# Astro2020 Science White Paper

# The Virtues of Time and Cadence for Pulsars and Fast Transients

**Thematic Areas:** ☐ Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ■ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ■ Multi-Messenger Astronomy and Astrophysics

**Principal Author:**
Name: Ryan S. Lynch
Institution: Green Bank Observatory
Email: rlynch@nrao.edu
Phone: (304) 456-2357

**Co-authors:** Paul Brook (West Virginia University), Shami Chatterjee (Cornell University), Timothy Dolch (Hillsdale College), Michael Kramer (Max-Planck-Institut für Radioastronomie), Michael T. Lam (West Virginia University), Natalia Lewandowska (West Virginia University), Maura McLaughlin (West Virginia University), Nihan Pol (West Virginia University), Ingrid Stairs (University of British Columbia)

This white paper summarizes science opportunities enabled by high-cadence and long-duration observing strategies. More details about these opportunities are presented in the following Astro2020 science white papers:

- *Gravitational Waves, Extreme Astrophysics, and Fundamental Physics with Precision Pulsar Timing* (Principal authors: James Cordes & Maura McLaughlin)
- *Supermassive Black Hole Demographics & Environments with Pulsar Timing Arrays* (Principal authors: Stephen R. Taylor & Sarah Burke-Spolaor)
- *Physics Beyond the Standard Model with Pulsar Timing Arrays* (Principal authors: Xaxier Siemens & Jeffrey Hazboun)
- *Fundamental Physics with Radio Millisecond Pulsars* (Principal author: Emmanuel Fonseca)
- *Multi-Messenger Astrophysics with Low-Frequency Gravitational Waves and Pulsar Timing Arrays* (Primary Authors: Luke Zoltan Kelley, Maria Charisi, Sarah Burke-Spolaor, & Joseph Simon)
- *Twelve Decades: Probing the ISM from Kiloparsec to Sub-AU Scales* (Principal author: Dan Stinebring)

# Key Ideas

- Pulsars, magnetars, and fast radio bursts act as precision probes of gravity, dense matter, exotic physics, high-energy processes, compact objects, and ionized gas. They can also be used to detect gravitational waves, and thus to study the growth and evolution of massive black holes.
- Some of the most valuable scientific results in these areas come from measuring weak secular effects and/or time-variable behavior.
- This requires observations that are carried out over many years with daily to monthly cadence.

# Background

Pulsars and fast radio transients, such as radio magnetars and fast radio bursts (FRBs), are powerful tools for studying astrophysics. Here, we will focus on the high-impact science that can be achieved by observing pulsars and fast radio transients with high observing cadence (where observations repeat on timescales of days to months) and long-duration data sets (spanning years and even decades). This includes, but is not limited to, gravitational wave (GW) and multi-messenger (MM) astrophysics, extreme gravity, exotic physics, high-energy and high-magnetic-field environments, the evolution of supermassive binary black hole (SMBBH) systems and their host galaxies, properties of neutron stars (NSs), the dynamics of the interstellar and intergalactic media (ISM/IGM), and the nature of FRBs and their use as cosmological probes.

High cadence/long duration observations are important for two key reasons.

1. They allow us to measure weak, secular effects. In the context of pulsars, this is typically achieved through *pulsar timing*.
2. They allow us to study time-variable processes. This is especially true of radio magnetars and repeating FRBs, both of which are more variable than typical radio pulsars (see Figure 1).

Pulsars are phenomenally stable clocks whose "ticks" are pulse times of arrival (TOAs). Any process that impacts the observed TOA can be incorporated into a model that accounts for *every rotation of the pulsar* over timescales of years—a technique known as *pulsar timing*. Relevant processes include the rotation of the pulsar and its evolution with time, the effects of ionized gas along the line of sight, the Römer, Shapiro, and Einstein delays arising in our Solar system and the pulsar's orbital system when it is in a binary or triple, and path-length differences caused by GWs. For the best pulsars, TOAs can be measured *and predicted* with sub-$\mu$s precision and accuracy over timescales of years (see Figure 1). Taken together, this allows us to measure rotational, astrometric, and binary parameters with fantastic precision, which can, in turn, be used for precise fundamental and astrophysical tests.

# Compelling Science Themes

- **The GW Universe:** Dozens of MSPs *observed over many years with daily to monthly cadence* as part of a pulsar timing array (PTA), such as NANOGrav, are the best way of studying the nanohertz GW Universe [1]. SMBBHs in the early stages of inspiral, producing both a stochastic background and individual signals, are expected to be the dominant source class at nHz GW frequencies. Upper limits on the GW background have already been used to constrain coupling between SMBBHs and their stellar environments, as well as the eccentricity distribution of SMBBHs [2, 3]. PTAs also set the best limits on the energy density of cosmic strings [3], and could potentially probe other exotic physics.

