Gravitational wave detection using pulsars: status of the Parkes Pulsar Timing Array project

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Abstract:
The first direct detection of gravitational waves may be made through observations of pulsars. The principal aim of pulsar timing array projects being carried out worldwide is to detect ultra-low frequency gravitational waves ($f \sim 10^{-9}$–10^{-8} Hz). Such waves are expected to be caused by coalescing supermassive binary black holes in the cores of merged galaxies. It is also possible that a detectable signal could have been produced in the inflationary era or by cosmic strings. In this paper we review the current status of the Parkes Pulsar Timing Array project (the only such project in the Southern hemisphere) and compare the pulsar timing technique with other forms of gravitational-wave detection such as ground- and space-based interferometer systems.

Keywords: gravitational waves—pulsars: general

1 Introduction

Direct detection of gravitational waves (GWs) would be of huge importance to the physics and astrophysics communities. Detection would simultaneously verify our basic understanding of gravitational physics and usher in a new era of astronomy. Using models of galaxy merger rates and the properties of coalescing black holes, Sesana, Vecchio & Colacino (2008) and references therein predict the existence of an isotropic, stochastic, low-frequency GW background. Various models of cosmic strings (Damour & Vilenkin 2001; Caldwell, Battye & Shellard 1996) and the inflationary era (Turner 1997; Boyle & Buonanno 2008) also predict the existence of a low-frequency GW background (Maggiore 2000). In the frequency range accessible by pulsar timing these backgrounds can be described by their characteristic strain spectrum, $h_c(f)$,

which can be approximated as

$$h_c(f) = A_g \left(\frac{f}{f_{1\mathrm{yr}}} \right)^{\alpha} \tag{1}$$

where $f_{1\mathrm{yr}} = 1/1\,\mathrm{yr}$. The dimensionless amplitude of the background, A_g, and the spectral exponent, α, depend on the type of background (Jenet et al. 2006). Sazhin (1978) and Detweiler (1979) showed that these GW signals could be identified through observations of pulsars.

Standard pulsar timing techniques (e.g. Edwards, Hobbs & Manchester 2006; Lorimer & Kramer 2005) are used to search for the existence of GWs. Timing software (Hobbs, Edwards & Manchester 2006) is used to compare the predictions of a pulsar timing model with measured pulse times of arrival (TOAs). The timing model for each pulsar contains information about the pulsar's astrometric, spin and orbital parameters. Any deviations of the actual arrival
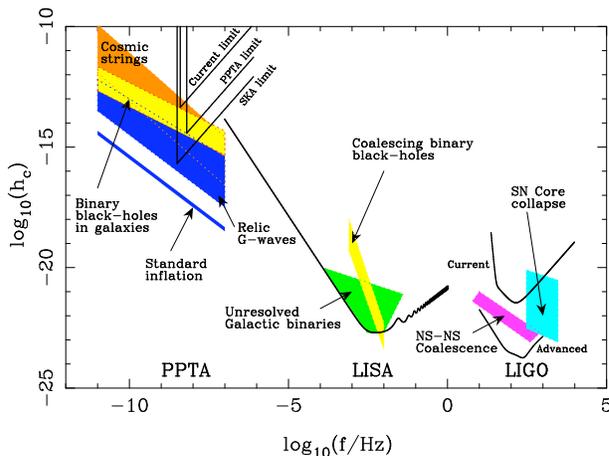
Figure 1: Characteristic strain sensitivity for existing and proposed GW detectors as a function of GW frequency. Predicted signal levels from various astrophysical sources are shown. Figure from Hobbs (2008b).

times from the model predictions - the pulsar timing residuals - represent the presence of unmodelled effects which will include calibration errors, spin-down irregularities and the timing signal caused by GWs. The signal from GWs can be disentangled from other unmodelled effects by looking for correlations in the timing residuals of a large number of pulsars that are distributed over the entire sky. Pulsar timing experiments are sensitive to GW signals in the ultra-low frequency ($f \sim 10^{-9}$–10^{-8} Hz) band making them complementary to the space- and ground-based interferometers such as the Laser Interferometer Space Antenna (LISA) and the Laser Interferometer Gravitational Wave Observatory (LIGO), which are sensitive to higher frequency GWs (see Figure 1 and §4).

