Research Experience

The principal goal of the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) is to detect nanohertz gravitational waves (GWs) using the technique of pulsar timing; it is predicted that this detection will occur by 2022 [14]. A detection in the lower frequency region of the spectrum will offer characterization of the GW universe through a diverse population of sources. 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 heavily 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. These systems give direct evidence for recent massive mergers and help in inferring the properties of anticipated pulsar timing array signals [2]. 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 [3, 4]. 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 [9]. The identification of potential recoiling SMBHs is therefore important in exploring past galaxy mergers, constraining kick properties, and investigating predictions made via numerical relativity.

I led a radio search to corroborate a purported displaced active galactic nucleus (AGN) in the nearby galaxy NGC 3115 [12]. I investigated the possibilities that the source is a SMBH binary or a post-merger recoiling SMBH by corroborating any offset and determining the presence of a secondary AGN. Compact radio emission and an X-ray candidate nucleus that are both coincident with the optical center in the galactic nucleus have been previously detected; these detections suggest the existence of a low-luminosity AGN residing in the center of this galaxy [16, 15]. I analyzed 10 GHz data obtained with the VLA, resulting in the detection of a single radio AGN (seen in Figure 2). By analyzing the relative positioning of the radio core, X-ray nucleus, and stellar bulge in this galaxy, 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, several orders of magnitude below the span of published radio-quiet quasar distributions. A secondary SMBH in this system could still exist if it was classified as "radio-silent" [13]. *If a companion SMBH can be confirmed in the future, this system could be a future GW 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 pulsar timing array (PTA) must be as sensitive as possible to detect

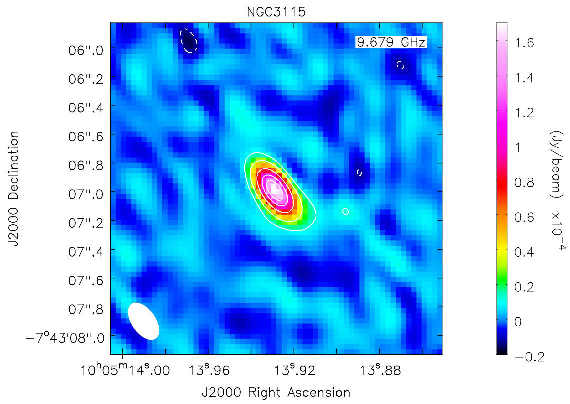

Figure 1: Contours of the 10-GHz emission from NGC 3115 obtained with the VLA. [7]

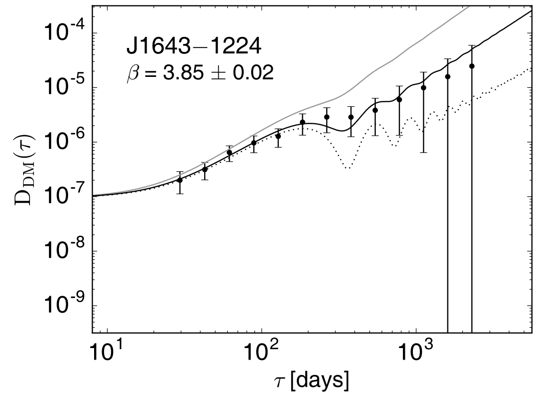

Figure 2: DM variation structure function. The solid black line is the best fit model, which shows better agreement than less robust models in previous studies [6].

GWs, requiring the mitigation of all other astrophysical delays, including those from the interstellar medium (ISM). As the emission from a pulsar travels through the ISM, it encounters free electrons; these free electrons cause dispersion, quantified by the dispersion measure (DM). Dispersion will cause a frequency-dependent time delay that can be 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 frequency-dependent dispersion in the timing data for 37 pulsars in the NANOGrav 9-year data release [1]. 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 models characterizing interstellar turbulence in the DM structure functions than has been applied previously, seen in Figure 3.

