18 GBNCC DISCOVERIES: PROBING THE RECYCLED PULSAR POPULATION

The Green Bank North Celestial Cap Survey (GBNCC) aims to survey the whole sky for pulsars to higher sensitivity than ever done before, with a strong motivation being the discovery of new stable millisecond pulsars (MSPs) suitable for pulsar timing arrays (PTAs). The survey began in 2009 and is now $\sim 70\%$ complete in covering the entire celestial sphere at declinations, $\delta \geq -40°$. The GBNCC survey is currently the most successful low frequency (< 1 GHz) pulsar survey to date (see ATNF pulsar catalog[1]; Manchester et al. 2005, AJ, 129, 1993), having discovered 145 pulsars and detected 256 more previously-known sources. The raw number of GBNCC detections (401) is surpassed only by completed 1400 MHz surveys using the Parkes Radio Telescope – the Parkes Multibeam Pulsar survey (1122; Manchester et al. 2001, MNRAS, 328, 17) and the southern High Time Resolution Universe survey (996; Keith et al. 2010, MNRAS, 409, 619), both of which probe the more densely-populated Galactic plane. The GBNCC survey is sensitive to more diffusely-populated regions of the sky, away from the Galactic plane; therefore we find a higher proportion of nearby, interesting recycled pulsars (Stovall et al. 2014, ApJ, 791, 67).[2] Increasing the overall number of known pulsars improves our understanding of their spatial distribution in the Galaxy, birthrate, period, spectral index and luminosity distributions of the pulsar population through statistical analysis (e.g. Lorimer et al. 2006, MNRAS, 372, 777; Faucher-Giguère & Kaspi 2006, ApJ, 643, 332; Lorimer et al. 2015, MNRAS, 450, 2185). In order to realize the full scientific potential of newly-discovered pulsars however, timing follow-up observations are essential to produce phase connected timing solutions.

Phase connection over ≥ 1 yr yields precise spin period (P) and spindown ($\dot{P}$) measurements, milliarcsecond-precision pulsar positions (otherwise covariant with $\dot{P}$ on timescales < 1 yr), constraints on parallax and proper motion and binary parameters (Lorimer & Kramer 2004). All of these parameters are important for informing population models as described above; their distribution provides a snapshot of the full scope of pulsars' evolutionary possibilities, from birth to death. While pulsar timing provides this underlying context for expected sets of parameters, it is also the only way to reveal exotic systems that test our understanding of pulsars and fundamental physics.

We request a total of 46 hours over the course of a year to conduct initial phase connection observations of 18 recycled pulsars discovered in the GBNCC survey, followed by monthly timing observations. These pulsars – most of them MSPs and double neutron star (DNS) candidates – are the most interesting results of this survey, and justify intensive follow-up observations.

Scientific Justification

The known pulsar population is made up of $\sim 90\%$ normal pulsars with spin periods (P) between $0.2 - 10$ s, the majority of which are solitary. Normal pulsars slowly spin down over their lifetimes (typically 10 Myr$-$1 Gyr) before reaching the "death line" (Bhattacharya et al. 1992, A&A, 254, 198), at which point they no longer produce coherent, observable radio emission (e.g. Sturrock 1971, ApJ, 164, 529; Ruderman & Sutherland 1975, ApJ, 196, 51). In some cases, a pulsar can accrete material from a binary companion evolving at the end of its main sequence life, and get spun up via a process called *recycling* (Alpar et al. 1982, Nature, 300, 728) to resume radio emission. Recycled pulsars, of which there are only ~250 known (ATNF catalog), are characterized by their short spin periods ($P \lesssim 200$ ms) and small period derivatives ($\dot{P} \lesssim 10^{-17}$ s / s) compared to normal pulsars. Since the recycling process relies on a pulsar's interaction with a binary companion, the spin period and binary system parameters (if the system remains bound) provide significant information about the nature of that interaction. However, the exceptions from this paradigm often prove to be equally interesting and provide extra insight into the formation process. For example, PSR J1434+7257 is isolated and based on its spin period ($P = 42$ ms; see Table 1) and period derivative ($\dot{P} = 5.5 \times 10^{-19}$; Stovall et al. 2014, ApJ, 791, 67), partially recycled. Its companion was massive enough to undergo a supernova explosion at the end of its main sequence lifetime, disrupting the binary system and abruptly ending the recycling process. Therefore J1434+7257 is an example of a disrupted recycled pulsar (DRP; e.g. Lorimer et al. 2004, MNRAS, 347, L21) and continued timing will yield a proper motion measurement, which is necessary for studying the velocity distribution of isolated recycled pulsars compared to their binary counterparts.