For a given pulsar and GW source, the induced timing residuals caused by a GW signal only depend on the GW characteristic strain at the pulsar and at the Earth. The GW strains at the positions of well-separated pulsars will be uncorrelated, whereas the component at the Earth will lead to a correlated signal in the timing residuals of all pulsars (Hellings & Downs 1983). It is this correlated signal that the pulsar timing experiments aim to detect.

The first high-precision pulsar timing array experiments were carried out using the Arecibo and Green-Bank radio telescopes (e.g. Foster & Backer 1990). Observations of PSRs B1937+21 and B1855+09 were subsequently used to obtain a limit on the existence of a GW background (e.g. Stinebring et al. 1990; Kaspi, Taylor & Ryba 1994; McHugh et al. 1996; Lommen 2002). Unfortunately, the timing precision presented in these early papers was too poor to attempt to *detect* the expected GW signals. New pulsar discoveries and better instrumentation has significantly improved the timing precision achievable. Recently Verbiest et al. (2008) showed that PSR J0437−4715 could be timed using the Parkes radio telescope with an rms timing residual

of only 200 ns over a 10 yr period. Timing precisions are continuing to improve.

Lommen & Backer (2001) described how pulsar data sets could be used to constrain the existence of binary black holes in the centre of our Galaxy and in close-by galaxies. In 2003, a VLBI experiment detected motions in the radio galaxy 3C66B that were thought to be evidence of a binary supermassive black hole system (Sudou et al. 2003). Jenet et al. (2004) determined the expected PSR B1855+09 timing residuals that would occur due to GW emission from the postulated system and compared them with archival Arecibo data. The pulsar timing observations allowed the existence of the binary system to be ruled out with 95% confidence.

The Parkes Pulsar Timing Array (PPTA) project began in the year 2003. The three main aims of this project are 1) to detect GW signals, 2) to establish a pulsar-based time scale for comparison with terrestrial time standards and 3) to improve the Solar system planetary ephemerides. In this paper, we describe the work that has already been carried out towards our first aim of GW detection. This includes determining the number of pulsars and observing parameters required to detect a GW signal, obtaining the most stringent constraint on the existence of a GW background and producing high quality data sets for use in GW astronomy.

2 Current status of the Parkes Pulsar Timing Array project

The PPTA project has been described in numerous papers (for an historical overview see Hobbs 2005; Manchester 2006; Hobbs 2008b; Manchester 2008). In brief, the 20 millisecond pulsars listed in Table 1 are observed with an $\sim$ 2-week cadence using the 64-m Parkes radio telescope. The pulsars were chosen because they 1) only exhibit small-scale timing irregularities, 2) have been well studied by earlier projects and 3) have a range of separations on the sky. Observations are carried out with a 20cm receiver (providing 256 MHz of bandwidth) and with a 10cm/50cm dual-band system (giving 64MHz of bandwidth at 50cm and 1GHz of bandwidth at 10cm). Multiple backend systems are used including digital filterbanks and the Caltech-Parkes-Swinburne Recorder 2 (CPSR2; Hotan, Bailes & Ord 2006) which provides two 64 MHz bands of coherently dedispersed data. New backends that are currently being commissioned should further improve our timing precision. All our observations are processed using the PSRCHIVE software (Hotan, van Straten & Manchester 2004) and pulse TOAs are analysed using TEMPO2 (Hobbs, Edwards & Manchester 2006; Edwards, Hobbs & Manchester 2006).