- **Strong-field Gravity:** Pulsars in relativistic binary systems are unique laboratories for studying gravity. These include the most stringent constraints on dipolar gravitational radiation predicted by tensor-scalar-vector theories [4, 5] (three orders of magnitude more precise than what is possible with LIGO [5]), as well as violations of the strong equivalence principle and quasi-Brans-Dicke theories of gravity [6, 7]. The Double Pulsar system [8, 9] provides better than $0.05\%$ tests of relativity and has also revealed higher order effects in the propagation of light [5], namely retardation in the Shapiro delay and changes in the direction of pulsar A's signals due to the gravity of pulsar B. The latter effect has allowed a first-ever measurement of the prograde rotation of pulsar A in its orbit. *These weak effects can only be measured with many years of sensitive pulsar timing data.*
- **Ultra-dense Matter:** As the densest objects known with a physical extent and a surface (i.e., not singularities), NSs are the best laboratories for studying the equation of state (EoS) of matter at supra-nuclear densities. The most direct method is to measure pulsar masses that exceed the limits imposed by certain theories via the Shapiro delay. *Significance is improved over timescales of years by repeatedly observing relevant orbital phases, and/or by measuring other relativistic effects that manifest over long time scales.*
- **Energetic Processes in Strong Magnetic Fields:** Short-term changes in pulsar emission—including pulse-to-pulse variability [e.g. 10, 11, 12], mode-changing, giant pulses [13, 14], and nulling [15, 16]—were first observed soon after the discovery of pulsars. *Decades-long data sets also reveal long term variability* in pulse profiles that are often accompanied by simultaneous changes in the pulsar's rotation rate [e.g. 17, 18]. These phenomena encode information about the interior and magnetospheric structure of NSs.
- **Dynamics of Globular Clusters:** Globular clusters are rich sources of MSPs, with some containing dozens of pulsars. Each acts as a test mass that can be used to map the cluster's gravitational potential and place limits on the mass of any potential intermediate-mass black holes contained within the cluster through measurement of the pulsars' accelerations and jerks [19, 20] *that become measurable after many years*. An ensemble of MSP proper motion measurements also allows the peculiar velocity of each star to be separated from the bulk proper motion of the globular cluster [21].
- **Radio Magnetars**: Radio emission has only been observed from four magnetars to-date, but they are important for understanding the strongest magnetic fields found in nature. *Comparison between the evolution of magnetars and FRBs over many years* may illustrate a connection between the two (e.g. [22] and [23]).
- **Fast Radio Bursts:** FRBs have emerged as one of the biggest mysteries in astronomy. Repeating FRBs provide a unique opportunity to study individual sources and their environments in detail, especially how they evolve with time. *However, identifying repeating FRBs requires many hours of follow-up [24], and changes in the activity level, rotation measure, and plasma density may only manifest over many years [25].* While many possibilities for the origin of FRBs remain viable, the properties of the original repeater, FRB121102, have led to a focus on

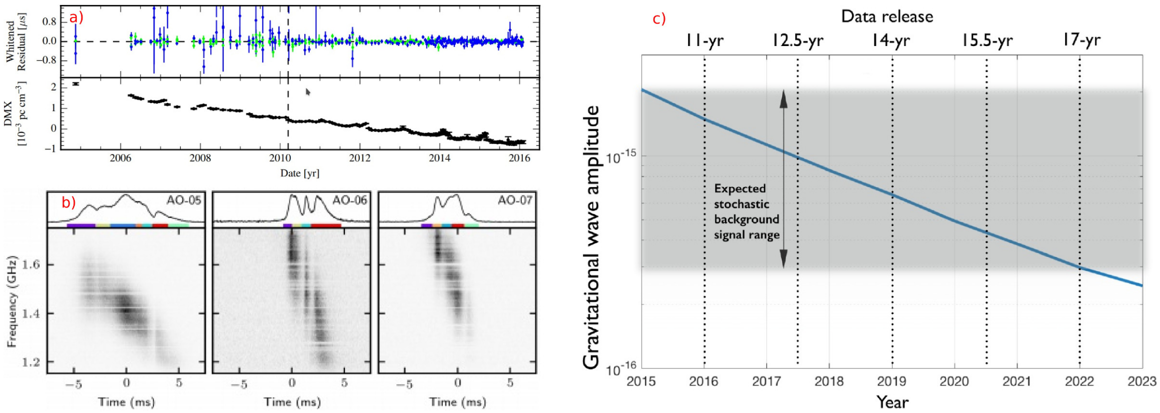

Figure 1: **a)** Pulsar timing residuals for PSR J1909-3744, showing sub-$\mu$s timing accuracy (top panel; colors indicate different radio frequencies) and changes in dispersion measure (the electron column density, bottom panel) over 10 years of NANOGrav observations [3]; **b)** A selection of bursts from FRB121102 showing dramatic variation in spectro-temporal structure [33]; **c)** The improvement in GW strain sensitivity with time for the NANOGrav PTA and the plausible amplitude range for the stochastic background signal, using reasonable assumptions for growth in the number of pulsars and access to sensitive radio telescopes (see the Astro2020 White Paper *Gravitational Waves, Extreme Astrophysics, and Fundamental Physics with Precision Pulsar Timing* by J. Cordes & M. McLaughlin for details; figure courtesy of NANOGrav).

an association with young magnetars, possibly originating in superluminous supernovae [e.g. 26, 27, 28].

- **Ionized Interstellar and Intergalactic Media:** *The dynamics of the ISM and IGM can be studied by measuring changes in the electron column density towards pulsars and FRBs* (see Figure 1). Besides understanding the characteristics of turbulence through the Galaxy, we can probe small-scale structures [29, 30], variable scattering properties, Solar wind variations [31], and more. Similar techniques can be applied using FRBs to study the circumgalactic medium, IGM, and FRB host galaxies [32].

