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]. NANOGrav produces high quality, long term data sets with many uses [e.g., 10, 15]. 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.

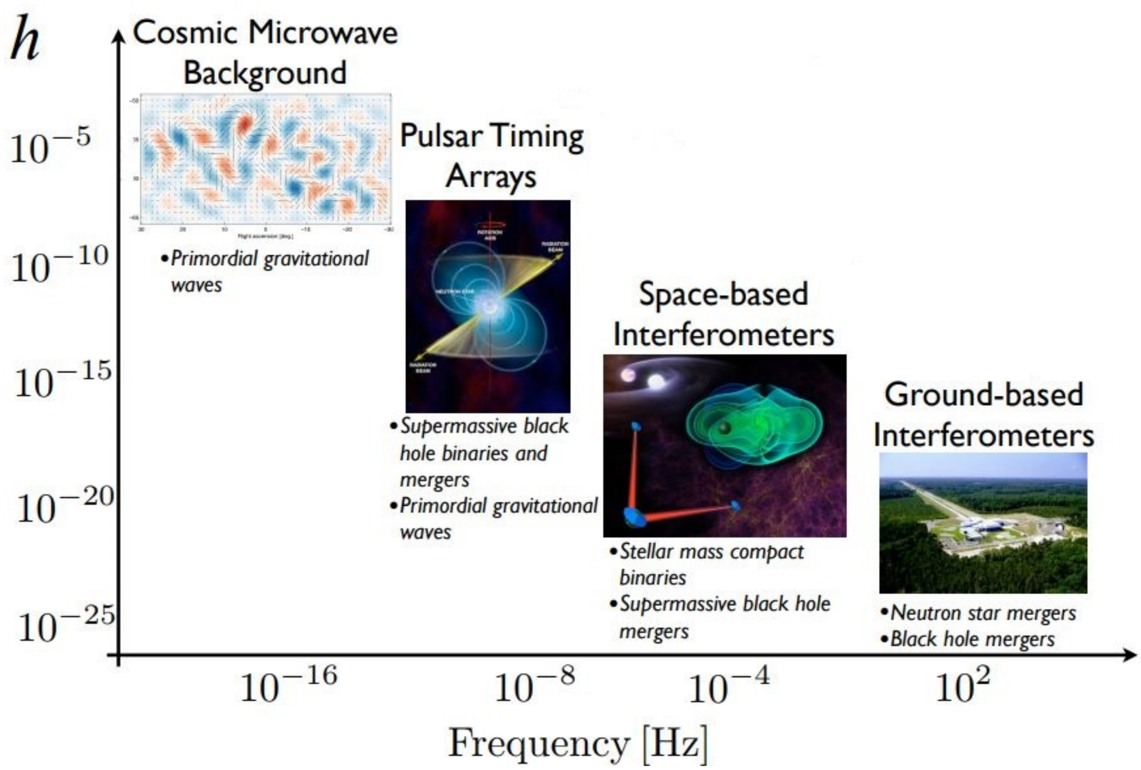

Figure 1: Coverage of GW experiments with detectable sources in each regime. Image credit: NANOGrav.

My past research 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.

Investigating the Candidate Displaced Active Galactic Nucleus in NGC 3115. SMBH binaries should form during major galaxy mergers. Interactions of the binary with its environment will eventually drive it to merger, releasing an enormous amount of energy in the form of GWs. While asymmetric GW emission can produce a kick to the final SMBH, the SMBH should eventually settle into the host galaxy's center due to drag and other dynamical interactions with the stellar and gas environment [6, 8]. SMBH recoils induced by these kicks have astrophysical implications for the host galaxy, such as SMBH and galaxy evolution, galactic core structures, galaxy-SMBH scaling relations, and the dependence of GW signals on redshift, among others [20].

