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 [20] and for single source continuous waves (CWs) in the next decade [18]. NANOGrav produces high quality, long term data sets with many uses [e.g., 8, 11]. 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. *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.*

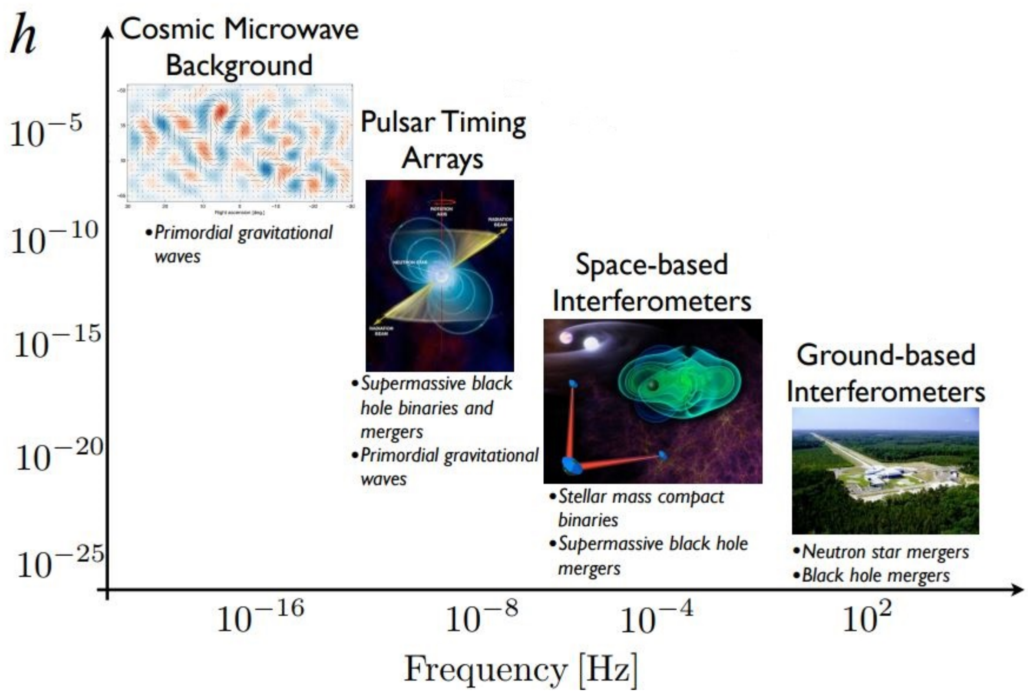

Figure 1: Coverage of GW experiments with detectable sources in each regime. Image credit: NANOGrav.

Research experience

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.

Investigating the Candidate Displaced Active Galactic Nucleus in NGC 3115. Supermassive black hole (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. I led a radio search to corroborate a purported displaced active galactic nucleus (AGN) in the nearby galaxy NGC 3115 [17], 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" [19]. *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. *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 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. 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.

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

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.

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; if the pulsars are close to a source, improving the noise in those pulsars will 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 [6]. Fitting more parameters lowers our sensitivity to certain frequencies (and therefore, certain sources) of GWs [16]; fixing part of the timing model, like the astrometric parameters, can improve fitting if other high precision measurements exist. If a pulsar does not have a well constrained distance, historical practice in software is to assume $d = 1 \pm 0.2\,\mathrm{kpc}$ [e.g., 10], which may not always be a good astrophysical approximation. *Better estimation of astrometric parameters (and therefore pulsar distances) can aid in the detection of CWs.*

For the period of the LSA Collegiate Fellowship, I propose using astrometric timing priors and complex DM fitting to improve CW sensitivity. Using distance priors for non-linear Bayesian timing [e.g., 21], including DM-derived distance [e.g., 7], GAIA [e.g., 12], and VLBI [e.g., 9]. By using distance priors to put limits on modeled astrometric parameters, I will quantify the improvement in RMS timing residuals as well as the reduction in power absorption that could be due to CWs.

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. Of the 47 pulsars in the NANOGrav 12.5-year data set, 14 show significant red noise; GWs will manifest as red noise, therefore higher precision astrometric parameters resulting in detectable red noise can be a good sign for GW detection.

I will apply this technique to 4-5 pulsars to better constrain DM variations for the timing model, and quantify any change in significance of astrometric parameters and red noise.

After developing this interstellar model, I will apply the DM modeling more fully to the NANOGrav 15-year data set. I will analyze how different models fit each pulsar and use this to characterize the ISM along that line of sight. As mentioned earlier, I completed a robust modeling of DM structure in the NANOGrav 9-yr data [13]. The more complex modeling proposed here will be used to place priors on sources of non-Kolmogorov turbulence, and investigate any DM anomalies in the newer, longer data set. My previously led DM paper has over 50 citations and is one of the highest cited 9-year papers, therefore I think this would also be a great project for a student that I could supervise.

In tandem with this research plan, I will be working on timing efforts for the NANOGrav 17-year data set and can get students involved in that efforts. NANOGrav timers are included as authors on any collaboration work using the data, which is not only a great opportunity for a student to learn timing techniques but also get them involved on other publications and science using the data set they helped complete.

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