# New Science Opportunities

Ongoing high-cadence, long-duration observations of known pulsars and FRBs will continue to improve sensitivity to weak physical phenomena. At the same time, more sensitive large-area pulsar and FRB surveys with wide-field instruments on existing telescopes (such as phased array feeds at the Arecibo Observatory and Green Bank Telescope [GBT]), and with new facilities such as CHIME, MeerKAT, FAST, and the SKA, will undoubtedly find interesting new systems. However, *finding new pulsars and repeating FRBs is only the first step*—detailed follow-up is required to fully realize the scientific potential of these surveys. Some of the most promising discovery areas are:

- **Understanding SMBBHs through the detection of nHz GWs:** PTAs are expected to detect the GW background within the next three to five years [34, also see Figure 1]. The shape of the background spectrum encodes information about the rate of galaxy mergers, the growth of SMBBHs, how they couple to their environments, and how they overcome the last parsec problem [3]. Individual SMBBH systems will start to be resolved within the next ten years [35]. Direct observables will include the masses of the BHs and orbital periods. Electromagnetic variability on similar timescales will provide a MM counterpart that can be used to pinpoint the location of these binary systems. Alternatively, if a SMBBH system is first detected through an EM signature, it will enable a more targeted search for a GW counterpart in pulsar timing data.

- **New Frontiers in Fundamental Physics:** Long-term timing of compact binaries will become sensitive to relativistic effects of orders greater than $\mathcal{O}(v^2/c^2)$, opening new parameter space in the strong-field regime. If one or more pulsars are found in orbit around the Milky Way's central black hole, they will be used to measure its spin properties and test the no-hair theorem [36]. PTAs will be able to test alternative theories of gravity by searching for non-Einsteinian GW polarization modes [37, 38, 39]. PTAs can also detect or constrain the existence of cosmic strings [40], and may even probe the inflationary epoch [41, 42, 43] and quantum chromodynamic phase transitions in the early Universe [44, 45]. These breakthroughs will require steady improvement in PTA sensitivity over very long timescales, which in turn requires *unbroken, long duration data sets*.
- **Determining the NS EoS:** Continuing observations of the Double Pulsar system will lead to the first-ever measurement of a NS moment of inertia, which, when combined with the already-known mass, will provide the most stringent constraints on the NS EoS [46]. There are several globular cluster pulsars with intriguingly high, but still imprecise, allowable masses [47]. Precision is improving with time, and may eventually confirm masses that rule out most EoS's.
- **Diamonds in the Rough:** One of the most exciting possibilities for new surveys is a pulsar in orbit around a stellar-mass black hole. However, without long-term monitoring that can reveal its binary nature and the relativistic effects that will identify the companion, such a system is likely to be indistinguishable from the hundreds–thousands of typical, isolated pulsars that will also be found. To identify the remarkable systems that warrant additional study, it will be critical to monitor all new pulsars for at least weeks to months, using telescopes with sufficient sensitivity to detect the faint pulsars that will be discovered in next-generation surveys.
- **Understanding Pulsar Variability:** High cadences will elucidate the physics of pulsar variability on short, medium, and long-term timescales, addressing questions regarding the links between emission and rotation, how and why some pulsars null [e.g. 48], switch emission modes [e.g. 48], display drifting subpulses [e.g. 49], produce giant pulses [e.g. 50], and why pulse profiles evolve with time [e.g. 51]. We may also be able to connect phenomena occurring on different timescales [52]. This will improve pulsars' utility as precision timing tools.
- **Explaining FRBs and Using them as Cosmological Probes:** Telescopes like CHIME, ASKAP, and MeerKAT are well positioned to discover hundreds–thousands of FRBs, which will certainly include many repeaters [53, 54, 55]. This will give us a clear picture of the statistical properties of the FRB population. Localization will identify host galaxies and redshifts, providing new insight into the ionized IGM [56, 32]. However, high cadence, long duration observations will be essential for understanding the *dynamics* of repeating FRBs and their environments, specifically, how the energy distribution and morphology of bursts, as well as their magneto-ionic host environments, change with time. Detailed follow-up will also be necessary for uncovering any potential periodic nature to the bursts, and for measuring the physical properties of the

source through pulsar timing. Continued observations of radio magnetars may reveal additional similarities with FRBs. These are the crucial observables that will put existing and future FRB models to the test and answer the question, "What are FRBs?"

- **Commensal Science:** Pulsar observations require full-polarization spectra sampled with high time and frequency resolution—the same requirements for observations of FRBs. As such, FRB surveys can be carried out simultaneously with pulsar timing observations. Pulsar and FRB emission is also qualitatively similar to terrestrial transmitters (e.g. the planetary radars at Arecibo and the Goldstone Solar System Radar). Searches for extraterrestrial technosignatures, therefore, represent another commensal science opportunity, and a natural extension of searches for biosignatures [57].

