The principal goal of the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) is to detect low-frequency gravitational waves (GWs) using high precision pulsar timing; it is predicted that a detection will occur for the stochastic GW background in the next several years [27] and for continuous waves (CWs) due to individual supermassive black hole (SMBH) binaries in merging galaxies in the next decade [25]. In contrast to quantifying a better constrained upper limit on the GW background (as was done with previous NANOGrav data sets), the latest GW result reported a highly significant "common process" among all pulsars [5], which we would expect as a harbinger en route to a GW background detection. We are currently working hard on the analysis of our next data set, the NANOGrav 15-year. GWs were featured in the very recent astronomy decadal survey, with NANOGrav featured prominently as well. *Pulsar timing arrays (PTAs) will explore a new frontier in the GW universe not accessible by other experiments, and drastically expand our understanding of gravitation, stellar and galaxy evolution.* A PTA detection of GWs would be complementary to the LIGO detections in a different frequency range, and therefore offering sensitivity to different astrophysics.

My thesis work presented results from radio campaigns at frequencies from 322 MHz to 10 GHz aimed at both multi-messenger constraints on GW sources and improving timing sensitivity. I am an experienced observer with the Green Bank Telescope (GBT) and Parkes Telescope, and have expertise processing data from the Very Large Array (VLA) and Giant Metrewave Radio Telescope (GMRT). I have also been highly involved in the timing efforts for the NANOGrav 9-year, 11-year, 12.5-year, and 15-year data releases. Two selected papers are briefly summarized below.

Measurement and Analysis of Dispersion Measure Variations. Free electrons along the line of sight to the pulsar, quantified by the dispersion measure (DM), cause a frequency-dependent time delay that is significant when compared to the pulse period. *DM is a leading order effect that has to be mitigated before studying other interstellar time delays like scattering and refraction.* As incompletely mitigated DM variations manifest as red noise, understanding structure in the ISM and distinguishing sources of noise will help us form a more complete model of the timing delays present in PTA data, and therefore increase our sensitivity to GWs. I led a paper using wideband multi-frequency observations to characterize dispersion in the NANOGrav 9-year data release [3]. I applied more robust modeling to characterize interstellar turbulence than had been applied previously in the literature.

Evaluating Low Frequency Observations at the GMRT. I led a paper comparing DMs measured with dual-frequency observations obtained with the GMRT to those in the NANOGrav 11-year data release to assess the possible precision measurements of frequency-dependent interstellar effects with the now upgraded uGMRT. I wrote a processing pipeline for legacy GMRT data taken in phased-array mode and made it available on github. I detected and characterized a $\sim$50 Hz baseline sinusoid (i.e., baseline ripple) that is very likely present in current uGMRT observations, and made estimates for its effect on high precision timing.

Proposed research

All pulsars in the PTA contribute to the sensitivity to the GW background; if a single pulsar has poorly constrained noise, the PTA sensitivity will not be effected as long as there are enough other pulsars. But for any kind of individual GW signal, unmodeled or poorly modeled processes can significantly hurt sensitivity [e.g., 1, 2]. *CWs are very sensitive to individual pulsars that are close to the source; improving the noise in those pulsars will make the entire PTA significantly more sensitive to that source.*

An unmodeled red noise signal will show a reduction in power during timing that will vary with GW frequency; this power absorption is characterized by the transmission function [7]. Fitting more parameters lowers our sensitivity to certain frequencies (and therefore, certain sources) of GWs; fixing part of the timing model, like the astrometric parameters, can not only improve fitting if other high precision measurements exist but also decreases the power absorption of unmodeled processes [22].

For CW detection, the pulsar distances enter into the signal model by determining how much the GW frequency has evolved between the Earth and the pulsars. Pulsar distances are difficult to measure, and often have large uncertainties of 20% or more [e.g., 28]. For CW detection, pulsar distances should be known to $\sim$0.01–1 pc [13]; however, even without this precision, the distance and properties of the GW source can be determined by the GW frequency evolution between the Earth and the pulsar. This is especially important for high-frequency GW sources (up to $\sim$300 nHz for PTAs), which evolve on short timescales.

I propose developing complex interstellar modeling with astrophysical priors in combination with Bayesian fitting to improve NANOGrav's sensitivity to CWs.

Increasing sensitivity to CWs by modeling interstellar turbulence. Timing model parameters can have significant covariances; one leading example of this is interstellar propagation effects. Preliminary work shows that fitting for DM and $\dot{\mathrm{D}}$M terms in the timing model, using the 12.5-year data for PSR J1455–3330 as a test case, results in a highly significant parallax detection ($\sim 5\sigma$), smaller uncertainties on proper motion measurements ($\sim 0.5\times$), and a newly significant red noise detection, which could be indicative of a growing GW signal. Better constraints on these astrometric parameters will not only improve the timing residuals, but also result in a quantifiable reduction in the power absorbed by the transmission function, and therefore a calculable increase in CW sensitivity for that pulsar.

