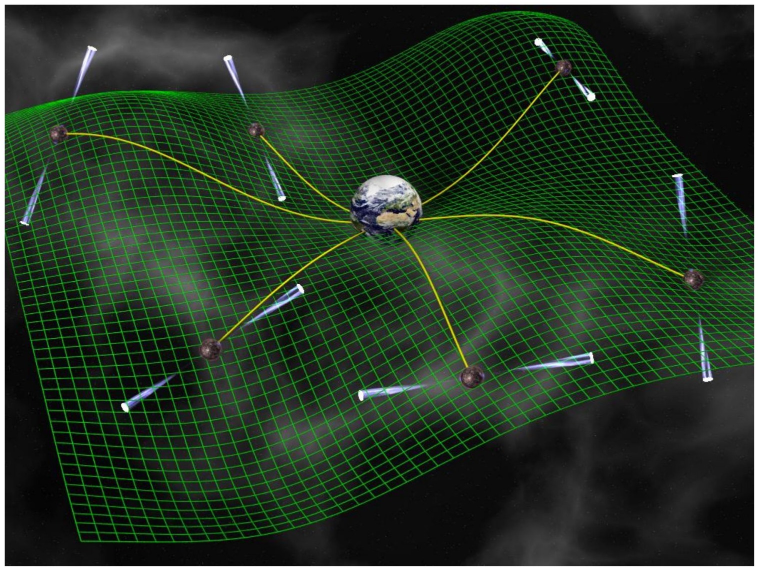
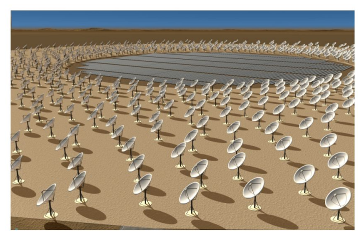
Gravitational Wave Astronomy Using Pulsars: Massive Black Hole Mergers & the Early Universe

A White Paper for the Astronomy & Astrophysics Decadal Survey

NANOGrav: The North American Nanohertz Observatory for Gravitational Waves





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1 Science Opportunity: Exploring the Low-Frequency Gravitational Wave Spectrum

Gravitational waves are fluctuations in the fabric of spacetime predicted by Einstein's theory of general relativity. Using a collection of millisecond pulsars as high-precision clocks, the nHz band of this radiation is likely to be detected within the next decade (Jenet et al. 2005). The fundamental questions that will be addressed by these studies are:

1. **What is the nature of space and time?** We suspect the local spacetime metric is perturbed by the cumulative effect of gravitational waves (GWs) emitted by numerous massive black hole (MBH) binaries. What is the energy density contained in this stochastic background of GWs?

2. **How did structure form in the Universe?** Detection of GWs in the pulsar timing band will tell us whether MBHs formed through accretion and/or merger events.

3. **What is the structure of individual MBH binary systems?** Recovering the gravitational waveform from individual systems will give us unprecedented insight.

4. **What contribution do cosmic strings make to the GW background (GWB)?** The detection of cosmic strings would open a window into the early universe at a time inaccessible via the electromagnetic spectrum.

5. **What currently unknown sources of GW exist in the Universe?** Every time a new piece of the electromagnetic spectrum has been opened up to observations (e.g. radio, X-rays, and γ-rays), new and entirely unexpected classes of objects have been discovered.

The existence of GWs has already been inferred via the Nobel Prize-winning observations of the orbital decay of the PSR B1913+16 binary system (Hulse and Taylor 1975). While compelling and entirely consistent with general relativity, the behavior of this system offers only indirect evidence for GWs – the objective for the 21$^{\text{st}}$ century is the *direct* detection and exploitation of GWs as a non-photonic probe of the Universe.

Millisecond pulsars are old neutron stars that have been spun-up by mass accretion from a companion star to spin rates of hundreds of Hz. The rotational stability of these pulsars surpasses the majority of "normal" pulsars, and rivals that of atomic clocks. Pulsars emit a beam of radio waves that sweeps past the Earth once per rotation, appearing to us as a series of pulses. By precisely measuring the times of arrival of the the radio pulses on Earth, we can search for tiny perturbations due to GWs. This is distinct from detecting GWs emitted by the pulsars themselves. Rather, pulsar timing provides a means to detect any gravitational radiation crossing the Earth–pulsar line of sight, potentially from sources far outside our galaxy.