2.1 The initial data sets

The choice of 20 pulsars was based on work reported by Jenet et al. (2005) who determined the minimum number of pulsars required to detect the expected GW background. This work highlighted the requirement

Table 1: Observational parameters for current and future PPTA data sets. N_p is the total number of observations, T_s the data span, σ the weighted rms timing residual over the entire data span. For the most recent data, $\sigma_{\mathrm{med}}^{\mathrm{rec}}$ gives the TOA uncertainty, $S/N_{\mathrm{med}}^{\mathrm{rec}}$ the median S/N and S/N_{max} the maximum S/N. $S/N_{100\mathrm{ns}}$ is the predicted S/N required to produce a TOA uncertainty of 100 ns and σ_p is the predicted rms timing residual that may be possible with current instrumentation.

PSR J	N_p	T_s (yr)	σ (μs)	$\sigma_{\mathrm{med}}^{\mathrm{rec}}$ (μs)	$S/N_{\mathrm{med}}^{\mathrm{rec}}$	$S/N_{\mathrm{max}}^{\mathrm{rec}}$	$S/N_{100\mathrm{ns}}$	σ_p (μs)
J0437−4715	712	4.3	0.2	0.23	2271	2691	400	0.1[†]
J0613−0200	432	5.5	1.1	0.75	123	226	917	0.5
J0711−6830	141	4.4	1.6	2.59	58	439	1699	1.0
J1022+1001	515	5.5	2.2	1.58	141	950	2301	0.5
J1024−0719	216	5.5	1.3	1.85	65	351	1219	1.0
J1045−4509	155	5.2	3.0	2.08	158	240	3750	1.0
J1600−3053	567	5.5	1.0	0.44	157	297	693	0.3
J1603−7202	159	5.5	1.9	1.00	230	1462	2672	0.5
J1643−1224	186	5.4	1.7	0.63	324	500	2047	0.5
J1713+0747	303	5.5	0.5	0.20	270	702	584	0.1
J1730−2304	158	4.6	1.9	1.08	212	459	2290	1.0
J1732−5049	188	5.5	3.5	2.12	76	118	1688	1.0
J1744−1134	413	5.5	0.8	0.67	79	252	693	0.3
J1824−2452	169	3.1	1.7	1.57	18	43	323	1.0
J1857+0943	205	4.4	1.4	0.91	115	415	1087	0.5
J1909−3744	1398	5.5	0.6	0.16	127	620	204	0.1
J1939+2134	45	4.3	0.3	0.19	69	222	77	0.1
J2124−3358	125	3.8	2.4	2.81	61	205	2000	1.0
J2129−5721	189	5.5	1.2	2.75	47	252	1234	1.0
J2145−0750	205	4.3	1.1	0.81	275	1665	2346	0.3

[†] The timing residuals for PSR J0437-4715 are currently dominated by systematic effects. Understanding and removing of these effects may allow us to reach a TOA timing precision of ~ 20 ns; see text.

for extremely high precision timing observations - in order to detect the GW background within five years all 20 pulsars need to have rms timing residuals of ~ 100 ns. You et al. (2007a) showed that the interstellar medium and Solar wind can produce much larger signals in the timing residuals. For instance, at an observing frequency close to 1.4 GHz, the Solar wind can produce delays of ~ 100 ns for lines-of-sight to the pulsar that pass within $60°$ of the Sun and much larger delays for closer lines-of-sight (You et al. 2007b). Fortunately dispersive effects can be removed by comparing pulse arrival times at different observing frequencies. An optimal subtraction technique was presented by You et al. (2007a).