I propose building on the historical methodology by incorporating individualized per-pulsar noise modeling utilizing multiple interstellar priors. I will develop an advanced, astrophysically driven model of interstellar effects to better constrain astrometric timing parameters. I will add astrophysically driven terms to a DM model that works in tandem with the current NANOGrav DM encoding parameter, DMX, to account for epochs that cannot be modeled by stochastic interstellar turbulence. This will include modeling interstellar turbulence, flagging outlier DM-epochs to search for interesting and discrete interstellar structure, and will use Bayesian inference to analyze favorability of different interstellar models and disentangle covariant frequency-dependent effects. I will apply this technique to several test pulsars (e.g., J1640+2224 [30], those with poor constraints on parallax, etc.) in the NANOGrav 15-year data set to better constrain interstellar turbulence and quantify any change in significance of astrometric parameters and red noise. I will discuss discrepancies between traditional timing fits, published measurements, and those obtained via complex interstellar modeling. Not only will this work increase PTA sensitivity to CWs, I will also put astrophysical constraints on the structure of the ISM along the line of sight and can use the increase in distance precision to put constraints on our precision on the chirp mass for CWs.

Interstellar modeling for more robust non-linear timing. Timing parameters are routinely modeled using linear least squares and χ^2 statistic; performing a maximum likelihood for the linear least squares will depend on the precise combination of parameters included in the timing model, resulting in the model varying as the parameter space varies. Therefore, the mere presence of GWs could hypothetically introduce a bias in parameter fitting. Non-linear Bayesian-inference timing samples across the timing parameter space and computes the timing model at each point, resulting in more robust parameter uncertainty estimates, the ability to use astrophysical priors on parameter fitting, and more complex noise characterization from different processes/sources [29]. While not necessary for all pulsars, non-linearities will become much more important with longer data sets and higher quality receivers. For current as well as next generation instruments, like the ngVLA and SKA, accounting for non-linearities will become a must. *I will incorporate the advanced interstellar modeling into Bayesian timing to do a simultaneous fit and more robust parameter estimation.* Incorporating this timing technique for relevant pulsars will make a more robust timing pipeline for NANOGrav. I will quantify the increased sensitivity to CWs for these individual pulsars.

Noise modeling for individual problem pulsars in the GW dropout analysis. The GW background will manifest as a correlated signal across all pulsars in the PTA; while this may be the case for a CW, the signal will be strongest for pulsars nearest to the GW source sky location. Due to pulsar locations in the Galaxy, PTAs have an asymmetric distribution of pulsars across the sky, resulting in an asymmetric sensitivity to CWs depending on the sky location of the source; incidentally, most CW sources are expected to be in the lowest sensitivity sky regions. Past searches for GWs from individual sources have found non-genuine signals, which initially were confused for a GW signal but were later identified as resulting from an unmodeled noise source in a single pulsar [1].

To search for a common process in the PTA, the contribution of each pulsar can be examined using a dropout analysis, which quantifies how much each pulsar contributes to the common signal. A pulsar strongly disfavoring a common process suggests that either the common process is somehow fundamentally different at a particular sky location, which is extremely unlikely, or that there is unmodeled noise absorbing the common process. *I will use the interstellar modeling code to diagnose unmodeled noise in pulsars that are extremely favored or disfavored for a common process by the dropout analysis.* I will test the diagnostic for all pulsars to assess its relevance to the entire PTA and develop it as a standalone software package in the NANOGrav suite of tools.

Immense thanks for your consideration of my application.

References

[1] Aggarwal et al., *ApJ*, 880, 2, 2019.
[2] Aggarwal et al., *ApJ*, 889, 1, 2020.
[3] Arzoumanian et al., *ApJ*, 813, 1, 2015.
[4] Arzoumanian et al., *ApJ*, 859, 47, 2018.
[5] Arzoumanian et al., *ApJL*, 905, L34, 2020.
[6] Begelman, Blandford & Rees, *Nature*, 287, 307, 1980.
[7] Blandford, Narayan, & Romani, ApJ, 5, 369, 1984.
[8] Campanelli, Lousto, & Zlochower, *Physical Review Letters*, 98, 23, 2007.
[9] Cordes & Lazio, *arXiv e-prints*, astro-ph/0207156, 2002.
[10] Cromartie et al., *Nature*, 4, 72, 2019.
[11] Deller et al., *ApJ*, 875, 2, 2019.
[12] Edwards, Hobbs, & Manchester, *MNRAS*, 372, 4, 2006.
[13] Ellis et al., *ApJ*, 756, 2, 2012.
[14] Ellis et al., *Zenodo*, 2020.
[15] Fonseca et al., *ApJL*, 915, L12, 2019.
[16] Jennings et al., *ApJ*, 864, 1, 2018.
[17] Jones et al., *ApJ*, 841, 2, 2017.
[18] Jones et al., *ApJ*, 874, 2, 2019.
[19] Jones et al., *ApJ*, 915, 15, 2021.
[20] Komossa, *Advances in Astronomy*, 364, 973, 2012.
[21] Luo et al., *ApJ*, 911, 1, 2021.
[22] Madison et al., *ApJ*, 777, 2, 2013.
[23] Manchester et al., 1998. http://tempo.sourceforge.net
[24] Menezes et al., *ApJL*, 796, 1, 2014.
[25] Madison et al., *Nature*, 1, 886, 2017.
[26] Padovani et al., *MNRAS*, 452, 2, 2015.
[27] Taylor et al., ApJL, 819, L6, 2016.
[28] Verbiest et al., ApJ, 755, 39, 2012.
[29] Vigeland et al., *MNRAS*, 440, 2, 2014.
[30] Vigeland, *in prep.*