Analyzing DM variations aids in characterizing properties of the ISM and informs our timing observation strategy. Understanding structure in the ISM and being able to distinguish interstellar effects from other kinds of noise will help us form a more complete model of the time delays present in PTA data. Incompletely mitigated DM variations manifest as red noise in pulsar timing data, decreasing our sensitivity to GWs. sum up here?

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 scattering, as well as improving timing precision. I led a paper which compares 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 analyzed the predicted effect of incorporating this lower frequency data on DM uncertainties and investigated possible astrophysical sources of variations in daily DM measurements. I wrote a processing pipeline specifically for legacy GMRT data taken in phased-array mode and made it available on github[1]. I also detected and characterized a ∼50 Hz baseline sinusoid (i.e., baseline ripple; Fig. 3) in the legacy data that is very likely present in current uGMRT observations, and made estimates for its effect on high precision timing. (rephrase?) I explored anticipated challenges in future data combination, including the need for establishing data guidelines and uniformity in data acquisition/recording.

Global pulsar timing efforts through the International Pulsar Timing Array (IPTA; [11]) are the future. This project represented a test case for incorporating new instruments into a subset of IPTA data and establishing uniform data standards development, which are important achievements for the future of the IPTA. *PTAs need to optimize their ability to characterize and model processes correlated over long timescales (e.g. DM) that can be covariant with a GW signal, making GW detection more difficult.*

Hidden long period pulsar-black hole binaries. Pulsar-BH binaries have been described as the holy grail of astrophysics, with less than 100 such binaries predicted to exist in our Galaxy [10]. The discovery of a pulsar-BH binary would reveal a wealth of information on how the Universe works. I am currently working on identifying long-period pulsar binaries in timing data. I have identified constraints on the properties of systems that may remain undetected in current data, and that may be detectable with more observations. With this determination of pulsar-BH binary candidates, we plan to apply targeted algorithms resulting in detection. This work is in preparation to be submitted to ApJ and is currently in collaboration review.

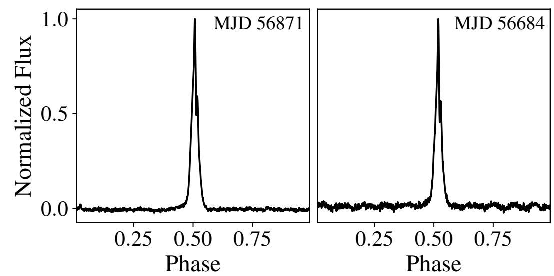

Figure 3: Pulse profiles for PSR B1929+10 observed with the GMRT at 607 MHz. The left profile does not show a visible level of baseline ripple, whereas the right profile from 2 weeks later shows clearly evident ripple. [8]

[1] Arzoumanian et al., *ApJ*, 813, 65, 2015.
[2] Arzoumanian et al., *ApJ*, 859, 47, 2018.
[3] Begelman et al., *Nature*, 287, 307, 1980.
[4] Campanelli et al., *Physical Review Letters*, 98, 23, 2007.
[5] Demorest et al., *ApJ*, 762, 94, 2013.
[6] Jones et al., *ApJ*, 841, 125, 2017.
[7] Jones et al., *ApJ*, 874, 2, 2019.
[8] Jones et al., *ApJ*, 915, 15, 2021.
[9] Komossa, *Advances in Astronomy*, id. 364973, 2012.
[10] Lorimer & Kramer, *Handbook of Pulsar Astronomy*, 2012.
[11] Manchester et al., *Classical and Quantum Gravity*, 30, 22, 2013.
[12] Menezes, Steiner, & Ricci, *ApJL*, 797, L13, 2014.
[13] Padovani et al., *MNRAS*, 452, 1263, 2015.
[14] Taylor et al., *ApL*, 819, L6, 2016.
[15] Wong et al., *ApJL*, 736, L23, 2011.
[16] Wrobel & Nyland, *AJ*, 144, 160, 2012.

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