Combining the initial PPTA data sets (that spanned ~ 2 yr) with archival Arecibo observations allowed Jenet et al. (2006) to obtain the most stringent limit to date on the amplitude of a GW background of $A_g \leq 1.1 \times 10^{-14}$. This corresponds to $\Omega_g[1/(8\mathrm{yr})]h^2 \leq 1.9 \times 10^{-8}$ for the fractional energy density per unit logarithmic frequency interval for an astrophysical background (the Hubble parameter $H_0 = 100h\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$). This result constrained the merger rate of supermassive binary black-hole systems, ruled out some relationships between the black-hole mass and the galactic halo mass, constrained the rate of expansion in the inflationary era and provided an upper bound on the dimensionless tension of a cosmic-string background. Unfortunately, the technique of Jenet et al. (2006) is only valid for data sets that have a "white spectrum" (defined as being a spectrum that is independent of frequency). The initial data sets, and previously published work (e.g. Kaspi, Taylor & Ryba 1994; Cognard & Backer 2004; Splaver et al. 2005; Verbiest et al. 2008), clearly show that many millisecond pulsar timing residuals are affected by unexplained timing irregularities which may be related to the timing noise phenomena seen in younger pulsars (Hobbs, Lyne & Kramer 2006), unmodelled instrumental effects, poor removal of interstellar medium effects (e.g Stinebring 2006) or intrinsic pulse shape variability. This limitation restricted our initial analysis to only seven of the 20 PPTA pulsars. We have recently developed a new technique that makes no assumption on the spectrum of the timing residuals. This work will be presented in a forthcoming paper.

3   Towards detecting GW signals

Timing residuals for our current PPTA data sets are summarised in Table 1. To form these data sets we have selected the backend systems providing most precise TOAs. The earliest data are usually from the CPSR2 coherent dedispersion system and the most recent data from the digital filterbank systems. Columns 2, 3 and 4 provide the total number of observations, the time span and the weighted rms timing residual over our entire data span respectively (obtained after fitting only for the pulsar's astrometric and orbital parameters along with the pulse frequency and its first derivative). These timing residuals have not been corrected for the effects of dispersion measure variations caused by the interstellar medium. Note also that multiple, independent observations at different frequencies have been made during the same observing session. A weighted average (in 2-weekly intervals) of the residuals for PSR J0613−0200 gives an rms of 842 ns with 102 data points (cf. 1.1μs listed in the table). As our observing systems have been improved over this period, the median arrival-time uncertainties for our most recent observations are listed in Column 5 of Table 1.

Even though many of these data sets have lower rms values than have been achieved in the past, we are still far from the goal of ~ 100 ns for the majority of our sample. For a given backend system it is possible to use a noise-free approximation of the pulse profile to determine the best timing precision achievable for a given pulsar. This can be carried out through simulations or by using analytical expressions (van Straten 2006; Downs & Reichley 1983). A typical example is shown in Figure 2 where the actual arrival time uncertainties for PSR J1713+0747 are compared with the theoretical prediction. For this pulsar it is clear that we should be able to achieve typical arrival time uncertainties ~ 100 ns. PSR J0437−4715 provides our best quality data sets. However, as shown in Figure 2 we are far from the theoretical timing precision achievable of ~ 20 ns for this pulsar because of un-explained systematic effects. In Table 1 we list the signal-to-noise (S/N) ratio of an individual observation that would be required in order to measure an arrival time with a precision of 100 ns (S/N$_{100\text{ns}}^{\text{rec}}$). The table also contains the median (S/N$_{\text{med}}^{\text{rec}}$) and maximum (S/N$_{\text{max}}^{\text{rec}}$) S/N ratios achieved to date using our most recent observing system. Further improvements should be possible by improved calibration, using a new coherent dedispersion system currently being commissioned, longer observation lengths and by obtaining pulse times-of-arrival using the information available from the Stokes parameters (van Straten 2006) instead of considering only the total intensity profile.

In order to achieve rms timing residuals of ~ 100 ns over five years of observations it is necessary that the pulsars are intrinsically stable over this time scale. A generalisation of the Allan variance has been developed for analysing pulsar timing residuals (Matsakis, Taylor & Eubanks 1997). This measure of stability as a function of time-
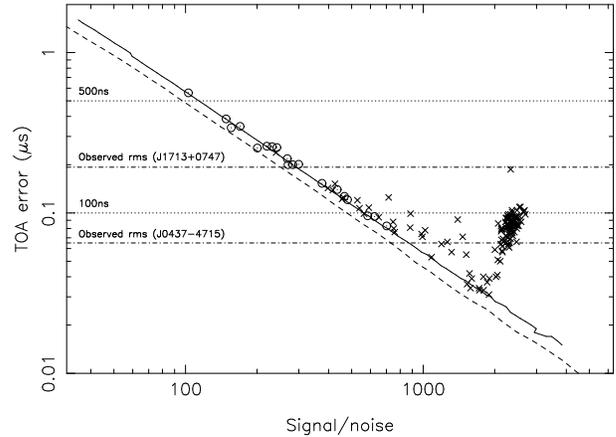
Figure 2: Arrival time precision versus signal to noise ratio for PSRs J1713+0747 and J0437−4715. For PSR J1713+0747 the measured values are plotted as circles and a theoretical estimate is drawn as the solid line. For PSR J0437−4715 we use 'cross' symbols and a dashed line respectively. The observed weighted rms timing residuals are indicated by dashed lines. The dotted lines represent timing precisions of 100 ns and 500 ns.

