The International Pulsar Timing Array project: using pulsars as a gravitational wave detector

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Abstract
The International Pulsar Timing Array project combines observations of pulsars from both northern and southern hemisphere observatories with the main aim of detecting ultra-low frequency (∼10^{-9}–10^{-8} Hz) gravitational waves. Here we introduce the project, review the methods used to search for gravitational waves emitted from coalescing supermassive binary black-hole systems in the centres of merging galaxies and discuss the status of the project.

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1. Introduction
Since their discovery (Hewish et al 1968), pulsars have been repeatedly monitored by many large radio telescopes. The characteristic signature of a radio pulsar is a regular train of pulsed radiation. The intensity, shape and arrival times of the pulses are determined by the physical phenomena causing the emission, the pulsar’s magnetosphere, the pulse propagation through the interstellar medium and effects caused by the detection systems at the observatory. As emphasized throughout this paper, encoded into the pulse arrival times will also be information relating to gravitational waves (GWs) passing the Earth and/or the pulsar.

Pulsar observations have aided many new discoveries in physics and astronomy. For instance, the first extrasolar planets were discovered around a pulsar (Wolszczan and Frail 1992), the first observational evidence for gravitational waves was obtained by studying a pulsar–neutron star binary system (Hulse and Taylor 1975) and the most stringent tests of general relativity in the strong-field limit came from pulsar observations (Kramer et al 2006).

These results all relied on a technique known as ‘pulsar timing’. Details of this technique have been described numerous times in the literature (see Lorimer and Kramer (2005) for an overview and Edwards et al (2006) for full details of the method). In brief, the observed pulse times-of-arrival (TOAs) are compared with a prediction for the arrival times obtained with a model of the spin, astrometric and orbital parameters of the pulsar and details of the pulse propagation through the interstellar medium. The deviations between the predicted and the observed TOAs are known as the pulsar ‘timing residuals’ and indicate unmodelled effects, i.e. \( R_i = (\phi_i - N_i) / \nu \) where \( \phi_i \) describes the time evolution of the pulse phase based on the model pulse frequency (\( \nu \)) and its derivatives. \( N_i \) is the nearest integer to \( \phi_i \). GW signals are not included in a pulsar timing model and, hence, any such waves will induce residuals. Unfortunately, the expected signal induced by GWs is small, with typical residuals being <100 ns.
The TOA precision achievable for the majority of pulsars is $\sim 1$ ms and most pulsars show long-term timing irregularities that would make the detection of the expected GW signal difficult or impossible (e.g. Hobbs et al 2006). However, a sub-set of the pulsar population, the millisecond pulsars, have very high spin rates and much smaller timing irregularities and can be observed with much greater TOA precision. Recent observations of PSR J0437−4715 have shown that TOA precisions of $\sim 30$ ns can be achieved (see section 4) and for over 10 years the root-mean-square (rms) timing residuals are 200 ns (Verbiest et al 2008).

In section 2 we describe the induced timing residuals caused by GWs. The expected sources of detectable GW signals are given in section 3. We summarize the International Pulsar Timing Array project in section 4 and highlight future telescopes and timing array projects in section 5.

2. Induced timing residuals caused by gravitational waves

Sazhin (1978) and Detweiler (1979) first showed that a GW signal causes a fluctuation in the observed pulse frequency $\delta \nu/\nu$ which affects the pulsar timing residuals at time $t$ from the initial observation as

$$R(t) = -\int_0^t \frac{\delta \nu(t)}{\nu} \, dt.$$  \hspace{1cm} (1)

The Doppler shift can be shown to have the form

$$\frac{\delta \nu}{\nu} = H_{ij}^e \left( h_{ij}^e - h_{ij}^p \right)$$ \hspace{1cm} (2)

where $h_{ij}^e$ is the GW strain at the Earth at the time of observation, $h_{ij}^p$ is the strain at the pulsar when the electromagnetic pulse was emitted (typically $\sim 1000$ years ago) and $H_{ij}$ is a geometrical term that depends upon the angle between the Earth, pulsar and GW source. This equation was derived assuming a plane gravitational wave and is accurate to first order in $h_{ij}$ for all GW wavelengths. Note that this expression holds even if the wave is not sinusoidal. Full details of the exact form of the induced residuals are given by Hobbs et al (2009a).

