15 New Nulling Pulsars from the GBNCC Survey

Introduction

Pulsar surveys to date have found ∼2,500 pulsars,[1] most of which move across the $P - \dot{P}$ diagram and turn off in $\sim 10^7$ yr. Just how and why pulsars turn off is still a subject of intense scrutiny, with ongoing observational and theoretical investigations (see references that follow). Nulling pulsars – pulsars whose radio emission ceases for one or more rotations – offer an invaluable population to study pulsar emission mechanisms and magnetospheres. Pulsar nulling was discovered in 1970 (only 3 years after pulsars themselves were discovered) but is still poorly understood. The meaning of null durations, the intervals between them, and an explanation behind their underlying mechanisms have been matters of debate ever since this behavior was first recognized. However, while data-collection capabilities, processing techniques, and theories explaining pulsar nulling have become more sophisticated, we are still in a regime where increasing the sample size of nullers has a significant impact on our understanding. We propose observations meant to further increase the sample size and systematically characterize the nulling behavior of 15 new pulsars found in the Green Bank North Celestial Cap (GBNCC) survey (e.g. Stovall et al. 2014, ApJ, 791, 67). The GBNCC pulsar survey is unbiased (searching the entire sky available to the GBT, at declinations, $\delta > -40°$), relatively complete (∼80% of the sky has been observed and processed to date), and high yield, with 160 discoveries so far. Of these discoveries, 15 exhibit strong nulling behavior and have been included as sources in this pilot study. An additional 10 discoveries appear to be marginal nulling pulsar candidates, but we have reserved these and other pulsars discovered in GBNCC survey observations for future studies.

The pulsars included in this proposal have periods between 0.5−6.8 seconds; six have full, coherent timing solutions to be included in Lynch et al. (in prep.), and nine more were included in this proposal as strong nulling candidates, evidenced by intensity variations in their discovery plots. Long, continuous scans are necessary to accurately measure each pulsar's nulling fraction and timescale and full-polarization data will provide additional information in order to properly account for profile morphology – all of these pieces are necessary to effectively compare our results to previous studies. **In total, we request 31.5 hours to conduct these observations.**

Pulsar Nulling

The nulling phenomenon was initially claimed to be a periodic mechanism intrinsic to the pulsar (Backer 1970, Nature, 228, 42). However, although it still appears tied to individual sources it is now recognized as a more stochastic process. In the first comprehensive study of nulling pulsars, it was originally thought that as a pulsar ages, the time interval between regular bursts of pulsed emission increases, eventually leading to "death," when the interval between these bursts become much greater than the duration of the bursts themselves (Ritchings 1976, MNRAS, 176, 249). Rankin (1986, ApJ, 301, 901) went on to suggest that nulling is a common behavior exhibited by all pulsars and that roughly half of the population should be nulling. Drawing on her previous work classifying pulsar profile morphology (Rankin 1983, 274, 333) and in contrast to previous claims by Ritchings (1976), Rankin (1986) found little evidence for increased nulling with pulsar age; rather, she suggested nulling to be related to profile classification (exhibited by pulsars with conal single, double, triple, and multiple profiles, but not core single profiles) which may be tied to magnetic field geometry.

A later study suggested that the null fraction (NF; the amount of time that a pulsar spends in a null state) was more strongly correlated with pulse period, implying that nulling could be caused by a faltering emission mechanism (Biggs 1992, ApJ, 394, 574). Biggs further deduced that nulling behavior appears to be related to profile morphology – that is, pulsars with the same Rankin classifications tended to exhibit similar nulling characteristics. Working with a larger sample size, Wang et al. (2007, MNRAS, 377, 1383) found the strongest correlation between NF and characteristic age, not pulse period. Wang et al. (2007) did not find a strong correlation of NF with profile morphology (e.g. Rankin 1986), but the authors made no apparent distinction between conal/core single profiles in that study. More recent results suggest that both nulling and profile mode changes are most likely a global reorganization of a pulsar's magnetosphere (Gajjar et al. 2012, MNRAS, 424, 1197), implying a greater correlation to Rankin's profile classifications than to characteristic age, or pulse period.