span, $\sigma_z(\tau)$, has been plotted in Figure 3 for our best-timed pulsar, PSR J0437−4715, and for one of our poorer pulsars, PSR J1045−4509. The figure also includes measurements of σ_z for the difference between the realisations of terrestrial time published by the National Institute of Standards and Technology (NIST) and the Physikalisch-Technische Bundesanstalt (PTB). These initial results demonstrate that our best pulsars are stable enough to search for irregularities in the terrestrial time scales and could be used to form a pulsar-based time scale.

3.1   The GW background

A GW background will induce timing residuals that are correlated between different pulsars. The general relativistic prediction for this correlation is shown as the solid line in Figure 4 (Hellings & Downs 1983). Determining the correlation coefficients for our data sets is not trivial due to the uneven sampling, differing data lengths and the presence of low-frequency noise. However, an initial analysis in which we averaged the measured timing residuals into 2-weekly sessions before using standard correlation techniques, produced the correlation coefficients shown in Figure 4. Clearly we have not yet made a significant detection.

A reference timing array project was defined by Jenet et al. (2005) containing 20 pulsars, timed with an rms timing residual of 100 ns with weekly sampling over 5 years. Such observations would give a detection significance of ~ 3 for a background with $A_g = 2 \times 10^{-15}$. With our current rms timing residuals and fortnightly sampling we would require data spanning more than 16 yr in order to achieve this sensitivity. For rough estimates of the timing precision
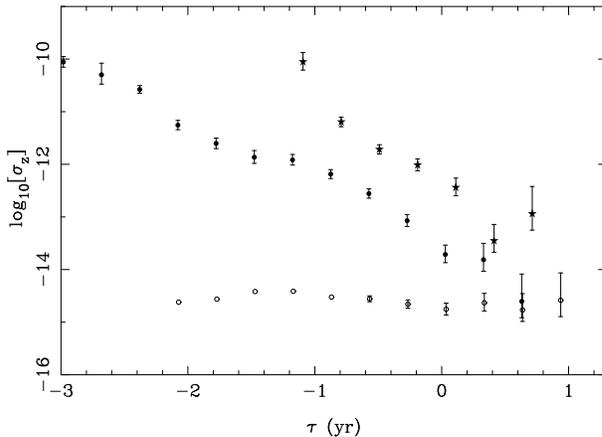
Figure 3: The $\sigma_z(\tau)$ stability parameter for PSRs J0437−4715 (solid circle) and J1045−4509 (star symbols). For comparison the difference between two realisations of the terrestrial time scale is also shown (open circles). Error bars are only plotted if they are larger than the size of the data point.

Figure 4: Correlation between all pairs of pulsars plotted versus their angular separation. The solid line is the predicted correlation curve due to a GW background.

that we are likely to achieve with improved instrumentation (listed in column 9 in Table 1 and obtained by postulating possible future S/N ratios and their corresponding TOA errors), we require data spans of $\sim$10 yr to reach this sensitivity.