# Requirements

PTAs require at least monthly cadence carried out over decades for sensitivity at GW frequencies of $\sim 10^{-7}$–$10^{-10}$ Hz, which is expected to be the richest portion of parameter space. Overall sensitivity also improves with time as $T_{\rm obs}^{5/3}$. *Overlapping datasets between existing and new instruments are essential for characterizing systematic differences, and maintaining coherence over the full data set.* An ideal strategy observes a large number of pulsars with $\sim$monthly cadence to increase sensitivity to the stochastic background while observing select sources with higher cadence (i.e., daily to weekly) to increase sensitivity to continuous GW sources [58]. We stress, however, that given the unknown nature of the GW Universe, higher cadence observations of all pulsars that increase sensitivity at higher frequencies represent an important discovery opportunity for both GWs [59, 60] and for ISM phenomena [30].

Tests of fundamental physics using binary pulsars require good orbital phase coverage, either to measure effects that depend on the phase or to measure changes to the orbit. Once the orbit is well characterized, cadences of one to six months maintained over many years are sufficient.

Repeating FRBs and radio magnetars undergo periods of high activity and quiescence which can last for many months. This motivates a flexible scheme in which activity is monitored using snapshot observations with weekly or monthly cadence, switching to approximately daily sampling during active periods.

In all cases, precision pulsar timing and sensitivity to faint transient sources requires telescopes with large collecting area and low system noise (100-m class equivalent or larger, such as the GBT, Arecibo, MeerKAT, FAST, SKA, ngVLA, and/or DSA-2000), operating from $\sim$few hundred MHz–few GHz (or higher for magnetars and FRBs), with access to a wide declination range and good hour-angle coverage. Wide instantaneous bandwidths are especially important for mitigating systematic effects in timing and for capturing a complete spectral picture of variable sources. PTAs like NANOGrav currently observe dozens of sources using 1400 hours per year on the GBT and Arecibo, but this will grow into hundreds of pulsars in the next decade. The population of FRBs and pulsars in extreme systems will also grow rapidly. With typical dwell-times of $0.5$–$1\ \rm hr$ per source and daily to monthly cadence, the total time required will quickly meet or exceed what is available on a single telescope. *This motivates the use of multiple facilities, sub-arraying capabilities, and dedicated telescopes for pulsars and fast transients.* Well-maintained data archives are also critical to the success of long-term projects.

With these resources secured, the long-term future of pulsar and fast transient science is very bright.

# References

[1] F. A. Jenet, G. B. Hobbs, K. J. Lee, and R. N. Manchester. Detecting the Stochastic Gravitational Wave Background Using Pulsar Timing. ApJ, 625:L123–L126, June 2005.

[2] Z. Arzoumanian, A. Brazier, S. Burke-Spolaor, S. J. Chamberlin, S. Chatterjee, B. Christy, J. M. Cordes, N. J. Cornish, K. Crowter, P. B. Demorest, X. Deng, T. Dolch, J. A. Ellis, R. D. Ferdman, E. Fonseca, N. Garver-Daniels, M. E. Gonzalez, F. Jenet, G. Jones, M. L. Jones, V. M. Kaspi, M. Koop, M. T. Lam, T. J. W. Lazio, L. Levin, A. N. Lommen, D. R. Lorimer, J. Luo, R. S. Lynch, D. R. Madison, M. A. McLaughlin, S. T. McWilliams, C. M. F. Mingarelli, D. J. Nice, N. Palliyaguru, T. T. Pennucci, S. M. Ransom, L. Sampson, S. A. Sanidas, A. Sesana, X. Siemens, J. Simon, I. H. Stairs, D. R. Stinebring, K. Stovall, J. Swiggum, S. R. Taylor, M. Vallisneri, R. van Haasteren, Y. Wang, W. W. Zhu, and NANOGrav Collaboration. The NANOGrav Nine-year Data Set: Limits on the Isotropic Stochastic Gravitational Wave Background. ApJ, 821:13, April 2016.

[3] Z. Arzoumanian, P. T. Baker, A. Brazier, S. Burke-Spolaor, S. J. Chamberlin, S. Chatterjee, B. Christy, J. M. Cordes, N. J. Cornish, F. Crawford, H. Thankful Cromartie, K. Crowter, M. DeCesar, P. B. Demorest, T. Dolch, J. A. Ellis, R. D. Ferdman, E. Ferrara, W. M. Folkner, E. Fonseca, N. Garver-Daniels, P. A. Gentile, R. Haas, J. S. Hazboun, E. A. Huerta, K. Islo, G. Jones, M. L. Jones, D. L. Kaplan, V. M. Kaspi, M. T. Lam, T. J. W. Lazio, L. Levin, A. N. Lommen, D. R. Lorimer, J. Luo, R. S. Lynch, D. R. Madison, M. A. McLaughlin, S. T. McWilliams, C. M. F. Mingarelli, C. Ng, D. J. Nice, R. S. Park, T. T. Pennucci, N. S. Pol, S. M. Ransom, P. S. Ray, A. Rasskazov, X. Siemens, J. Simon, R. Spiewak, I. H. Stairs, D. R. Stinebring, K. Stovall, J. Swiggum, S. R. Taylor, M. Vallisneri, R. van Haasteren, S. Vigeland, W. W. Zhu, and NANOGrav Collaboration. The NANOGrav 11 Year Data Set: Pulsar-timing Constraints on the Stochastic Gravitational-wave Background. ApJ, 859:47, May 2018.

