pulsars in our Galaxy with a radio luminosity $L = SD^2 > 0.1 \, \text{mJy kpc}^2$ (Lorimer et al. 2006), or $\sim 100\,000$ with $L > 1.0 \, \text{mJy kpc}^2$ (Vrbanec et al. 2004). These estimates are arrived at from accounting for known observational selection effects of surveys and extrapolating from the observed properties of pulsars (e.g., the observed luminosity distribution and empirical beaming models). However, we note that if the population of RRATs is indeed a factor of a few times larger than that of the radio pulsars not all RRATs can be accounted for as weak and/or distant pulsars. With the addition of these new

<table>
<thead>
<tr>
<th>Source</th>
<th>$g$</th>
<th>$D$ (kpc)</th>
<th>$g = 1$ distances (kpc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1047−58</td>
<td>0.0021(1/476)</td>
<td>2.3</td>
<td>(α = 1.5) 0.01</td>
</tr>
<tr>
<td>J1423−56</td>
<td>0.0014(1/714)</td>
<td>1.3</td>
<td>(α = 2) 0.12</td>
</tr>
<tr>
<td>J1514−59</td>
<td>0.0058(1/172)</td>
<td>3.1</td>
<td>(α = 3) 0.50</td>
</tr>
<tr>
<td>J1554−52</td>
<td>0.0016(1/625)</td>
<td>4.5</td>
<td>(α = 4) 0.83</td>
</tr>
<tr>
<td>J1703−38</td>
<td>0.0137(1/73)</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>J1707−44</td>
<td>0.0013(1/769)</td>
<td>5.7</td>
<td></td>
</tr>
<tr>
<td>J1724−35</td>
<td>0.0013(1/769)</td>
<td>5.7</td>
<td></td>
</tr>
<tr>
<td>J1727−29</td>
<td>0.0048(1/208)</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>J1807−25</td>
<td>0.00845(1/11.8)</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>J1841−14</td>
<td>0.0018(1/85)</td>
<td>5.3</td>
<td></td>
</tr>
</tbody>
</table>

To determine $g$, the period must be known as $g$ is the average number of pulses per period, or $g = (3600 / P) / h$. The radio luminosity $L$ has units of $\text{Jy.kpc}^2$ or equivalently $\text{W.Hz}^{-1}$.
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PMPS RRAT sources, there are now 22 confirmed RRAT sources in the survey. There are a further six single-pulse sources in the literature recently reported by Deneva et al. (2009; although some of these are detectable in FFT searches also) and one source discovered in the GBT350 survey (Hessels et al. 2007). Of these 29 currently known sources, 27 have determined periods and seven (of the original 11) sources now have known period derivatives (McLaughlin et al. 2009). The initial RRAT population estimate suggested that there were approximately four times as many RRATs as pulsars (McLaughlin et al. 2006). We defer a complete population analysis until we have investigated all of our best candidates but we can already comment on some of the selection effects impacting upon this estimate. These include the RRAT beaming fraction, their observed on-off fraction and the fraction missed due to contaminating RFI:

(a) with no reliable information on a beaming model for RRATs, we continue to use the empirical pulsar beaming model, \( f_{\text{beam}}(P) = 0.09[\log(P/s) - 1]^2 + 0.03 \), of Tauris & Manchester (1998). Still, it remains to be seen what the actual RRAT beaming model might be or whether this beaming model even still applies for pulsars with long periods. The latter is highlighted by the recent discovery of a slow pulsar with an extremely narrow pulse by Keith et al. (2008). If beaming fractions were in fact overestimated, the projected populations of both pulsars and RRATs may be much larger. (b) The assumed averaged on-off fraction during a PMPS observation was taken to be 1/2, i.e. half of the RRATs that exist were assumed not to emit pulses during the 35 min observation which was consistent with the observed burst rates at the time. With the discovery and continued monitoring of a growing population of known RRATs, it will be possible to determine the true burst rate distribution and thus to improve this value in population estimates. (c) The factor used to compensate for those sources missed due to the presence of RFI was quite uncertain and taken to be 0.5. Taking into consideration the pointings with strong residual RFI and the fraction of sources removed by zero-DM in the light of the PMSingle analysis, the number of beams still affected by RFI is \((41561 - 693)0.016 + 693\) which is \(\sim 3\) per cent of all beams, so that 97 per cent are now cleaned of RFI. We have doubled the number of known RRATs while simultaneously reducing the fraction missed by RFI to almost zero. The inferred population estimate is thus related to the initial estimate by a factor of \((97/50)\)/2 \(\approx 1\) so that the confirmed number of new sources is consistent with the original population estimate (McLaughlin et al. 2006). However, if even a small fraction of the large number of other candidates are confirmed as new RRATs, the initial population estimate will need to be revised upwards so that the number of transient radio-emitting neutron stars in the Galaxy is even larger than initially thought. Of course, with the continued monitoring and thus characterization of more sources, we can also improve our knowledge of the other selection effects.

Assuming the population of RRATs is indeed much larger than that of the normal radio pulsars, the neutron star birthrate problem remains. In addition to pulsars and RRATs, there are the INSs, magnetars, neutron stars in accreting binary systems and the Central Compact Objects (of which some are thought to be neutron stars, e.g. see de Luca 2008). Kondratiev et al. (2009) suggest that more than 30 new INS sources need to be discovered before unfavourable beaming can be ruled out, i.e., that these sources are pulsars and/or RRATs whose beams do not cross our line of sight. Recently, several tens of new INS candidates have been identified (Pires, Motch & Janot-Pacheco 2009) so that progress may come in this area despite the difficulty in finding such sources (Posselt et al. 2008). Besides pulsars, many more sources are needed for the other classes to

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**Figure 6.** Amplitude distributions for (top panel) J1514–59, (middle panel) J1554–52 and (bottom panel) J1841–14.

**Table 6.** The best-fitting parameters to the amplitude distributions in Fig. 6 for a lognormal probability density distribution of the form \( P(x) = (a/x)\exp[-(\log x - b)^2/c] \). The parameter a is an arbitrary scaling factor and the values given here correspond to the scales used in Fig. 6.

<table>
<thead>
<tr>
<th>Source</th>
<th>a</th>
<th>b</th>
<th>c</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1514–14</td>
<td>7613(748)</td>
<td>5.57(0.03)</td>
<td>0.47(0.03)</td>
</tr>
<tr>
<td>J1554–52</td>
<td>15662(1182)</td>
<td>6.13(0.03)</td>
<td>0.53(0.03)</td>
</tr>
<tr>
<td>J1841–14</td>
<td>16130(1704)</td>
<td>5.86(0.04)</td>
<td>0.53(0.04)</td>
</tr>
</tbody>
</table>

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reach a conclusive answer as to the links (if any) between these populations.

5 CONCLUSIONS

We have presented an overview of the steps involved in performing searches for sources showing single pulses of radio emission. These have enabled us to discover 11 new PMPS sources from which between two and 231 pulses have been detected. Underlying periodicities for these sources lie in the range of 125 ms up to 6.6 s. These join the original 11 RRAT sources identified previously in the survey. We have reduced the uncertainties with regard to the number of sources missed due to the contaminating effects of RFI. The projected population of these sources still appears to be larger than the regular radio pulsars. However, we are yet to determine the burst rate and beaming distributions for the RRATs – key ingredients in a complete population synthesis. These characteristics will be determined with continued monitoring of the new sources and followup investigations of the other promising candidates (of which there are now more than 100). It seems also that there will be many candidates for whom it will be impractical or impossible to follow up at present with current observing facilities. These will require followup with instruments like LOFAR, FAST or the SKA. We note that these instruments will produce extraordinarily large volumes of data so that searching for transient RRAT-like sources will necessitate the development of automated algorithms which will use the steps as outlined above.

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REFERENCES

McLaughlin M. A. et al., 2006, Nat, 439, 817

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