I led a radio search to corroborate a purported displaced active galactic nucleus (AGN) in the nearby galaxy NGC 3115 [24], with the goal of determining if the source is a SMBH binary or a post-merger recoiling SMBH. By comparing the compact radio emission, X-ray nucleus, and stellar bulge of the galactic nucleus, I determined that the radio source is centrally located with no offset from the galactic bulge; due to the excellent sensitivity of the VLA, the limit placed on the luminosity of any secondary AGN is exceptionally low, although a secondary SMBH in this system could still exist if it was classified as "radio-silent" [26]. *If a companion SMBH can be confirmed in the future, this system could be a continuous wave source detectable with pulsar timing, which NANOGrav could tune its array to specifically target.*

The NANOGrav 9-Year Data Set: Measurement and Analysis of Dispersion Measure Variations. Our PTA must be as sensitive as possible to detect GWs, requiring the mitigation of all other astrophysical delays, including those from the interstellar medium (ISM). 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. Inhomogeneities in the ISM, solar wind, and differences in the relative velocity of the pulsar and the Earth can change the free electron density along the line of sight (LOS), resulting in a DM that changes on timescales of hours to years. *DM is a leading order effect that has to be mitigated before studying other interstellar time delays like scattering and refraction.*

I led a paper using wideband multi-frequency observations to characterize dispersion in the NANOGrav 9-year data release [3]. I measured and analyzed trends in the DM time series, proposed sources of these trends, and identified timescales over which the DM varies beyond measurement errors. I applied more robust modeling to characterize interstellar turbulence than had been applied previously in the literature. *Analyzing DM variations aids in characterizing properties of the ISM and informs our timing observation strategy.* As incompletely mitigated DM variations manifest as red noise, understanding structure in the

ISM and being able to distinguish interstellar effects from other 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.

Evaluating Low Frequency Observations at the GMRT. Multi-telescope observations around the globe and at complementary frequencies can be used to more sensitively constrain DMs. Incorporating lower frequency data into timing efforts can aid in understanding and mitigating interstellar effects in addition to DM, like pulse scattering, as well as improving timing precision.

I led a paper comparing DMs measured with dual-frequency observations obtained with the GMRT to those calculated in the NANOGrav 11-year data release to assess the possible precision measurements of frequency-dependent interstellar effects with the now upgraded uGMRT. The lower frequency coverage as well as simultaneous dual-frequency observations available at the uGMRT have the potential to provide better dispersion measurement than the data taken by NANOGrav alone. I wrote a processing pipeline specifically for legacy GMRT data taken in phased-array mode and made it available on github[1]. I detected and characterized a $\sim$50 Hz baseline sinusoid (i.e., baseline ripple) in the legacy data that is very likely present in current uGMRT observations, and made estimates for its effect on high precision timing.

Hidden long period pulsar binaries. Pulsar timing models fit a number of parameters (more depending on the complexity of the system) to account for time delays in the data. If a system parameter is unmodeled, its resulting delays can be absorbed by other fit parameters. While short-period binaries are detectable due to a clear signal in the timing residuals, effects from a long-period binary could be masked by other timing delay effects, allowing them to go undetected. A long-period binary measured over comparably short timescales that is not accounted for in the timing model could instead be fit out through a sum of polynomial terms (i.e., frequency derivatives). I constrained the range of binary properties that may remain undetected in current data, and that may be detectable with further observations. I placed limits on orbital period and companion mass using the pulsar magnetic field and published constraints on the second frequency derivative f_2; when no constraints existed in the literature, I used the published RMS timing residuals while accounting for power loss to fit parameters in the timing model. This work is in preparation to be submitted to The Astrophysical Journal this month.