[4] J. Antoniadis, P. C. C. Freire, N. Wex, T. M. Tauris, R. S. Lynch, M. H. van Kerkwijk, M. Kramer, C. Bassa, V. S. Dhillon, T. Driebe, J. W. T. Hessels, V. M. Kaspi, V. I. Kondratiev, N. Langer, T. R. Marsh, M. A. McLaughlin, T. T. Pennucci, S. M. Ransom, I. H. Stairs, J. van Leeuwen, J. P. W. Verbiest, and D. G. Whelan. A Massive Pulsar in a Compact Relativistic Binary. *Science*, 340:448, April 2013.

[5] M. Kramer, in prep.

[6] S. M. Ransom, I. H. Stairs, A. M. Archibald, J. W. T. Hessels, D. L. Kaplan, M. H. van Kerkwijk, J. Boyles, A. T. Deller, S. Chatterjee, A. Schechtman-Rook, A. Berndsen, R. S. Lynch, D. R. Lorimer, C. Karako-Argaman, V. M. Kaspi, V. I. Kondratiev, M. A. McLaughlin, J. van Leeuwen, R. Rosen, M. S. E. Roberts, and K. Stovall. A millisecond pulsar in a stellar triple system. Nature, 505:520–524, January 2014.

[7] A. M. Archibald, N. V. Gusinskaia, J. W. T. Hessels, A. T. Deller, D. L. Kaplan, D. R. Lorimer, R. S. Lynch, S. M. Ransom, and I. H. Stairs. Universality of free fall from the orbital motion of a pulsar in a stellar triple system. Nature, 559:73–76, July 2018.

[8] A. G. Lyne, M. Burgay, M. Kramer, A. Possenti, R. N. Manchester, F. Camilo, M. A. McLaughlin, D. R. Lorimer, N. D'Amico, B. C. Joshi, J. Reynolds, and P. C. C. Freire.

A Double-Pulsar System: A Rare Laboratory for Relativistic Gravity and Plasma Physics. *Science*, 303:1153–1157, February 2004.

[9] M. Burgay, N. D'Amico, A. Possenti, R. N. Manchester, A. G. Lyne, B. C. Joshi, M. A. McLaughlin, M. Kramer, J. M. Sarkissian, F. Camilo, V. Kalogera, C. Kim, and D. R. Lorimer. The Highly Relativistic Binary Pulsar PSR J0737-3039A: Discovery and Implications. In F. A. Rasio and I. H. Stairs, editors, *Binary Radio Pulsars*, volume 328 of *Astronomical Society of the Pacific Conference Series*, page 53, July 2005.

[10] A. G. Lyne, F. G. Smith, and D. A. Graham. Characteristics of the radio pulses from the pulsars. MNRAS, 153:337, 1971.

[11] A. G. Lyne. Mode changing in pulsar radiation. MNRAS, 153:27P, 1971.

[12] J. H. Taylor, R. N. Manchester, and G. R. Huguenin. Observations of pulsar radio emission. I - Total-intensity measurements of individual pulses. ApJ, 195:513–528, January 1975.

[13] D. H. Staelin and E. C. Reifenstein, III. Pulsating Radio Sources near the Crab Nebula. *Science*, 162:1481–1483, December 1968.

[14] J. M. Sutton, D. H. Staelin, and R. M. Price. Individual Radio Pulses from NP 0531. In R. D. Davies and F. Graham-Smith, editors, *The Crab Nebula*, volume 46 of *IAU Symposium*, page 97, 1971.

[15] D. C. Backer. Peculiar Pulse Burst in PSR 1237 + 25. Nature, 228:1297–1298, December 1970.

[16] D. C. Backer. Pulsar Nulling Phenomena. Nature, 228:42–43, October 1970.

[17] M. Kramer, A. G. Lyne, J. T. O'Brien, C. A. Jordan, and D. R. Lorimer. A Periodically Active Pulsar Giving Insight into Magnetospheric Physics. *Science*, 312:549–551, April 2006.

[18] A. Lyne, G. Hobbs, M. Kramer, I. Stairs, and B. Stappers. Switched Magnetospheric Regulation of Pulsar Spin-Down. *Science*, 329:408, July 2010.

[19] P. C. C. Freire, A. Ridolfi, M. Kramer, C. Jordan, R. N. Manchester, P. Torne, J. Sarkissian, C. O. Heinke, N. D'Amico, F. Camilo, D. R. Lorimer, and A. G. Lyne. Long-term observations of the pulsars in 47 Tucanae - II. Proper motions, accelerations and jerks. MNRAS, 471:857–876, October 2017.

[20] B. J. Prager, S. M. Ransom, P. C. C. Freire, J. W. T. Hessels, I. H. Stairs, P. Arras, and M. Cadelano. Using Long-term Millisecond Pulsar Timing to Obtain Physical Characteristics of the Bulge Globular Cluster Terzan 5. ApJ, 845:148, August 2017.

[21] M. Cadelano, E. Dalessandro, F. R. Ferraro, P. Miocchi, B. Lanzoni, C. Pallanca, and D. Massari. Proper Motions and Structural Parameters of the Galactic Globular Cluster M71. ApJ, 836:170, February 2017.