All modern GW observatories operate on the principle that passing GWs cause tiny deviations in the distance between point masses. GWs are detected as changes in the light travel time between the points. In the case of the *pulsar timing array* (PTA) the path from each pulsar to Earth forms an arm of the GW detector. This detector is most sensitive to GWs with periods comparable to the total observation timespan, typically 1–10 years, which corresponds to nHz frequencies. The most desirable PTA involves millisecond pulsars evenly distributed on the sky. A passing GW modifies the spacetime around the Earth in a manner that produces correlated shifts in the pulse times of arrival from the different pulsars.

The North American Nanohertz Observatory for Gravitational Waves (NANOGrav)[1] is an organization of astronomers, primarily from the U.S. and Canada, working to achieve GW detection using pulsar timing. Current projects include ongoing high-precision pulsar timing programs at Arecibo Observatory[2] and the Green Bank Telescope (GBT)[3]. Here we describe the potential sources of low-frequency GWs (§2) and the current status and key advances needed for the detection and exploitation of GWs through pulsar timing (§3).

2 Science Context: Gravitational Wave Astrophysics

2.1 Mergers of MBH Binaries

It is now well established that mergers are an essential part of galaxy formation and evolution, and that massive black holes (MBHs, $M > 10^6\,\mathrm{M}_\odot$) exist in the nuclei of most, if not all, large galaxies (see e.g. Ferrarese and Merritt 2000). Consequently, the product galaxy of many mergers will contain two MBHs. Due to dynamical friction, these two MBHs sink toward the center of the resulting galaxy's potential.

As a MBH binary hardens, the strength of its GW emission increases. Once the system reaches a point where its semi-major axis is $\lesssim$1 pc, GW emission becomes the dominant form of energy loss, and the two MBHs continue to spiral towards each other. Further, as the binary tightens, the frequency of the GW emission increases. For reference, an MBH binary with total mass M and semi-major axis a produces GWs with a frequency

$$f \sim 1\,\mathrm{nHz}\left(\frac{M}{10^9\,\mathrm{M}_\odot}\right)^{1/2}\left(\frac{a}{1000\,\mathrm{AU}}\right)^{3/2}. \tag{1}$$

Despite theoretical difficulties in fully understanding the production of these hard binary systems, observational results continue to provide evidence for their existence. One dramatic piece of evidence is the galaxy B0402+679, where high resolution radio imaging reveals two radio-loud nuclei separated by only 7 pc (Rodriguez et al. 2006). Follow-up observations of SDSS galaxies show strong evidence for MBH binaries with semi-major axes less than 1 kpc. A small number of these galaxies show [O III] emission offset from the systemic redshift of the host galaxy. In two specific cases double-lined [O III] profiles have been found, suggesting double AGN (Comerford et al. 2008). Most recently, a dual-broad-line QSO system has been identified where the inferred MBH binary separation is only 0.1 pc (Boroson and Lauer 2009).

The general relativistic metric perturbation amplitude due to a GW is commonly presented in terms of a dimensionless quantity called the *characteristic strain* h_c. The ensemble of MBH binaries is expected to produce a GWB whose amplitude spectrum has a power-law shape, $h_c(f) \propto f^\alpha$, for a GW frequency f, where it is predicted that $\alpha = -2/3$ (Phinney 2001; Jaffe and Backer 2003). The strain amplitude is less certain, but expected to be in the range 10^{-16} to 10^{-15} at $f = 1$ yr^{-1} (Jaffe and Backer 2003; Sesana et al. 2008). The

[1] `http://www.nanograv.org`

[2] The Arecibo Observatory is a facility of the National Astronomy and Ionosphere Center, operated by Cornell University under a cooperative agreement with the National Science Foundation