[1] http://www.atnf.csiro.au/research/pulsar/psrcat

[2] An up-to-date list of discoveries can be found at: http://astro.phys.wvu.edu/GBNCC/.

PSR J-Name	P (ms)	DM (pc cm^{-3})	Est. S_{350} (mJy)	$P_{\rm b}$ (days)	$a \sin i$ (lt-s)	$m_{\rm c,min}$ (M$_\odot$)	Likely Class.	Timing Solution?	FWHM Position Uncertainty
J0034+69	37	80	4.2	528	179	0.41	?	Yes	($\sim$arcsec)
J0125−23	3.7	9.6	5.4	7.3	4.7	0.17	MSP	Prelim.	$36'$
J0214+5222	25	22	2.3	512	174	0.41	?	Yes	(sub-arcsec)
J0509+3801	76	69	3.5	0.38	2.0	0.61	DNS	Yes	(sub-arcsec)
J1017−15	83	17	3.6	8.98	20.95	0.84	DNS	No	$36'$
J1045−04	24	4.8	5.4	10.3	22.5	0.82	DNS	No	$2'$
J1122−35	7.8	39	1.7	—	—	—	MSP	No	$\sim 5'$
J1154−19	11	11	3.3	?	?	?	MSP	No	$36'$
J1239+32	4.7	17	3.3	4.1	2.4	0.12	MSP	No	$36'$
J1308−23	2.8	22	5.3	0.15	0.0017	0.008	MSP*	Prelim.	($\sim$arcsec)
J1434+7257	42	12	1.3	—	—	—	DRP	Yes	(sub-arcsec)
J1517−32	64	25	4.6	4	1.1	0.05	?	No	$36'$
J1649+80	2.0	31	1.1	0.091	0.064	0.04	MSP*	Yes	(sub-arcsec)
J1806+28	15	19	4.6	44	22	0.24	MSP	Prelim.	(sub-arcsec)
J1940−24	98	53	1.5	0.27	0.15	0.05	?	No	$36'$
J2022+25	2.6	54	2.0	1.3	0.61	0.07	MSP	No	$10'$
J2038−36	3.3	24	3.7	5.8	3.4	0.14	MSP	No	$15'$
J2150−03	3.5	21	13.3	4.0	3.3	0.18	MSP	Prelim.	(sub-arcsec)

Table 1: Summary of sources included in this proposal with pertinent discovery parameters, estimated 350 MHz fluxes and binary parameters from preliminary analysis. With spin period and $m_{\rm c,min}$, we can infer likely classifications for recycled pulsars included: millisecond pulsars (MSP; asterisks (*) denote black widow systems), double neutron star (DNS) systems and disrupted recycled pulsars (DRP).

Based on discovery parameters and in some cases, preliminary binary solutions, we have determined likely classifications for most sources included in this proposal (see Table 1) and in the following sections, describe how the proposed observations will help improve our understanding of these sources, binary evolution, General Relativity (GR) and the recycled pulsar population.

1. Millisecond Pulsars (MSPs) typically accrete matter from low-mass companions during their recycling phase and attain especially short spin periods because these systems are rarely disrupted. For the same reason, MSPs are usually found in binary systems with low-mass white dwarf (WD) companions. PSR J1122−35 is a notable exception – it has a 7.8 ms spin period, but shows no initial signs of acceleration due to orbital motion.