Standard pulsar timing techniques absorb any low-frequency GWs by fitting for the pulsar’s spin-down and so the time span of the data provides a lower bound on the GW frequencies that are detectable (currently $>10^{-9}$ Hz). Pulsars are typically observed only once every few weeks and so the data sampling limits the maximum detectable GW frequency to $\sim 10^{-7}$ Hz.

It is not possible to determine the exact origin of the timing residuals with a single pulsar data set. For instance, residuals may be caused by irregularities in terrestrial time standards, errors in the planetary ephemeris, irregular spin-down of the pulsar, calibration effects or GWs. These different effects may be distinguished by searching for correlations in the residuals of many pulsars. Residuals caused by the irregular spin-down of one pulsar will be uncorrelated with the residuals observed for a different pulsar. If there are irregularities in terrestrial time standards, then the residuals for all pulsars will be correlated. For an isotropic, stochastic GW background, the GW strain at each pulsar will be uncorrelated, but the GW strain at the Earth provides a common signal. The expected correlation as a function of angular separation between two pulsars was determined by Hellings and Downs (1983) and is shown in figure 1. Note that this figure shows the expected function for GWs described by general relativity. Lee et al (2008) produced similar angular correlation functions for more general theories of gravity.
3. Expected sources of gravitational waves

Expected sources of GWs in the pulsar frequency band can be divided into (1) single persistent sources, (2) individual burst sources and (3) stochastic GW backgrounds. Here we will only consider the GW emission from coalescing supermassive binary black-hole systems in the centres of merging galaxies. Details on the GW emission from other sources such as cosmic strings or from the inflationary era can be found in Maggiore (2000).

Sudou et al (2003) obtained observational evidence for a coalescing supermassive black-hole binary system at the centre of the radio galaxy 3C66B. Jenet et al (2004) calculated the expected induced timing residuals from such a system (see figure 2) and, by comparison with actual pulsar data (Kaspi et al 1994), were able to rule out the existence of the postulated...
Table 1. Pulsars observed as part of the International Pulsar Timing Array project. The best possible rms values for observations (with current observing systems) from the PPTA, EPTA and NANOGrav projects are estimated in the final three columns.