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

Project Goals

The number of known nulling pulsars is currently about 136 (see e.g. Biggs 1992, Wang et al. 2007, Gajjar 2017) — only about 5% of the total pulsar population — which makes drawing larger conclusions difficult. However, recent additions to the population, along with improved methods of data-collection and data-analysis, has allowed astronomers to dig deeper into the nulling phenomenon. Previous studies have been conducted (Backer 1970; Ritchings 1976; Rankin 1983, ApJ, 274, 333, Rankin 1986; Biggs 1992; Wang et al. 2007; Gajjar et al. 2012) in an attempt to find correlations between nulling and pulse period, characteristic age, profile morphology (Rankin classification), mode changing, etc. These studies have not converged on a definitive or consistent correlation that provides a satisfactory explanation of the nulling process. The proposed sample for this study represents a wide variety of ages, periods, and (preliminary) nulling fractions. Adding 15 new nulling pulsars increases the known population of this subset of pulsars by $\sim$10%, providing additional opportunities to calculate nulling fraction, classify profile morphology, and discover possible correlations with other pulsar characteristics.

We have already conducted a preliminary analysis of six pulsars included in this proposal as part of a larger project, establishing coherent timing solutions for 45 GBNCC discoveries (Lynch et al., in prep.). Following a procedure similar to that described in the literature (e.g. Ritchings 1976), we used existing 820 MHz GBT timing data to analyze single pulse behavior for six pulsars included here (see Figure 1) to calculate preliminary nulling fractions (see Table 1) and compare with previous studies – all of the preliminary nulling fractions shown here are relatively high compared to the rest of the population, making these sources potentially interesting.

Previous studies (e.g. Wang et al. 2007) summed consecutive pulses due to poor sensitivity to single pulse emission on short timescales, and were therefore relatively insensitive to short nulls. Due to the high instantaneous sensitivity of the GBT, we expect to record single pulses, making our two-hour scans more sensitive to short-duration nulling episodes, and better able to measure low nulling fractions. Extended observing time also allows for better probability of detection and more accurate nulling time-scale analysis for high null fraction sources. Furthermore, two hours per source enables us to properly disentangle nulling behavior from interstellar scintillation (Table 1 shows that all pulsars included in this proposal have significantly shorter scintillation timescales, $\tau_{\rm s} \lesssim 10$ minutes), and potentially detect any mode-changing, or sub-pulse drifting.

With the proposed observations, we hope to:

- Measure the nulling fractions with uncertainties for all pulsars in the sample,
- Complete a nulling timescale analysis for each pulsar by computing the autocorrelation function,
- Record full-polarization data for each pulsar and model the geometry of its magnetosphere by applying the rotating vector model, then properly classify the profile using the Rankin classification scheme,
- Record any potential mode-changing or sub-pulse drifting behavior.

Finally, we have also been exploring the use of Gaussian Mixture Modeling in studying nulling pulsars (see also Arjunwadkar et al. 2014). This provides a superior statistical framework that allows more robust determination of nulling fractions and can help study situations with multiple pulse distributions (i.e., not just nulling and pulsing) and can be extended to non-Gaussian distributions. See Figure 2 for an example applied to PSR J0323+6742. Preliminary results are largely consistent with previous techniques; for J0323+6742, our Gaussian Mixture Modeling technique finds a nulling fraction of 0.51, compared to 0.55 found with the technique described by Ritchings 1976 (see Table 1).

Proposed Observations

All 15 pulsars described above were discovered at 350 MHz (the GBT beam has FWHM $\sim 36'$), so higher frequency (e.g. 820 MHz) observing normally requires further localization since the 820 MHz GBT beam is smaller – FWHM $\sim 15'$. For pulsars included in this proposal that lack full timing solutions (and therefore sub-arcsecond localization), we have already collected/analyzed data with the Low Frequency Array (LOFAR) telescope in order to improve positions to within $2'$ uncertainty regions (well within the 820 MHz beam).