[22] R. P. Eatough, H. Falcke, R. Karuppusamy, K. J. Lee, D. J. Champion, E. F. Keane, G. Desvignes, D. H. F. M. Schnitzeler, L. G. Spitler, M. Kramer, B. Klein, C. Bassa, G. C. Bower, A. Brunthaler, I. Cognard, A. T. Deller, P. B. Demorest, P. C. C. Freire, A. Kraus, A. G. Lyne, A. Noutsos, B. Stappers, and N. Wex. A strong magnetic field around the supermassive black hole at the centre of the Galaxy. Nature, 501:391–394, September 2013.

[23] A. M. Matthews, D. J. Nice, E. Fonseca, Z. Arzoumanian, K. Crowter, P. B. Demorest, T. Dolch, J. A. Ellis, R. D. Ferdman, M. E. Gonzalez, G. Jones, M. L. Jones, M. T. Lam, L. Levin, M. A. McLaughlin, T. T. Pennucci, S. M. Ransom, I. H. Stairs, K. Stovall, J. K. Swiggum, and W. Zhu. The NANOGrav Nine-year Data Set: Astrometric Measurements of 37 Millisecond Pulsars. ApJ, 818:92, February 2016.

[24] L. G. Spitler, P. Scholz, J. W. T. Hessels, S. Bogdanov, A. Brazier, F. Camilo, S. Chatterjee, J. M. Cordes, F. Crawford, J. Deneva, R. D. Ferdman, P. C. C. Freire, V. M. Kaspi, P. Lazarus, R. Lynch, E. C. Madsen, M. A. McLaughlin, C. Patel, S. M. Ransom, A. Seymour, I. H. Stairs, B. W. Stappers, J. van Leeuwen, and W. W. Zhu. A repeating fast radio burst. Nature, 531:202–205, March 2016.

[25] D. Michilli, A. Seymour, J. W. T. Hessels, L. G. Spitler, V. Gajjar, A. M. Archibald, G. C. Bower, S. Chatterjee, J. M. Cordes, K. Gourdji, G. H. Heald, V. M. Kaspi, C. J. Law, C. Sobey, E. A. K. Adams, C. G. Bassa, S. Bogdanov, C. Brinkman, P. Demorest, F. Fernandez, G. Hellbourg, T. J. W. Lazio, R. S. Lynch, N. Maddox, B. Marcote, M. A. McLaughlin, Z. Paragi, S. M. Ransom, P. Scholz, A. P. V. Siemion, S. P. Tendulkar, P. van Rooy, R. S. Wharton, and D. Whitlow. An extreme magneto-ionic environment associated with the fast radio burst source FRB 121102. Nature, 553:182–185, January 2018.

[26] B. D. Metzger, E. Berger, and B. Margalit. Millisecond Magnetar Birth Connects FRB 121102 to Superluminous Supernovae and Long-duration Gamma-Ray Bursts. ApJ, 841:14, May 2017.

[27] B. Margalit and B. D. Metzger. A Concordance Picture of FRB 121102 as a Flaring Magnetar Embedded in a Magnetized Ion–Electron Wind Nebula. ApJ, 868:L4, November 2018.

[28] E. Platts, A. Weltman, A. Walters, S. P. Tendulkar, J. E. B. Gordin, and S. Kandhai. A Living Theory Catalogue for Fast Radio Bursts. *arXiv e-prints*, October 2018.

[29] M. T. Lam, J. M. Cordes, S. Chatterjee, M. L. Jones, M. A. McLaughlin, and J. W. Armstrong. Systematic and Stochastic Variations in Pulsar Dispersion Measures. ApJ, 821:66, April 2016.

[30] M. T. Lam, J. A. Ellis, G. Grillo, M. L. Jones, J. S. Hazboun, P. R. Brook, J. E. Turner, S. Chatterjee, J. M. Cordes, T. J. W. Lazio, M. E. DeCesar, Z. Arzoumanian, H. Blumer, H. T. Cromartie, P. B. Demorest, T. Dolch, R. D. Ferdman, E. C. Ferrara, E. Fonseca, N. Garver-Daniels, P. A. Gentile, V. Gupta, D. R. Lorimer, R. S. Lynch, D. R. Madison, M. A. McLaughlin, C. Ng, D. J. Nice, T. T. Pennucci, S. M. Ransom, R. Spiewak, I. H. Stairs, D. R. Stinebring, K. Stovall, J. K. Swiggum, S. J. Vigeland, and W. W. Zhu. A Second Chromatic Timing Event of Interstellar Origin toward PSR J1713+0747. ApJ, 861:132, July 2018.

[31] D. R. Madison, J. M. Cordes, Z. Arzoumanian, S. Chatterjee, K. Crowter, M. E. DeCesar, P. B. Demorest, T. Dolch, J. A. Ellis, R. D. Ferdman, E. C. Ferrara, E. Fonseca, P. A. Gentile, G. Jones, M. L. Jones, M. T. Lam, L. Levin, D. R. Lorimer, R. S. Lynch, M. A. McLaughlin, C. M. F. Mingarelli, C. Ng, D. J. Nice, T. T. Pennucci, S. M. Ransom, P. S. Ray, R. Spiewak, I. H. Stairs, K. Stovall, J. K. Swiggum, and W. W. Zhu. The NANOGrav 11 yr Data Set: Solar Wind Sounding through Pulsar Timing. ApJ, 872:150, February 2019.

[32] V. Ravi. Measuring the Circumgalactic and Intergalactic Baryon Contents with Fast Radio Bursts. ApJ, 872:88, February 2019.