| PSR B | PSR J | P (ms) | P_b (d) | S1400 (mJy) | Array | PPTA (μs) | EPTA (μs) | NANOGrav (μs) |
|-------|-------|--------|---------|-------------|-------|-----------|-----------|---------------|
| – J0030+0451 | 4.87 | – | 0.6 | EPTA, NANOGrav | – | 0.54 | 0.31 |
| – J0218+4232 | 2.32 | 2.03 | 0.9 | NANOGrav | – | – | 4.81 |
| – J0437–4715 | 5.76 | 5.74 | 142.0 | PPTA | 0.03 | – | – |
| – J0613–0200 | 3.06 | 1.20 | 1.4 | PPTA, EPTA, NANOGrav | 0.71 | 0.45 | 0.50 |
| J0621+1002 | 28.85 | 8.32 | 1.9 | EPTA | – | 9.58 | – |
| – J0711–6830 | 5.49 | – | 1.6 | PPTA | 1.32 | – | – |
| – J0751+1807 | 3.48 | 0.3 | 3.2 | EPTA | – | 0.78 | – |
| – J0900–3144 | 11.1 | 18.7 | 3.8 | EPTA | – | 1.55 | – |
| – J1012+5307 | 5.26 | 0.60 | 3.0 | EPTA, NANOGrav | – | 0.32 | 0.61 |
| – J1022+1001 | 16.45 | 7.81 | 3.0 | PPTA, EPTA | 0.37 | 0.48 | – |
| – J1024–0719 | 5.16 | – | 0.7 | PPTA, EPTA | 0.43 | 0.25 | – |
| – J1045–4509 | 7.47 | 4.08 | 3.0 | PPTA | 2.68 | – | – |
| – J1455–3330 | 7.99 | 76.17 | 1.2 | EPTA, NANOGrav | – | 3.83 | 1.60 |
| – J1600–3053 | 3.60 | 14.35 | 3.2 | EPTA, PPTA | 0.32 | 0.23 | – |
| – J1603–7202 | 14.84 | 6.31 | 3.0 | PPTA | 0.70 | – | – |
| – J1640+2224 | 3.16 | 175.46 | 2.0 | EPTA, NANOGrav | – | 0.45 | 0.19 |
| – J1643–1224 | 4.62 | 147.02 | 4.8 | PPTA, EPTA, NANOGrav | 0.57 | 0.56 | 0.53 |
| – J1713+0747 | 4.57 | 67.83 | 8.0 | PPTA, EPTA, NANOGrav | 0.15 | 0.07 | 0.04 |
| – J1730–2304 | 8.12 | – | 4.0 | PPTA, EPTA | 0.83 | 1.01 | – |
| – J1732–5049 | 5.31 | 5.26 | – | PPTA | 1.74 | – | – |
| – J1738+0333 | 5.85 | 0.35 | – | NANOGrav | – | – | 0.24 |
| – J1741+1351 | 3.75 | 16.34 | – | NANOGrav | – | – | 0.19 |
| – J1744–1134 | 4.08 | – | 3.0 | PPTA, EPTA, NANOGrav | 0.21 | 0.14 | 0.14 |
| – J1751–2857 | 3.91 | 110.7 | 0.06 | EPTA | – | 0.90 | – |
| J1821–24 | J1824–2452 | 3.05 | – | 0.2 | PPTA, EPTA | 0.39 | 0.24 | – |
| – J1853+1303 | 4.09 | 115.65 | 0.4 | NANOGrav | – | – | 0.17 |
| B1855+09 | B1857+0943 | 5.37 | 12.33 | 5.0 | PPTA, EPTA, NANOGrav | 0.82 | 0.44 | 0.25 |
| – J1909–3744 | 2.95 | 1.53 | 3.0 | PPTA, EPTA, NANOGrav | 0.19 | 0.04 | 0.15 |
| – J1910+1256 | 4.98 | 58.47 | 0.5 | EPTA, NANOGrav | – | 0.99 | 0.17 |
| – J1918–0642 | 7.65 | 10.91 | – | EPTA, NANOGrav | – | 0.87 | 1.08 |
| B1937+21 | B1939+2134 | 1.56 | – | 10.0 | PPTA, EPTA, NANOGrav | 0.11 | 0.02 | 0.03 |
| B1953+29 | J1955+2908 | 6.13 | 117.35 | 1.1 | NANOGrav | – | – | 0.18 |
| – J2019+2425 | 3.94 | 76.51 | – | NANOGrav | – | – | 0.66 |
system with 95% confidence. Similarly, the blazar OJ287 has an observed periodicity of ∼12 years which can be modelled as a binary black-hole system (e.g. Valtonen et al 2009). The most recent model parameters for this system suggest that the induced timing residuals will lie around ∼1–10 ns and would therefore be undetectable in existing data sets.

Using models of black-hole masses and merging rates, Sesana et al (2008, 2009) studied theoretically the detectability of GW signals from coalescing black-hole systems. They showed that it is unlikely that an individual source of GWs would be detectable at current PTA sensitivities (rms timing residuals ∼10 ns are required to detect such individual sources), but that the amplitude of a stochastic background created by massive (10^9 M⊙) black-hole binary systems in distant (z ∼ 2) galaxies could be just below current observational limits.

The current best limit (Jenet et al 2006) used observations from the Parkes and Arecibo observatories. The characteristic strain spectrum of an isotropic, stochastic background can be written as^29 h_c(f) = A(f/f_{1 yr})^{-2/3}. The most recent limit gave A<10^{-14} (where f_{1 yr} = 1/[1 yr]). New techniques to obtain limits (e.g. van Haasteren et al 2009, Anholm et al 2009) and new data sets (see below) should significantly improve on this limit in the near future.