[3] The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc

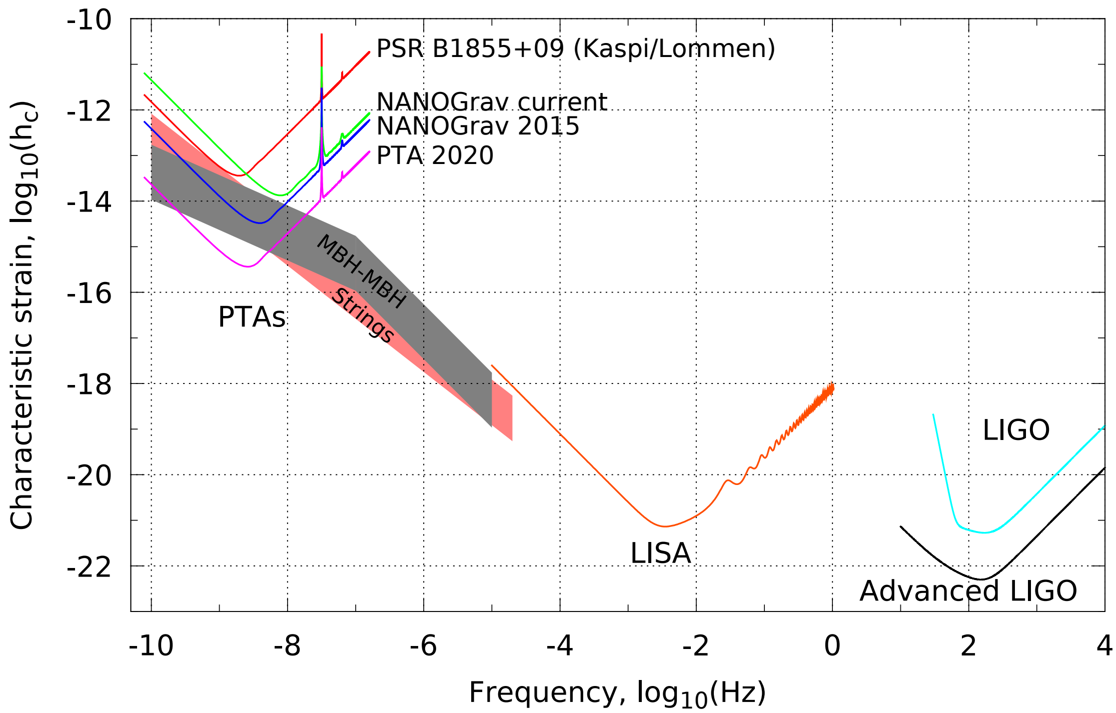

Figure 1: Comparison of current and planned GW detectors, showing characteristic strain (h_c) sensitivity versus frequency along with expected source strengths. The Laser Interferometer Gravitational Wave Observatory (LIGO), the Laser Interferometer Space Antenna (LISA) and PTAs occupy complementary parts of the GW spectrum.

main contributors to this nHz GWB signal are MBH systems of mass $M > 10^8\,\mathrm{M}_\odot$. Current pulsar timing experiments limit the GWB spectral amplitude to $\lesssim 7 \times 10^{-15}$, depending somewhat on the value of α (Hobbs 2005; Jenet et al. 2006; Lommen et al. 2009). With longer spans of data, PTA experiments become sensitive to lower GW frequencies, where the expected signal is stronger. The ongoing NANOGrav pulsar timing program will achieve a GW sensitivity well into the predicted h_c amplitude range in the next 3–5 years (Figures 1 and 2).

As these limits improve, and ultimately progress to a detection, they provide a new view of the history of MBH mergers throughout the Universe. Furthermore, measurements of the GWB spectral shape near 10 nHz could distinguish between various models of MBH binary formation (Sesana et al. 2008). LISA will be sensitive to the final MBH-MBH coalescence events for systems with $M < 10^7\,\mathrm{M}_\odot$. Pulsar timing arrays and LISA thus provide complementary views of these sources, encompassing the full range of MBH masses.

2.2 Gravitational Wave Bursts and Individual Sources

Pulsar timing has already been used to constrain GW emission from individual sources. For example, a proposed MBH binary within the radio galaxy 3C 66B (Sudou et al. 2003) was ruled out when its GW signature was not detected in existing millisecond pulsar data sets (Jenet et al. 2004).