[33] J. W. T. Hessels, L. G. Spitler, A. D. Seymour, J. M. Cordes, D. Michilli, R. S. Lynch, K. Gourdji, A. M. Archibald, C. G. Bassa, G. C. Bower, S. Chatterjee, L. Connor, F. Crawford, J. S. Deneva, V. Gajjar, V. M. Kaspi, A. Keimpema, C. J. Law, B. Marcote, M. A. McLaughlin, Z. Paragi, E. Petroff, S. M. Ransom, P. Scholz, B. W. Stappers, and S. P. Tendulkar. FRB 121102 Bursts Show Complex Time-Frequency Structure. *arXiv e-prints*, November 2018.

[34] S. R. Taylor, M. Vallisneri, J. A. Ellis, C. M. F. Mingarelli, T. J. W. Lazio, and R. van Haasteren. Are We There Yet? Time to Detection of Nanohertz Gravitational Waves Based on Pulsar-timing Array Limits. ApJ, 819:L6, March 2016.

[35] C. M. F. Mingarelli, T. J. W. Lazio, A. Sesana, J. E. Greene, J. A. Ellis, C.-P. Ma, S. Croft, S. Burke-Spolaor, and S. R. Taylor. The local nanohertz gravitational-wave landscape from supermassive black hole binaries. *Nature Astronomy*, 1:886–892, November 2017.

[36] C. M. Will. Testing the General Relativistic “No-Hair” Theorems Using the Galactic Center Black Hole Sagittarius A*. ApJ, 674:L25, February 2008.

[37] S. J. Chamberlin and X. Siemens. Stochastic backgrounds in alternative theories of gravity: Overlap reduction functions for pulsar timing arrays. Phys. Rev. D, 85(8):082001, April 2012.

[38] N. Yunes and X. Siemens. Gravitational-Wave Tests of General Relativity with Ground-Based Detectors and Pulsar-Timing Arrays. *Living Reviews in Relativity*, 16:9, November 2013.

[39] N. J. Cornish, L. O’Beirne, S. R. Taylor, and N. Yunes. Constraining Alternative Theories of Gravity Using Pulsar Timing Arrays. *Physical Review Letters*, 120(18):181101, May 2018.

[40] X. Siemens, V. Mandic, and J. Creighton. Gravitational-Wave Stochastic Background from Cosmic Strings. *Physical Review Letters*, 98(11):111101, March 2007.

[41] Alexei A. Starobinsky. Spectrum of relict gravitational radiation and the early state of the universe. *JETP Lett.*, 30:682–685, 1979. [,767(1979)].

[42] V. A. Rubakov, M. V. Sazhin, and A. V. Veryaskin. Graviton creation in the inflationary universe and the grand unification scale. *Physics Letters B*, 115:189–192, September 1982.

[43] L. F. Abbott and M. B. Wise. Constraints on generalized inflationary cosmologies. *Nuclear Physics B*, 244:541–548, October 1984.

[44] E. Witten. Cosmic separation of phases. Phys. Rev. D, 30:272–285, July 1984.

[45] C. Caprini, R. Durrer, and X. Siemens. Detection of gravitational waves from the QCD phase transition with pulsar timing arrays. Phys. Rev. D, 82(6):063511, September 2010.

[46] M. Kramer, I. H. Stairs, R. N. Manchester, M. A. McLaughlin, A. G. Lyne, R. D. Ferdman, M. Burgay, D. R. Lorimer, A. Possenti, N. D'Amico, J. M. Sarkissian, G. B. Hobbs, J. E. Reynolds, P. C. C. Freire, and F. Camilo. Tests of general relativity from timing the double pulsar. *Science*, 314(5796):97–102, 2006.

[47] P. C. C. Freire, S. M. Ransom, S. Bégin, I. H. Stairs, J. W. T. Hessels, L. H. Frey, and F. Camilo. Eight New Millisecond Pulsars in NGC 6440 and NGC 6441. ApJ, 675:670–682, March 2008.

[48] N. Wang, R. N. Manchester, and S. Johnston. Pulsar nulling and mode changing. MNRAS, 377:1383–1392, May 2007.

[49] J. Gil, J. Kijak, O. Maron, and M. Sendyk. Drifting subpulses and polarization of pulsar radiation. A&A, 301:177, September 1995.

[50] A. G. Lyne, C. A. Jordan, F. Graham-Smith, C. M. Espinoza, B. W. Stappers, and P. Weltevrede. 45 years of rotation of the Crab pulsar. MNRAS, 446:857–864, January 2015.

[51] A. Lyne, G. Hobbs, M. Kramer, I. Stairs, and B. Stappers. Switched Magnetospheric Regulation of Pulsar Spin-Down. *Science*, 329:408, July 2010.

[52] N. Mahajan, M. H. van Kerkwijk, R. Main, and U.-L. Pen. Mode Changing and Giant Pulses in the Millisecond Pulsar PSR B1957+20. ApJ, 867:L2, November 2018.