[1] https://github.com/meg-jones/gmrt

Increasing Gravitational Wave Sensitivity with Advanced Interstellar Noise Modeling

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 affected as long as there are enough other pulsars. However, 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 power loss to other parameters fit 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]; this can be seen in Fig. 2. For CW detection, the pulsar distances enter into the signal model as they determine 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$0.01–1 pc [13]; however, even without this precision, the distance and properties of the GW source can be determined by the GW frequency evolution between the Earth and the pulsar. This is especially important for high-frequency GW sources ($\lesssim$ 300 nHz), which evolve on short timescales. *Therefore, better estimation of astrometric parameters (and therefore pulsar distances) will aid in the detection of CWs.*

For the period of the NASA Hubble Fellowship, 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 $\dot{\text{DM}}$ terms in the timing model, using the 12.5-year data for PSR J1455–3330 as a test case (among others), 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. Significant red noise 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

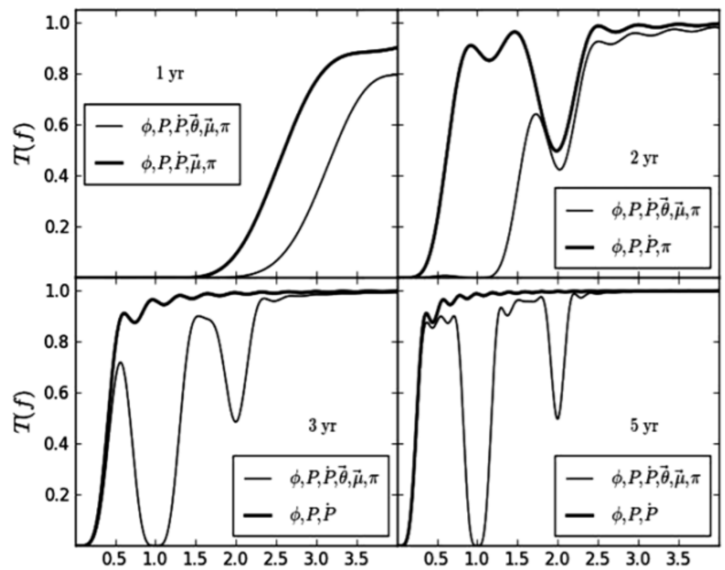

Figure 2: Transmission functions for various data baselines with and without higher precision astrometric measurements from VLBI. The decrease in power with more parameters being fit is clearly evident. Image credit: Madison et al., 2013.

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 (e.g., higher derivatives of DM), flagging outlier DM-epochs to search for interesting and discrete interstellar structure (e.g., lensing events, intervening clouds, solar flares, etc.), and will use Bayesian inference to analyze favorability of different interstellar models and disentangle covariant frequency-dependent effects. I will apply this technique to 4-5 test pulsars (e.g., J1455–3330 and 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, as in the highly-used pulsar-timing software packages TEMPO [23], TEMPO2 [12], and the newer PINT [21]. 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. Bayesian timing results 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. I will incorporate distance priors for this Bayesian timing, including DM-derived distance [e.g., 9], GAIA [e.g., 16], and VLBI [e.g., 11]. I will quantify the increased sensitivity to CWs for these individual pulsars. Incorporating this timing technique for relevant pulsars will make a more robust timing pipeline for NANOGrav.

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. Our PTA has an asymmetric distribution of pulsars across the sky due to pulsar locations in the Galaxy, 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, seen in Fig. 3. 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. An outlying dropout factor suggests either an extremely favored or disfavored common process, and necessitates investigation. A distinctly small dropout factor shows that a pulsar strongly disfavors a common process. This can be due to two things: first, that the common process is somehow fundamentally different at a particular sky location, which is extremely unlikely, or second, that there is unmodeled noise that is absorbing the common process. An inordinately large dropout factor, showing a strongly favored common process in one pulsar, could hypothetically occur if a pulsar had no nearby neighbors, there should still be some correlation across the PTA, with decreasing sensitivity the farther from the signal a pulsar is. A GW detection cannot be stated with confidence from a single pulsar.