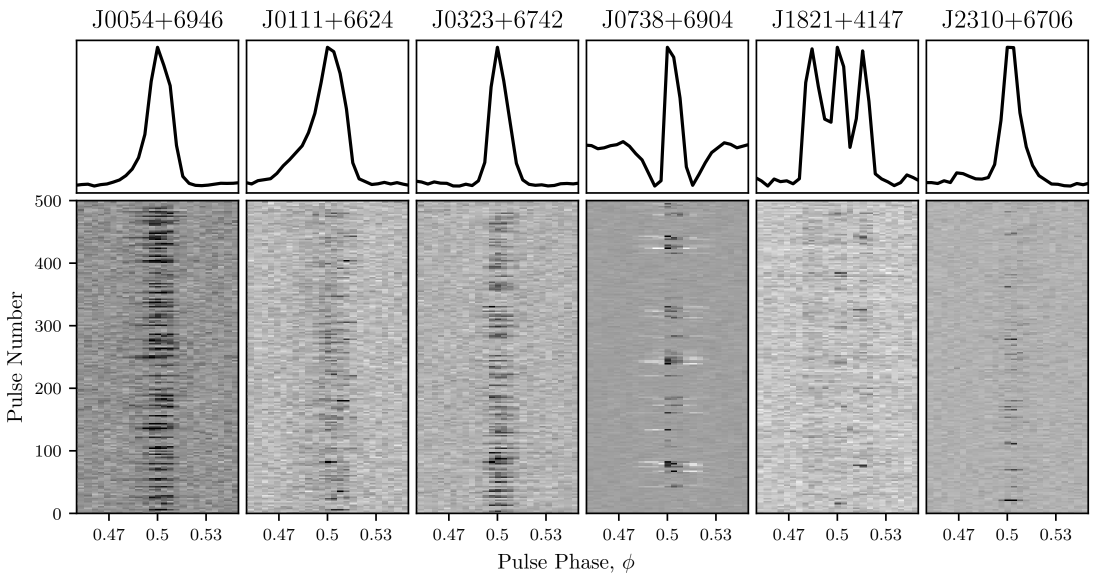

Figure 1: Preliminary single pulse analysis for six GBNCC nulling pulsars with existing timing solutions. For each source, 500 pulses are plotted in the bottom panels to show nulling behavior; folded profiles are shown in the top panels, corresponding to the same duration of pulse phase ($0.45 < \phi < 0.55$).