GW bursts (events lasting less than a few years) are also potentially detectable. Sources might include highly eccentric systems near periapsis or the final inspiral of merging black

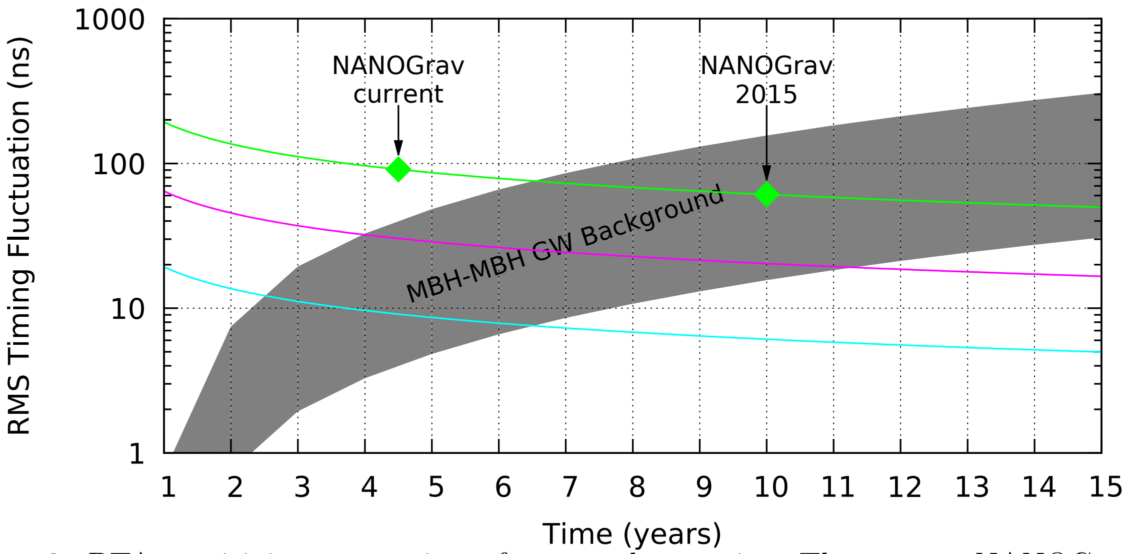

Figure 2: PTA sensitivity versus times for several scenarios: The current NANOGrav observing program, and potential future PTAs of 3 and 10 times better GW sensitivity. The shaded area shows the expected amplitude range of the MBH-MBH GW signal (see §2.1).

holes (Lommen et al. 2009). GW waveforms of such events would encode detailed information about the burst source, such as the masses and spins of the inspiraling black holes.

2.3 Cosmic Strings and Exotica

Pulsar timing experiments may provide a unique window into particle physics at the highest energy scales. Cosmic strings, theorized line-like topological defects, may form during phase transitions in the early Universe, due to the rapid cooling that took place after the Big Bang (Kibble 1976). Recently it was shown that cosmic string production is generic in supersymmetric grand unified theories (Jeannerot et al. 2003). Furthermore, string theoretical cosmology predicts the formation of so-called *cosmic superstrings*, different from regular field theoretical cosmic strings (Polchinski 2005).

Cosmic strings and superstrings are expected to produce a stochastic GWB analogous to the cosmic microwave background, as well as bursts of GWs (Damour and Vilenkin 2001, 2005; Siemens et al. 2006). Because of their sensitivity at very low frequencies, pulsar timing arrays place the best constraints on viable cosmic string models (Siemens et al. 2007). With increased sensitivity, PTAs could detect cosmic (super)strings.

Pulsar timing experiments could result in the detection of other exotica. Gravitational waves are a means for probing the fundamental structure of the space-time of the Universe. With less than 20% of the matter in the Universe emitting electromagnetic radiation, we are likely to be surprised by what we “see” in GWs, the generation of which is caused directly by the movement of mass, not the coupling to the electromagnetic force.

3 Key Advances For A Pulsar Gravitational Wave Observatory

The sensitivity of a PTA is determined by the number and distribution of the pulsars under observation, the cadence with which they are observed, and the precision with which the pulse times of arrival are measured.