Many other MSPs included in this proposal show promise for future inclusion in PTAs since they are bright, have narrow profiles and relatively short spin periods (see Table 1). An array of high-precision MSPs distributed across the sky is sensitive to a stochastic gravitational wave (GW) background in the nanohertz regime (e.g. Jenet et al. 2006, ApJ, 653, 1571). Such a background signal would likely be generated by coalescing super-massive black holes (e.g. Jaffe & Backer 2003, ApJ, 583, 616; Wyithe & Loeb 2003, ApJ, 590, 691), by relic cosmological GWs, or by cosmic strings (e.g. Maggiore 2000, Phys Rep, 331, 283) and detections of (or even upper limits on) such a background will significantly constrain the super-massive black hole merger rate at high redshift, the expansion rate of the Universe in the inflationary epoch and the existence of cosmic strings (Jenet et al. 2006). To this end, five new discoveries (PSRs J0125−23, J1239+32, J2022+25, J2038−36 and J2150−03)[3] are particularly interesting PTA candidates and three additional GBNCC MSPs (PSRs J1308−23, J1649+80 and J1806+28) have also been included to assess their long-term stability. Proposed observations will allow us to measure binary parameters, find coherent timing solutions and evaluate the potential for these sources as high-precision timers.

The best MSPs have root-mean-square (RMS) residuals of < 100 ns, but anything below 1 μs is useful. Achieving

[3] NANOGrav test observations for J0125−23 and J2150−03 will take place this fall; if they are added, we will drop them from this timing program and adjust the time request accordingly.

such small residuals requires two complementary properties: a bright, sharp pulse with a short spin period to minimize uncertainty on a single time-of-arrival (TOA) measurement; and a stable spin evolution. The first can be assessed quickly for newly-discovered MSPs using a few observations at frequencies $\gtrsim 1\,\mathrm{GHz}$ where most timing is done, while the second requires months to years of followup to check for long timescale timing noise. The North American Nanohertz Observatory for Gravitational Waves (NANOGrav) PTA conducts observations over multiple frequency bands in order to track variations in MSP dispersion measures (DMs)—due to changes in the integrated electron density along the line of sight, pulsar DMs change over time. Since DMs are used to correct for predictable delays in TOAs at different observing frequencies, high-precision timing requires measurements of ΔDM at each epoch (Lam et al. 2016, ApJ, 821, 66). Therefore, it is also important that PTA MSPs be easily detectable at multiple frequencies. For all of these reasons, we request 820 MHz rather than 350 MHz follow-up timing observations to best assess the suitability of these MSPs for PTAs. Observations at 820 MHz will also give concrete information about detectability at higher frequencies (rather than extrapolating from 350 MHz fluxes using assumed spectral indices).

In addition to improving our chances of detecting low-frequency gravitational waves with PTAs, MSPs have improved our understanding of GR (Kramer et al., 2006, Science, 314, 97), pulsar emission (e.g. Kramer et al. 1998, ApJ, 501, 270), binary evolution (Champion et al., 2008, Science, 320, 1309), and the equation of state for supranuclear material (e.g. Demorest et al. 2010, Nature, 467, 1081). Given the proximity of several MSPs included in this proposal and their projected timing precision, we expect to detect proper motion and in some cases, timing parallax. PSR J1154−19, for example, has a DM distance of 120 pc (Yao et al. 2017, ApJ, 835, 29; YMW16) and an expected timing parallax amplitude of 18.5 μs, which should be easily detectable given its spin period. At this distance, J1154−19 would be the closest binary pulsar known to date. Timing parallax may also be detectable for MSPs J1308−23, J2038−36 and J2150−03 (provided we can achieve RMS residuals $< 1\ \mu$s necessary for PTA sources) and J1045−04, a likely DNS described in the following section.