4. Status of the IPTA project

The IPTA project is a collaboration between three individual projects. The European project (EPTA; Janssen et al 2008) currently combines data from four European telescopes (Effelsberg, Jodrell Bank, Nançay and Westerbork—a new telescope in Sardinia is currently being commissioned). The North American project (NANOGrav; Jenet et al 2009) observes with the Arecibo and Green Bank telescopes. The Parkes project (PPTA; e.g. Hobbs et al 2009b) uses the Parkes radio telescope. The basic parameters of the pulsars observed are listed in table 1.

Some of our most precise timing residuals have been obtained for PSR J0437−4715. The rms timing residuals over ∼1 year obtained with the Parkes radio telescope at an observing frequency of ∼3 GHz is ∼60 ns and some individual TOA uncertainties are ∼30 ns. However, it is not yet clear whether the low rms of the residuals will continue with longer data spans. Verbiest et al (2008) presented observations of this pulsar over the previous 10 years and detected the presence of low-frequency timing irregularities. These irregularities may limit the rms achievable over many years. More recently Verbiest et al (2009) studied the timing stability for a sample of 20 ms pulsars over time scales of up to 10 years. Even though PSR J1939+2134 showed significant unmodelled residuals that may make this pulsar

### Table 1. (Continued.)

| PSR B | PSR J | P (ms) | P_b (d) | S1400 Array | PPTA (μs) | EPTA (μs) | NANOGrav (μs) |
|-------|-------|--------|---------|-------------|-----------|------------|---------------|
| − J2124−3358 | 4.93 | − | 1.6 | PPTA | 1.52 | − | − |
| − J2129−5721 | 3.73 | 6.63 | 1.4 | PPTA | 0.87 | − | − |
| − J2145−0750 | 16.05 | 6.84 | 8.0 | PPTA, EPTA, NANOGrav | 0.86 | 0.40 | 1.37 |
| − J2317+1439 | 3.44 | 2.46 | 4.0 | NANOGrav | − | 0.81 | 0.25 |

^29 see Sesana et al (2008) for a more accurate model.
Figure 3. Detection significance of a GW background with given amplitude for data spanning 5 years for different pulsar timing arrays. Also shown is the expected detection significance for the IPTA project after 10 years. The detection significance is defined in the appendix of Verbiest et al (2009).

unusable for long-term GW detection experiments, the timing of most of the other pulsars was shown to be stable enough for GW detection over decadal time scales.

For the pulsars in table 1 we have used typical, current signal-to-noise (S/N) measurements of pulse profiles obtained at each of the IPTA observatories to calculate the best possible timing precision given the period of the pulsar and its pulse shape. We emphasize that the actual rms timing residuals currently being obtained are usually significantly worse. Out of 37 pulsars, thirteen have expected TOA uncertainties <250 ns, seven between 250 and 500 ns, a further nine between 500 ns and 1 μs, five between 1 and 2 μs and the remaining three >2 μs.

For the case of a stochastic GW background created by coalescing supermassive black-hole systems, we have calculated the signal-to-noise ratio of a measurement of the GWB amplitude for the various PTAs. Our analysis is based on that presented by Verbiest et al (2009) who used the term ‘detection significance’ for this signal-to-noise ratio. The results are plotted in figure 3. Here we have assumed that (1) each project obtains approximately one observation every 3 weeks over 5 years and (2) the timing residuals (with no simulated GWs signals present) are white (i.e. they have a flat spectrum) with an rms given by the expected TOA uncertainties (i.e. all timing noise, ISM effects and calibration errors are assumed to be negligible). We know that some of the pulsars in table 1 exhibit non-white timing noise which would degrade the sensitivity on a 5 year scale significantly and would be even more detrimental on a 10 year scale. However, we do not have this information for all of the pulsars in table 1, so we cannot uniformly improve the analysis. Our result represents ‘the best we could do with current systems’. There is some reason to hope that timing noise can be modelled and corrected (Lyne et al in preparation). If the background amplitude is just below current upper bounds (Jenet et al 2006), then such a 5 year data set would produce a signal-to-noise ratio of ~6. However, if the amplitude is closer to $A = 10^{-15}$, then the background will be barely detectable. For similar data sets, but with data spanning 10 years, a background with $A = 10^{-15}$ will still only have a signal-to-noise ratio of ~5 (triangle symbols). Also shown on this plot are the detection significance obtained using the PPTA, NANOGrav and EPTA data individually. Clearly, a detection of the GW background will require the combination of these data sets. Finally, the
thin solid line (marked ‘cPTA’) indicates a canonical timing array where 20 pulsars are each timed for 100 ns over 5 years with weekly sampling.