Pulsar timing precision is quantified by the root-mean-square (RMS) residual pulse arrival

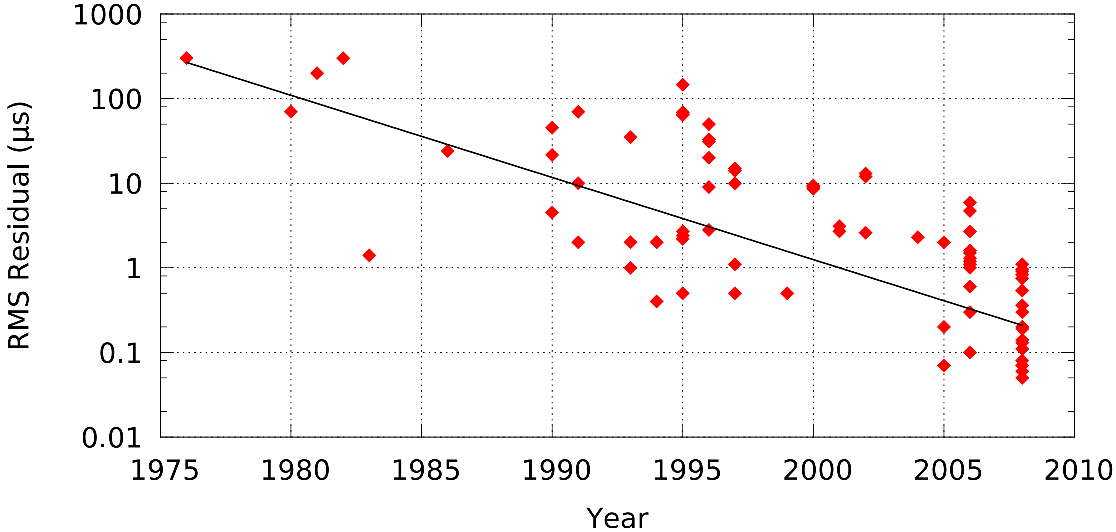

Figure 3: Published RMS pulsar timing residuals versus time, showing exponential improvement (Demorest & Jenet, 2009) which positions us to detect GWs within the next decade.

time after a χ^2 fit to a standard model of pulsar rotation, binary motion, Earth motion, and interstellar propagation effects. The RMS residual for a given source is determined by its flux density, characteristic pulse shape, emission stability, rotation stability, the scintillation and scattering of its signal as it traverses the interstellar medium, and the radio telescope equipment used to observe it (telescope area, system temperature T_{sys}, bandwidth, data acquisition instrumentation, and detection algorithms). Currently there are several pulsars with RMS residuals approaching 100 ns, and roughly 20 more with residuals less than 1 μs. Jenet et al. (2005) showed that with 100-ns level timing on 20 pulsars, the stochastic GWB is detectable in ∼5 years. Realizing this goal will come from a two-pronged approach: We must find additional pulsars suitable for high-precision timing and also improve the timing precision of known sources.

Demorest and Jenet (2009) have recently suggested that published RMS pulsar timing residuals over the past two decades show an exponential improvement with time analogous to Moore's Law for computer processors (Figure 3), improving by a factor of 2 every ∼3 years. Several observational advances are required if we are to continue this trend:

A. Pulsar Surveys The sensitivity of a PTA scales directly with the number of pulsars in the array (Jenet et al. 2005). Given sufficient observing time, we expect to be make a detection of GWs with currently known pulsars within 5 years. However, to fully characterize the gravitational waveforms and to maximize the scientific return, more high-timing precision millisecond pulsars are needed. It is especially important to include more pulsars in directions widely separated from the current set of objects. Three current searches are now turning up such objects: the PALFA L-band multibeam survey at Arecibo, the GBT 350 MHz drift scan survey, and the new Parkes L-band Digital Survey. In the next decade, a new GBT low-frequency pulsar survey would be particularly advantageous because it would increase the number of Northern hemisphere pulsars. This area of the sky is currently under-represented in timing arrays. As pulsar flux increases at low radio frequencies (from ∼1 mJy at 1.4 GHz to ∼10 mJy at 400 MHz), this survey will identify many new pulsars.

