Pulsars at Low Radio Frequencies, Cyclic Spectroscopy, and Pulsar Timing Arrays

Timothy Dolch
Department of Physics
Hillsdale College
Hillsdale, MI, USA
tdolch@hillsdale.edu

Abstract—**Pulsars at low radio frequencies (<400 MHz) are ripe with astrophysical applications. For the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) pulsar timing array (PTA), the continual search for and discovery of new pulsars with single-dish telescopes (Arecibo Observatory and the Green Bank Telescope) is an essential part of the project. At Long-Wavelength Array (LWA) frequencies of 10–88 MHz, pulsar signals are highly scattered from the ionized interstellar medium (IISM). However, monitoring IISM effects along the line of sight to each pulsar characterizes the overall noise budget for gravitational wave detection. In some cases the effects of the very low frequency IISM can be mitigated, either through wideband template profile timing or through cyclic spectroscopy. Aside from PTAs, monitoring pulsars at very low frequencies can inform a plethora of topics in pulsar astrophysics: additional neutron star discoveries, frequency-dependent dispersion measures, solar wind science through high-cadence pulsar monitoring campaigns, and giant pulses. An expanded continent-wide LWA-Swarm would assist gravitational wave (GW) detection by resolving pulsar scattering screens and by providing higher sensitivity, leading to improved cyclic spectroscopy IISM deconvolution on more pulsars. Pulsar discoveries can also be made by following up unidentified steep-spectrum point sources in a LWA-Swarm sky survey.**

I. Introduction

Pulsars at low radio frequencies (defined here as <400 MHz) have been a fruitful and growing area of research in recent years. At several telescope arrays, such as the LWA (10–88 MHz) in the US, the Low-Frequency Array (LOFAR; 10–230 MHz) in the Netherlands, and the Murchison Widefield Array (MWA; 70–300 MHz) in Australia, radio pulsars have become a prominent science topic. For large single-dish telescopes, such as the 305-m William E. Gordon Telescope at Arecibo Observatory (AO) operating at a center frequency of 327 MHz, and the 100-m Robert C. Byrd Green Bank Telescope (GBT) at Green Bank Observatory at 342 MHz, pulsar searches have discovered 418 pulsars at the time of this writing, about 16% of all known pulsars. These new pulsars were found in the Pulsars with the Arecibo L-band Feed Array (PALFA[1]) survey, the Green Bank North Celestial Cap (GBNCC[2]) survey, and the AO Drift survey[3], greatly benefiting the search for GWs with PTAs. With a view to larger arrays in decameter to meter wavelengths under construction, we discuss some notable avenues for expanding the science potential of radio pulsars at these frequencies even further.

II. Overview of Low-Frequency Pulsar Science Topics

The steep powerlaw spectra of pulsars makes them a prime target for low-frequency observations. For this reason, frequencies <0.4 GHz remain ideal for pulsar searching. The powerlaw Galactic synchrotron flux also results in higher $T_{\rm sys}$ values. The effects of the IISM on time-of-arrival (TOA) measurements become especially significant at <0.4 GHz, combined with the increased $T_{\rm sys}$: first, we have the cold plasma dispersion law yielding TOA perturbations of DM/ν^{-2}, where ν is the center frequency of an observing bandwidth (<1 octave), and the DM is the characteristic dispersion measure of a pulsar line-of-sight. Scattering from IISM inhomogeneities produces additional TOA perturbations $\propto \nu^{-4.4}$ assuming a Kolmogorov turbulence spectrum for the IISM's electron density fluctuations. Also, at decametric wavelengths, ionospheric and solar wind effects on timing also become significant. Despite these limitations, beyond pulsar searching, low-frequency pulsar science has been plentiful. This includes, but is not limited to: subpulse drifting, long-term dispersion measure and scattering monitoring, scintillation arcs, giant pulses, studying coronal mass ejections (CMEs) with background pulsars, and rapidly rotating astrophysical transients (RRATs). Most pulsar discoveries have occurred >300 MHz in part due to a spectral turnover in many pulsars, dimming their flux below 200 MHz. Nonetheless, $\sim$100 pulsar discoveries have occurred at very low frequencies[4].