In figure 4, we show the sensitivity of the IPTA project to single, persistent sources of GWs (Yardley et al in preparation). This figure indicates that sources similar to the postulated binary system in the radio galaxy 3C66B would be clearly detectable with any polarization and at any position in the sky.

A significant reduction in the required time to detect GWs would be made if the rms timing residuals could be further reduced. Techniques that may achieve such a reduction include (1) observing at higher frequencies, (2) discovering new millisecond pulsars, (3) obtaining pulse TOAs through the use of polarization information (van Straten 2006), (4) increasing bandwidth and/or observing time and (5) observing only during periods when the pulsar is bright because of scintillation. Also note that the simulations described above assume no previous data on each pulsar. Most of these pulsars have been observed for years to decades with various observing systems. The use of these earlier data sets will improve our sensitivity to GW signals.

5. Future data sets

Current pulsar timing array projects have the potential to make a detection of a GW background or a single GW source. Unfortunately, the predicted S/N of any such detection is too low for detailed studies of the GW properties. A high S/N detection of a background would provide a test of general relativity (Lee et al 2008) and allow a detailed understanding of the properties of the sources that form the GW background.

30 Note that for some pulsars improved TOA uncertainties can be obtained from low frequency observations. However, compared with higher frequency data such observations are more affected by interstellar medium propagation delays which add uncorrelated timing noise.
Within ~10 years it is expected that various new telescopes will be able to improve the existing timing projects. For instance, the Australian Square Kilometre Array Pathfinder (ASKAP) and the South African Karoo Array Telescope (MeerKAT) will increase the number of known pulsars and provide a larger number of telescopes in the Southern Hemisphere for high-precision pulsar timing (Johnston et al 2007, http://www.ska.ac.za/). It is also likely that a new 500 m diameter telescope (FAST) will be built in China by 2014 (Nan et al 2006). This telescope will be an ideal instrument for pulsar searching and timing and should significantly improve our timing precision for a large number of pulsars. The EPTA is currently undertaking a plan to create the Large European Array for Pulsars (LEAP). The LEAP project will coherently combine the signals from the five major European observatories to create a telescope that will have a sensitivity similar to that of the illuminated Arecibo telescope.

On a slightly longer timescale, the Square Kilometre Array (SKA) telescope is planned (current plans are for the full SKA to be completed in 2022, with initial observations with a 10% SKA to begin in 2018). The huge collecting area of this telescope implies that it will be able to time many hundreds of pulsars at the level currently achieved for a few pulsars (Kramer et al 2004). Such timing data sets will revolutionize GW detection and analysis projects by enabling high S/N detections of GW sources.

6. Outreach

Many of the IPTA projects have components that are being used to train the first generation of GW astronomers and to discover new pulsars useful for timing array projects. Arecibo pulsar survey data are currently being obtained and analysed both by high school students in the USA (through the Arecibo Remote Command Center) and by the public worldwide as part of the Einstein@Home project31. Students in West Virginia, USA, are able to search for pulsars using observations taken with the Green Bank telescope32. The PULSE@Parkes project (Hollow et al 2009) allows students in Australia and overseas to carry out timing observations for the PPTA project (Hobbs et al 2009c). The Mid-Atlantic Relativistic Initiative in Education (MARIE) is creating tools for introducing gravitational waves in high school and college courses33.

7. Conclusion

Given current theoretical models, it is likely that ultra-low frequency GWs will be detected by pulsar timing experiments within 5–10 years. The first detections are expected to be of an isotropic, stochastic GW background created by coalescing supermassive black-hole systems. It is expected that GW astronomy using pulsars will become commonplace in the SKA era during which the background will be analysed in detail and individual binary black-hole systems and burst GW sources will be detectable.

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31 http://arcc.phys.utb.edu/ARCC, http://einstein.phys.uwm.edu/
32 http://www.pulsarsearchcollaboratory.com
33 http://www.fandm.edu/marie
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