Table 1: International PTA telescope time in terms of a 100-m dish with $T_{sys} = 30$K.

Telescope	Diameter (m)	ϵ[a]	T_{sys} (K)	$\epsilon A/T_{sys}$ (normalized)	Allocated Time/mo (h)	100-m equiv. time (h)
Current Projects						
Arecibo	305	0.5	30	5.0	8	200
Europe	∼100	0.7	30	0.7	125[b]	60
GBT	100	0.7	20	1.1	18	20
Parkes	64	0.6	25	0.3	100	10
Future Projects						
Europe-LEAP	200[c]	0.7	30	3.0	24	220
EVLA	130[c]	0.5	30	0.9	*TBD*	–
ATA-350	110[c]	0.6	40	0.6	*TBD*	–
SKA	750[c]	0.6	35	30	*TBD*	–
Total (Current)						290
Requirements						
GW Detection[d]						500
Advanced GW Study[e]						>1000

[a] Includes the effects of reflector efficiency and partial illumination.
[b] This represents the combined observing time of four European 100-m class dishes.
[c] Equivalent single-dish diameter.
[d] 20 pulsars with $\lesssim$100 ns RMS timing.
[e] >40 pulsars with $\lesssim$100 ns RMS timing.

B. Time on High Sensitivity Facilities To achieve the necessary precision on these faint objects we require multifrequency observations on 100-m class or larger radio telescopes. Four-frequency observations are necessary in order to precisely fit for the frequency-dependent dispersion caused by free electrons in the ISM, which typically produces perturbations of $\sim\mu$s. Table 1 illustrates the total worldwide telescope time being devoted to pulsar timing with the goal of GW detection, weighted by telescope sensitivity. For reference, several future facilities are listed: By 2011 five European telescopes will be combined into a phased array, the Large European Array for Pulsars (LEAP), with an effective area equivalent to a 200-m single dish. Other future facilities are the full 350-dish Allen Telescope Array (ATA-350), the Expanded Very Large Array (EVLA) and the Square Kilometer Array (SKA).

The table shows that world resources currently provide about 300 100-m hours per month. We estimate that at minimum, GW detection requires ∼500 100-m hours per month, based on observing 20 pulsars every 2 weeks, for 3 hours at each of 4 radio frequencies in order to obtain 100-ns or better timing precision. To fully characterize the GW sources requires at least twice as many pulsars (Lee et al. 2008), and an effort to upgrade receivers and backend instrumentation to handle ∼1 GHz total bandwidth. This process is underway at many existing radio telescopes. Clearly, to fulfill the goal of detecting and characterizing the stochastic GWB, as well as continuous and burst sources, we require more resources than are currently available. The table suggests that the ATA and EVLA could possibly provide the additional time needed in the near future, and the SKA farther in the future.

NANOGrav, the Parkes Pulsar Timing Array (PPTA) and the EPTA are in the process of organizing themselves as the International Pulsar Timing Array (IPTA) for the purpose of optimizing these international resources. In addition to sensitivity, a full optimiziation must consider such additional factors as telescope sky coverage, frequency agility, and backend instrumentation.

C. Algorithm Development Algorithms for both radio pulse detection and GW detection must be improved. With increased telescope sensitivity, pulse arrival times are increasingly susceptible to systematic effects. Among the algorithms to be developed are methods for characterizing and compensating for the effects of the interstellar medium (Foster and Backer 1990; You et al. 2007); methods for effectively mitigating radio frequency interference (Stairs et al. 2000); and methods for fully utiziling the available polarization information (van Straten 2006). Algorithms for optimal extraction of the GW signal will be built upon the recent advances of LIGO and LISA data analysis; some of this work has already begun (Jenet et al. 2005; van Haasteren et al. 2008; Anholm et al. 2008; Lommen et al. 2009).

4 Summary

Given sufficient resources, we expect to detect GWs through the IPTA within the next five years. We also expect to gain new astrophysical insight on the detected sources and, for the first time, characterize the universe in this completely new regime. The international effort is well on its way to achieving its goals. With sustained effort, and sufficient resources, this work is poised to offer a new window into the Universe by 2020.

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