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. If I find widespread relevance and its computationally feasible to apply to the entire PTA (which will not be surely known until I run it), then it will be incorporated into current

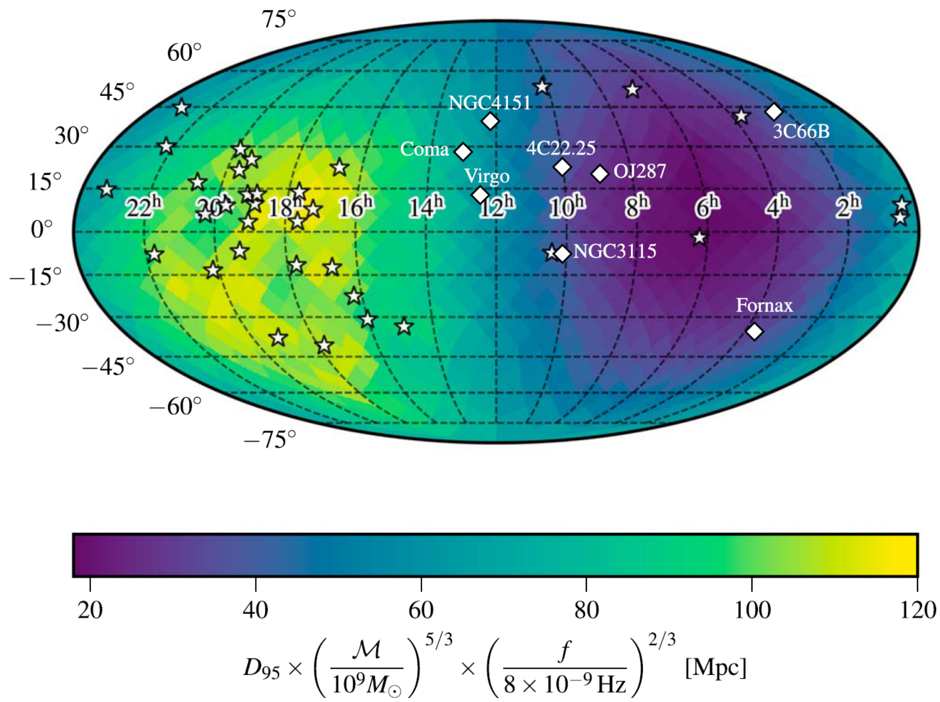

Figure 3: Sky sensitivity map for CW sources for the NANOGrav 11-year data set. Darker purple regions show less sensitive sky areas while lighter yellow regions show more sensitive areas. Note that the anticipated nearby CW sources labeled on the map are not in high sensitivity regions.Image credit: Aggarwal et al. 2019

GW search software [e.g., 14]. If I find that computationally the model is more feasible as a selected diagnostic, then I will develop it as a standalone software package in the NANOGrav suite of tools.

Timeline

Year 1: I will develop the advanced interstellar modeling code and apply it to 15-yr data set to identify several interesting test pulsars to fully characterize. I will write a paper on the methods, the improvement of CW sensitivity for the test pulsars, and any interesting ISM features flagged by modeling.

Year 2: I will implement the advanced modeling into Bayesian timing for NANOGrav data. Bayesian timing software is out of date from the mid-2010s, so I will update it. I will quantify improvement in CW sensitivity from full Bayesian parameter estimation, and assess universal vs. diagnostic relevance across the PTA. I will write a paper on this framework in year 2.

Year 3: I will conduct advanced modeling to specific pulsars identified as outliers by dropout analysis. I will assess computational cost and feasibility/relevance to full PTA.

Institution justification

I propose to fulfill the fellowship at Cornell University working with Jim Cordes. Professor Cordes has a extensive knowledge of characterizing the ISM as it pertains to pulsar timing, and is also an expert in red noise signatures in timing data, including searches for individual GW sources.

As alternate sites, I propose the University of Wisconsin-Milwaukee or the Jet Propulsion Lab based on the high level of expertise in both GW detection through pulsar timing and Bayesian analysis at both institutions.

Immense thanks for your consideration of my application.

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