In order to reduce the time required to create such data sets, we are developing collaborations with the North American[1], European (Janssen et al. 2008; Stappers et al. 2006) and Chinese (Wang et al. 2002) timing array projects. It is also expected that on-going pulsar surveys will discover new, stable pulsars that can be used in future timing array projects. In the longer term we expect that the Square Kilometre Array (SKA) telescope (Carilli & Rawlings 2004; Cordes et al. 2004; Kramer 2004) will provide high quality data sets for many hundreds of pulsars. Such observations will allow the properties of the GW background to be studied in detail. For instance, predictions of various theories of gravity for the polarisation properties of GWs could be tested (Lee et al., in press).

3.2 Single GW sources

Single GW sources can be divided into individual supermassive black-hole binary systems and burst GW sources. Order-of-magnitude calculations demonstrate that a system with a chirp mass of $10^9 M_\odot$ and an orbital period of 10 yr at a distance of 20 Mpc will induce a sinusoidal signal in the timing residuals with amplitude $\sim$ 100 ns at a frequency of twice the orbital frequency of the binary black holes. More detailed calculations, which take various cosmological effects into account when determining our sensitivity to single GW sources, will be published shortly. This new work demonstrates that our data sets can be used to place constraints on the merger rate of supermassive
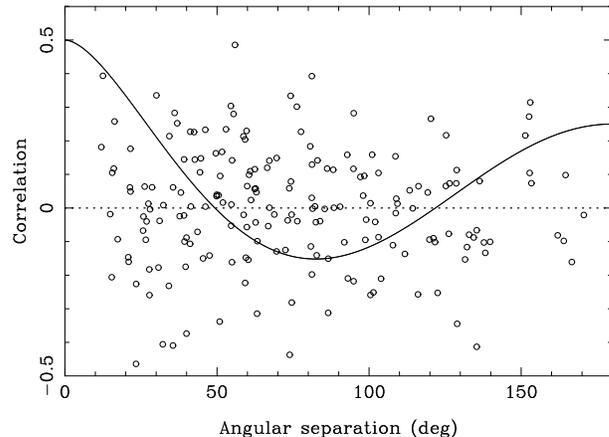
binary black-hole systems as a function of black-hole mass and redshift.

Sources of burst GW emission that may be detectable with current and proposed pulsar timing experiments include 1) the formation of supermassive black holes (Thorne & Braginskii 1976), 2) highly eccentric supermassive black hole binaries (Enoki & Nagashima 2007), 3) close encounters of massive objects (Kocsis, Gáspár & Márka 2006) and 4) cosmic string cusps (Damour & Vilenkin 2001). Our ability to detect and localise the position of burst sources depends on our having accurate data sets for a large number of pulsars. By sharing data with timing array projects in the Northern hemisphere we expect to improve both the angular resolution of our detector and our sensitivity to burst sources.

4 The pulsar timing GW band

Any GW signal with a period longer than the time-span of the data is largely absorbed by the fitting process. Pulsar timing is therefore only sensitive to GW signals with periods less than the time-span of the data ($f \lesssim 10^{-8}$ Hz). The planned space-based GW detector, LISA, is sensitive to higher frequency GWs ($f \sim 10^{-3}$ Hz) and the ground based interferometers to even higher frequencies ($f \sim 10^2$ Hz). In general, the expected GW sources are different for each type of detector. However, some models of cosmic strings and the inflationary era produce GW backgrounds which could, potentially, be detectable at all GW observing frequencies (Maggiore 2000).

As noted by Sesana, Vecchio & Colacino (2008), detection of a background from coalescing binary black hole systems by both the pulsar timing array experiments and LISA would provide strong constraints on models of the assembly of massive binary black hole systems. Recently, Pitkin et al. (2008) discussed other areas where pulsar timing and LISA may provide complementary observations. For instance, they consider the possibilities of studying the inspiral stage of a merger

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[1]http://nanograv.org

using pulsar observations and the ring-down stage using LISA.

5 Conclusions

Current pulsar timing array experiments have the potential to detect low-frequency GW signals within a decade. Future experiments with the Square Kilometre Array telescope should allow detailed observations of both a stochastic GW background and individual GW sources. The pulsar timing technique is complementary to other projects that are attempting to detect much higher frequency GWs.

Acknowledgments

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