[53] R. M. Shannon, J.-P. Macquart, K. W. Bannister, R. D. Ekers, C. W. James, S. Osłowski, H. Qiu, M. Sammons, A. W. Hotan, M. A. Voronkov, R. J. Beresford, M. Brothers, A. J. Brown, J. D. Bunton, A. P. Chippendale, C. Haskins, M. Leach, M. Marquarding, D. McConnell, M. A. Pilawa, E. M. Sadler, E. R. Troup, J. Tuthill, M. T. Whiting, J. R. Allison, C. S. Anderson, M. E. Bell, J. D. Collier, G. Gürkan, G. Heald, and C. J. Riseley. The dispersion-brightness relation for fast radio bursts from a wide-field survey. Nature, 562:386–390, October 2018.

[54] CHIME/FRB Collaboration, M. Amiri, K. Bandura, M. Bhardwaj, P. Boubel, M. M. Boyce, P. J. Boyle, C. Brar, M. Burhanpurkar, P. Chawla, J. F. Cliche, D. Cubranic, M. Deng, N. Denman, M. Dobbs, M. Fandino, E. Fonseca, B. M. Gaensler, A. J. Gilbert, U. Giri, D. C. Good, M. Halpern, D Hanna, A. S. Hill, G. Hinshaw, C. Höfer, A. Josephy, V. M. Kaspi, T. L. Landecker, D. A. Lang, K. W. Masui, R. Mckinven, J. Mena-Parra, M. Merryfield, N. Milutinovic, C. Moatti, A. Naidu, L. B. Newburgh, C. Ng, C. Patel, U. Pen, T. Pinsonneault-Marotte, Z. Pleunis, M. Rafiei-Ravandi, S. M. Ransom, A. Renard, P. Scholz, J. R. Shaw, S. R. Siegel, K. M. Smith, I. H. Stairs, S. P. Tendulkar, I. Tretyakov, K. Vanderlinde, and

P. Yadav. Observations of fast radio bursts at frequencies down to 400 megahertz. Nature, 566:230–234, January 2019.

[55] CHIME/FRB Collaboration, M. Amiri, K. Bandura, M. Bhardwaj, P. Boubel, M. M. Boyce, P. J Boyle, C. . Brar, M. Burhanpurkar, T. Cassanelli, P. Chawla, J. F. Cliche, D. Cubranic, M. Deng, N. Denman, M. Dobbs, M. Fandino, E. Fonseca, B. M. Gaensler, A. J. Gilbert, A. Gill, U. Giri, D. C. Good, M. Halpern, D. S. Hanna, A. S. Hill, G. Hinshaw, C. Höfer, A. Josephy, V. M. Kaspi, T. L. Landecker, D. A. Lang, H.-H. Lin, K. W. Masui, R. Mckinven, J. Mena-Parra, M. Merryfield, D. Michilli, N. Milutinovic, C. Moatti, A. Naidu, L. B. Newburgh, C. Ng, C. Patel, U. Pen, T. Pinsonneault-Marotte, Z. Pleunis, M. Rafiei-Ravandi, M. Rahman, S. M. Ransom, A. Renard, P. Scholz, J. R. Shaw, S. R. Siegel, K. M. Smith, I. H. Stairs, S. P. Tendulkar, I. Tretyakov, K. Vanderlinde, and P. Yadav. A second source of repeating fast radio bursts. Nature, 566:235–238, January 2019.

[56] S. Inoue. Probing the cosmic reionization history and local environment of gamma-ray bursts through radio dispersion. MNRAS, 348:999–1008, March 2004.

[57] NASA Technosignatures Workshop Participants. NASA and the Search for Technosignatures: A Report from the NASA Technosignatures Workshop. *arXiv e-prints*, page arXiv:1812.08681, Dec 2018.

[58] M. T. Lam. Optimizing Pulsar Timing Array Observational Cadences for Sensitivity to Low-frequency Gravitational-wave Sources. ApJ, 868:33, November 2018.

[59] T. Dolch, NANOGrav Collaboration, J. A. Ellis, S. Chatterjee, J. M. Cordes, M. T. Lam, C. Bassa, B. Bhattacharyya, D. J. Champion, I. Cognard, K. Crowter, P. B. Demorest, J. W. T. Hessels, G. Janssen, F. A. Jenet, G. Jones, C. Jordan, R. Karuppusamy, M. Keith, V. I. Kondratiev, M. Kramer, P. Lazarus, T. J. W. Lazio, D. R. Lorimer, D. R. Madison, M. A. McLaughlin, N. Palliyaguru, D. Perrodin, S. M. Ransom, J. Roy, R. M. Shannon, R. Smits, I. H. Stairs, B. W. Stappers, D. R. Stinebring, K. Stovall, J. P. W. Verbiest, and W. W. Zhu. Single-Source Gravitational Wave Limits From the J1713+0747 24-hr Global Campaign. In *Journal of Physics Conference Series*, volume 716 of *Journal of Physics Conference Series*, page 012014, May 2016.

[60] X.-J. Zhu, G. Hobbs, L. Wen, W. A. Coles, J.-B. Wang, R. M. Shannon, R. N. Manchester, M. Bailes, N. D. R. Bhat, S. Burke-Spolaor, S. Dai, M. J. Keith, M. Kerr, Y. Levin, D. R. Madison, S. Osłowski, V. Ravi, L. Toomey, and W. van Straten. An all-sky search for continuous gravitational waves in the Parkes Pulsar Timing Array data set. MNRAS, 444:3709–3720, November 2014.