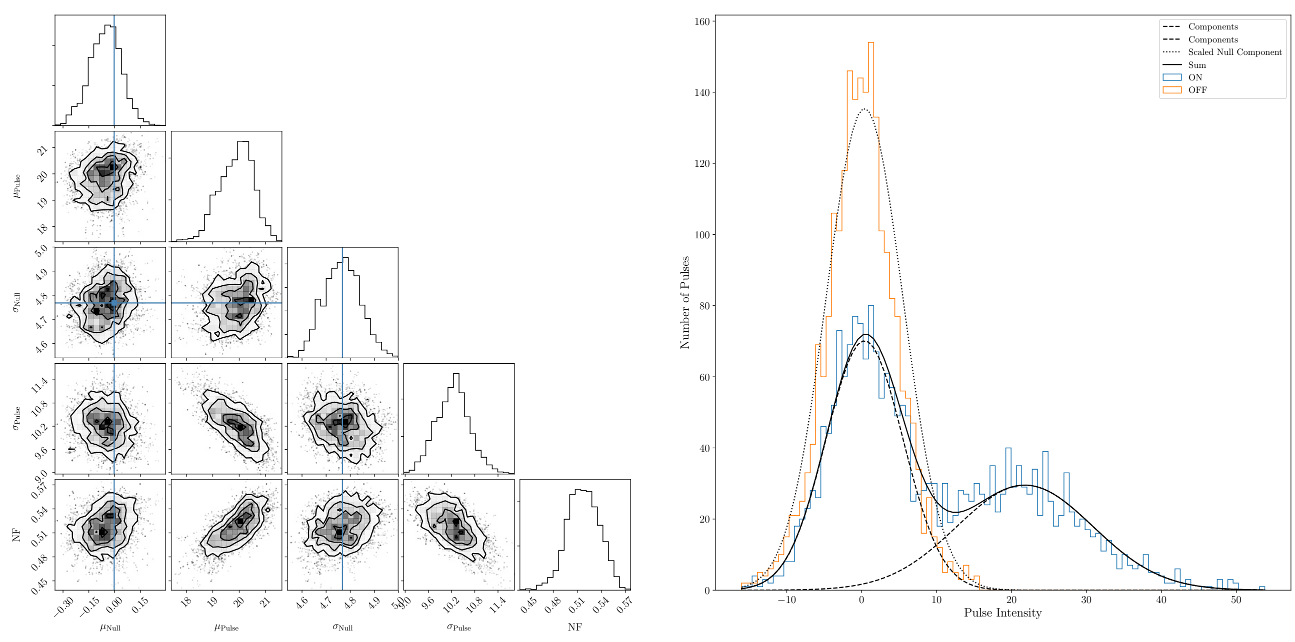

Figure 2: *Left:* Results of Markov-Chain Monte Carlo (MCMC) fit for a Gaussian Mixture Model to the pulse intensity distribution of PSR J0323+6742. In this case the best-fit model had two components as evaluated with a Bayes information criterion – pulse and null – although we explored up to 5 components. The corner plot shows the posterior distributions of the mean and standard deviation for the null and pulse along with the best-fit nulling fraction NF. *Right:* The blue horizontal/vertical lines are the parameters of the off-pulse region, which were used to set priors for the null distribution. The histograms show the measured on- (blue) and off-pulse (orange) intensities, along with the best-fit mixture. The individual components are the dashed lines, and the sum is the solid line. The dotted line is the inferred off-pulse distribution determined from the null scaled up by the nulling fraction: it is not a fit to the off-pulse data.

PSR J-Name	P (ms)	DM (pc cm^{-3})	$\dot{P}$ (10^{-15} s/s)	Age (Myr)	$\tau_{\rm s}$ (s)	Nulling Fraction	Profile Classification
J0054+6946	833	117	0.72	18	100	0.47	Single
J0111+6624	4302	112	8.4	8.1	70	0.33	Double, unresolved
J0323+6742	1365	65	1.6	14	190	0.55	Single
J0414+31	1080	64	–	–	210	0.82*	Single
J0614+83	1039	44	–	–	330	0.81*	Double, unresolved
J0738+6904	6828	17	28	3.9	550	0.80	Single
J1529−26	799	45	–	–	260	0.54*	Single
J1536−30	1901	63	–	–	190	0.66*	Double
J1629+33	1524	35	–	–	460	0.71*	Double
J1821+4147	1262	41	1.7	12	440	0.47	Triple
J1829+25	2857	74	–	–	260	0.37*	Single
J1901−04	1830	107	–	–	80	0.86*	Double, mode change?
J2040−21	563	24	–	–	440	0.23*	Double
J2131−31	3325	32	–	–	380	0.50*	Single
J2310+6706	1945	98	0.32	100	120	0.60	Single

Table 1: GBNCC nulling pulsars included in this proposal and their respective spin periods (P), dispersion measures (DM), period derivatives ($\dot{P}$), characteristic ages, scintillation timescales ($\tau_{\rm s}$), nulling fractions, and profile classifications. Preliminary nulling fractions are included for sources with existing timing data; nulling fractions estimated by inspecting discovery plots of promising candidates are noted with asterisks (*).

Therefore, we request 3×10.5 hour observing sessions to be conducted with the 820 MHz PF receiver. Following this plan, we expect to observe five sources per session, but since our observations do not require rigid scheduling, these sessions could theoretically be broken into smaller units, if necessary for scheduling convenience. Time estimates include 30 minutes per session for set-up/slew time; by grouping sources, we reduce our overall time request. When observing pulsars with existing, full timing solutions, we will collect data in coherent fold-mode; otherwise we will use incoherent search mode with 2048 frequency channels.[2] In both cases, we will observe a phase calibrator source to make use of full Stokes data. In total, we request **31.5 hours** observing time for the 15 GBNCC nulling pulsars discussed above.

[2]Since GUPPI availability is pending for this proposal cycle, we may need some help with VEGAS data reduction if the resulting file format differs from GUPPI PSRFITS files.