2. Recycled Pulsars with High-Mass Companions are thought to be disrupted ~90% of the time (Bailes 1989, ApJ, 342, 917) when the companion goes supernova (see previous discussion of J1434+7257, a likely DRP); otherwise, a bound DNS system remains (no NS-black hole systems have yet been observed). Like most other DNS systems, J0509+3801 is in a highly eccentric, relativistic orbit. The high eccentricity is thought to be signature of the natal kick that the companion neutron star (NS) received in the supernova that formed it. Although we already have TOAs spanning four years and have preliminary measurements for two post-Keplerian (PK) parameters (the advance of periastron, $\dot{\omega}$, and relativistic time dilation and redshift, γ), we expect to measure orbital period decay ($\dot{P}_{\rm b}$) with another year of timing. Together, all of these parameters provide independent constraints on the NS masses and one test of GR. Although the timing precision of J0509+3801 ($\sim 100\mu$s) is not adequate for measuring timing-based parallax, we recently completed VLBI follow-up on this system (15A-433; P.I. Deller), where preliminary astrometric results give parallax, $\varpi = 0.30^{+0.06}_{-0.07}$ mas ($d = 3.3^{+1.0}_{-0.6}$ kpc), proper motion, $\mu_\alpha = 2.84^{+0.12}_{-0.10}$ mas/yr and $\mu_\delta = -5.9^{+0.6}_{-0.2}$ mas/yr and therefore, transverse velocity, $v_{\rm T} = 100 \pm 17$ km/s. Of the four other DNS systems with measured proper motions, three have derived transverse velocities $v_{\rm T} < 75$ km/s, and a fourth has $v_{\rm T} \sim 120$ km/s. Our independent distance measurement for J0509+3801 is important, not only because it enters into the Shklovskii effect (Shklovskii 1970, Soviet Astronomy, 13, 562), affecting our measurement of the pulsar's intrinsic $\dot{P}$, but because $\dot{P}_{\rm b}$ is also affected by acceleration within the Galaxy. An accurate distance is essential for modeling the Galactic acceleration at the position of the pulsar (e.g., uncertainties in the distance and Galactic parameters now dominate the error in the GR test of B1913+16; Weisberg et al. 2010, ApJ, 722, 1030).

Also included in this proposal are recent GBNCC discoveries, PSRs J1045−04 and J1017−15, which have spin periods of 24 ms and 83 ms respectively – implying that they have been partially recycled – and orbital solutions that show they both have minimum companion masses of ~ 0.8 $\mathrm{M}_\odot$ (see Table 1). Although we have not yet fully solved their orbits, preliminary results show that they have high eccentricities, $e > 0.1$, suggesting that both are excellent DNS candidates. Phase connection and a year of timing follow-up will allow us to test our hypothesis that J1045−04 and J1017−15 are indeed recycled, fully solve their orbits and possibly measure one or more PK parameters. Using the YMW16 electron density model, we find DM-derived distances for J1045−04 and J1017−15 of 0.3 and 1.0 kpc, respectively. Their proximity will prove extremely useful for continued timing follow-up in an effort to measure proper motion and parallax (J1045−04 has an expected timing parallax amplitude of $A_{\rm PX} \sim 8\mu$s!). As noted earlier for J0509+3801, these astrometric parameters must be taken into account in order to properly constrain $\dot{P}$ and $\dot{P}_{\rm b}$.

3. Unusual Binaries: Four pulsars in Table 1 remain unclassified because their spin and orbital parameters do not obviously place them in any of the most common binary scenarios already described. PSRs J0034+69 and J0214+5222 are both partially recycled with $20\ {\rm ms} < P < 40$ ms, but have uncharacteristically long orbital periods (> 500 days).[4] Both companions have $m_{\rm c,min} \sim 0.4\ {\rm M}_\odot$ and lie directly on theoretical $P_{\rm b} - M_{\rm WD}$ curves (Tauris & Savonije 1999, A&A, 350, 928), assuming $M_{\rm WD} \simeq m_{\rm c,min}$. If this assumption is correct, the systems are highly inclined with respect to our line of sight, but given their intermediate spin periods, neither is fully recycled, so the validity of assuming evolutionary paths like those of He-core WDs (Tauris et al. 2012, MNRAS, 425, 1601) is not clear. Continued timing campaigns for both of these systems are essential for further constraining orbital parameters (due to the long timescale of $P_{\rm b}$) and extending existing timing solutions will provide proper motion measurements, estimates of space velocities and possibly, additional tests of the strong equivalence principle (e.g. Gonzalez et al. 2011, ApJ, 743, 102).