III. Gravitational Wave Detection with Pulsar Timing Arrays

The NANOGrav[5] PTA collaboration monitors millisecond pulsars (MSPs) to search for correlated TOA perturbations due to GWs. NANOGrav uses AO and GBT to monitor 76 pulsars, and is currently nearing the completion of the 14-year dataset. Combining datasets from NANOGrav, the European Pulsar Timing Array, and the Parkes Pulsar Timing Array as the all-sky International Pulsar Timing Array (IPTA), a

[1] http://www.naic.edu/~palfa/newpulsars/
[2] http://astro.phys.wvu.edu/GBNCC/
[3] http://www.naic.edu/~deneva/drift-search/
[4] http://www.astron.nl/lotaas/index.php
[5] http://nanograv.org

nanohertz GW detection is expected within several years. The S/N of a GW detection is $\propto N_{\rm pulsars}$, the number of pulsars in the PTA [1]. The constant addition of MSPs from AO and the GBT to the array, discovered at 327 MHz and 342 MHz respectively, is therefore of critical importance. To acquire NANOGrav's long-term TOA dataset, observations >400 MHz are needed in order to minimize IISM perturbations to TOAs. Nonetheless, many areas of supporting science are possible <400 MHz other than pulsar searching and timing. A long-term pulsar monitoring campaign with the LWA is underway, including several NANOGrav pulsars, in order to characterize the lines-of-sight [2]. With the advent of ultra-wideband backend receivers, chromatic DMs (e.g. $\rm DM(\nu)$) are eventually anticipated in many pulsars [3]. Joint monitoring of pulsars with GBT/AO and the LWA to characterize scattering and dispersion could characterize the degree to which achromatic DMs occur. As a test case on a slow pulsar, simultaneous LWA-GBT observations are underway on PSR B2224+65, the "Guitar Nebula" pulsar (Project IDs 16B-366 and 18B-321, PI Dolch). Additionally, the 11-year NANOGrav dataset has been used to study the solar wind [4], which can benefit from dense LWA campaigns on pulsars near the ecliptic.

IV. Interstellar Medium Mitigation and Cyclic Spectroscopy

Cyclic spectroscopy [5] is a novel data processing technique for radio pulsar data. It has been successfully used on LOFAR data [6] to measure the scintillation structure of several pulsars, given that it can produce spectra with extremely narrow frequency channels. On AO 430 MHz data from PSR B1937+21 [7], scattering effects can not only be resolved, but also deconvolved, removing the IISM's scattering tail just as coherent dedispersion removes the ν^{-2} effect on TOAs, at least in limited cases. Simulations show that deconvolution is possible for a variety of realistic scattering screens [8], and other simulations in preparation [9] show that MSPs with a S/N as low as 20 can be IISM-deconvolved starting with scattering timescales of $\sim$256μs or greater. This opens up the possibility that at LWA frequencies, some slow pulsars and a few MSPs lightly scattered at $\sim$1 GHz could have significantly improved timing, given sufficient real-time computing resources that are presently nontrivial but likely more reasonable in several years. In addition to cyclic spectroscopy, wideband timing pipelines can model and mitigate scattering [10]. These techniques will only work for a select set of lightly scattered pulsars at $\sim$1 GHz not scattered beyond the pulse period at LWA frequencies, but would nonetheless provide significantly improved timing. The mitigation of time-variable scattering would provide better pulse profile data for studies of the emission mechanism and of intrinsic profile evolution.

V. Conclusion: An LWA Swarm and Benefits for Pulsar Timing Arrays

Finally, an expansion of the LWA into a "swarm telescope" is currently being studied [11]. The current LWA stations would operate together with many mini-stations across North America, resulting in continent-spanning baselines and a sensitivity increase of at least a factor of two. In addition, the array could include the future Next-Generation Low-Band Observatory (ngLOBO) [12], an expanded network of LWA antennas situated near the antennas of the proposed Next-Generation Very Large Array (ngVLA). In addition to improving the pulsar science just outlined, a swarm telescope would allow for imaging of scattering screens (as has already been done with the ELWA - the expanded LWA, currently including the low-frequency capability of the VLA) but with baselines of $\sim$2000 km, helping to characterize lines-of-sight for PTAs. Deeper sky maps would allow for pulsar searching, following up on unidentified steep-spectrum point sources. The mini-stations could be built on existing telescope sites, including those of the Low-Frequency All-Sky Monitor stations in the US, both in Texas and at the recently constructed Low-Frequency All-Sky Monitor V in Hillsdale, Michigan.

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