Finally, J1517−32 and J1940−24 have parameters consistent with other DNS systems, but $m_{\rm c,min}$ values derived from preliminary orbital solutions do not provide any useful constraints on possible companion types (WD/NS). If these pulsars do have NS companions, they are nearly face-on with respect to our line of sight. We will be able to better characterize these systems with phase connection observations and continued timing sessions to measure orbital eccentricity and possibly, one or more PK parameters.

Proposed Observations

All 18 pulsars described above were discovered at 350 MHz (the GBT beam has FWHM $\sim 36'$), so higher frequency observing requires improved localization since the 820 MHz GBT beam is smaller, only about $15'$. We have already localized 12 of these sources with previous pulsar timing campaigns, preliminary timing solutions or gridding sessions with the Green Bank Telescope, Arecibo Observatory or LOFAR. In an effort to reduce our time request in this proposal, we will carry out dedicated localization observations for the remaining six pulsars included here using LOFAR, the Giant Metrewave Radio Telescope (GMRT) and Ooty Radio Telescope (ORT). None of these other telescopes offer adequate sensitivity and declination coverage to observe the included sources, however; nor do they provide RFI environments as clean as the GBT's at 820 MHz.

NANOGrav currently monitors 24 MSPs with the GBT at 820 MHz and 1.5 GHz (other MSPs are monitored with Arecibo). Observations at these higher frequencies yield sharper profile features and thus improved timing precision over that attainable at 350 MHz, despite the fact that most pulsars are brighter at lower frequencies. Higher-precision timing at higher frequencies is attainable for several reasons: (1) The sky temperature $T_{\rm sky}$ is significantly reduced ($T_{\rm sky} \propto \nu^{-2.5}$; Haslam et al. 1981, A&A, 100, 209), as is the ratio of $T_{\rm sky}$ to receiver temperature, resulting in lower system temperatures and thus less noise in the profile; (2) scattering, which broadens profile features, decreases significantly, since the scattering timescale, $\tau_s \propto \nu^{-4}$; (3) at the GBT, RFI occupies a smaller fractional bandwidth at 820 MHz and 1.5 GHz than it does at 350 MHz.

For all of these reasons (and those detailed in §1), we request follow-up timing observations be conducted with the 820 MHz prime focus receiver and Green Bank Ultimate Pulsar Processing Instrument (GUPPI) backend, with 200 MHz of bandwidth. For sources with existing timing solutions, we will observe in coherent fold mode, otherwise we will use incoherent search mode (2048 frequency channels).

Nine sources in this proposal are new discoveries and do not yet have phase connected timing solutions (see Table 1). Therefore, we split these sources into two groups and for each group, request 4×1.25 hr phase connection observations with 1–3 day separation. Phase connection sessions should take place over a ∼10 day period and the first regular timing observations should follow 1–2 weeks later. For regular timing, we have divided the full list of 18 sources into two groups and for each group, request 12×1.5 hr monitoring observations at ∼monthly cadence over a full year (individual observations can be spaced by anywhere between 3–6 weeks). For both phase connection and regular monitoring programs, we factor in 30 mins set-up/slew time and ∼6–7 mins integration time per source to determine our time request. **In total, we request 46 hours with the 820 MHz PF receiver to conduct follow-up timing observations for the 18 GBNCC discoveries discussed above.**

[4]These pulsars are good examples of why timing follow-up is crucial for *all* new discoveries; only after extended timing campaigns were we able to identify that both were in long-period binary systems.