Pulsars as gravitational wave detectors

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Abstract Pulsar timing array projects are carrying out high precision observations of millisecond pulsars with the aim of detecting ultra-low frequency (∼ $10^{-9}$ to $10^{-8}$ Hz) gravitational waves. We show how unambiguous detections of such waves can be obtained by identifying a signal that is correlated between the timing of different pulsars. Here we describe the ongoing observing projects, the expected sources of gravitational waves, the processing of the data and the implications of current results.

1 Introduction

The first strong evidence for the existence of gravitational waves (GWs) was obtained by measuring the orbital period decay in the PSR B1913+16 binary pulsar system [25][59][62]. Various ground- and space-based detectors have been developed with the aim of making a direct detection of GW signals. Unfortunately, to date, no such detection has been made.

Millisecond pulsars are amazingly stable rotators. In many cases a simple model for the pulsar spin-down can be used to predict pulse times-of-arrival (TOAs) with an accuracy and precision of < 1µs over many years of observation. The pulsar timing technique relies on this stability to obtain precise measurements of a pulsar's spin, astrometric and orbital parameters. However, in some cases the pulse TOAs are not exactly as predicted, suggesting that the model and analysis procedure do not parameterise all of the physical effects that are affecting the pulse emission, propagation and detection. As the effects of GWs are not included in the analysis, the existence of any such waves will induce deviations between the actual and predicted TOAs (commonly known as the ‘timing residuals’). Here we describe how these
signals may be unambiguously confirmed as being caused by GWs and provide upper bounds on their amplitude.

In §2 we provide a basic explanation of how pulsar data sets may be used in the search for GWs, §3 describes current data sets and highlights some aspects of the data that need careful consideration when the data are processed, §4 lists potential sources of GWs, §5 describes how data sets may be accessed and §6 highlights future possibilities.

\section{Using pulsars to search for GWs}

Pulsar observations lead to measurements of TOAs at an observatory. The TEMPO2 software package \cite{10,23} can be used to convert these TOAs to a time of emission by 1) transforming the TOAs to the Solar System barycentre, 2) determining excess propagation delays caused by the interstellar medium and, for binary systems, 3) transforming to the pulsar frame. The derived time of emission can then be compared with a pulsar model to form the timing residuals.

The induced pulsar timing residuals caused by a GW signal were first calculated at the end of the 1970s \cite{9,52}. This early work showed that a GW signal causes a fluctuation in the observed pulse frequency, \(\delta \nu/\nu\), which induces pulsar timing residuals at time \(t\) from the initial observation as

\begin{equation}
R(t) = -\int_0^t \frac{\delta \nu(t)}{\nu} \, dt.
\end{equation}

The Doppler shift can be shown to have the form (e.g. \cite{17})

\begin{equation}
\frac{\delta \nu}{\nu} = H^{ij}(h_{ij}^e - h_{ij}^p)
\end{equation}

where \(h_{ij}^e\) is the GW strain at the Earth at the time of observation, \(h_{ij}^p\) the strain at the pulsar when the electromagnetic pulse was emitted and \(H^{ij}\) is a geometrical term that depends upon the angle between the Earth, pulsar and GW source. The GW strains evaluated at the positions of multiple pulsars will be uncorrelated, whereas the component at the Earth will lead to a correlated signal in the timing residuals of all pulsars.

Hobbs et al. (2009 \cite{21}) demonstrated how pulsar TOAs affected by GWs can be simulated using the TEMPO2 software package. Since the intrinsic pulsar pulse period, spin-down, orbital motion and various astrometric parameters are \textit{a priori} unknown, they need to be determined from the pulsar timing data. Initial estimates of the pulsar parameters are used to form pre-fit timing residuals. A least-squares fitting procedure is subsequently used to fit an analytical model to obtain improved pulsar parameters and “post-fit” timing residuals (see \cite{23}). In Figure\textbf{1} we plot pre- and post-fit timing residuals for a simulated pulsar in the presence of GWs from 1)
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Fig. 1 Simulations of pre-fit (left column) and post-fit (right column) timing residuals. The first row simulates a non-evolving, black-hole binary system defined by $A_+ = A_\times = 5 \times 10^{-14}$ and $\omega = 1 \times 10^{-7}$. The second row contains a simulation of the predicted timing residuals from the evolving source 3C66B (see Section 3). The third row contains a GW burst with memory source leading to a change in rotational frequency $\Delta \nu = 1 \times 10^{-12}$ Hz and the bottom row is a realisation of a GW background defined by $\alpha = -2/3$ and $A = 10^{-14}$.
Fig. 2 The expected correlation in the timing residuals of pairs of pulsars as a function of angular separation for an isotropic GW background (solid line). The points correspond to simulated pulsar data sets in the presence of a GW background with power-law index $\alpha = +3/2$ and amplitude $A = 0.01$; Figure from Hobbs et al. (2009, [21]).

It is not possible to determine the exact origin of the timing residuals for a single pulsar data set. Any observed residuals may have been caused by, for example, irregularities in terrestrial time standards [48], errors in the planetary ephemeris, irregular spin-down of the pulsar [19], calibration effects (e.g. [65]) or GWs. These effects can only be distinguished by searching for correlations in the timing residuals of multiple pulsars. For instance, residuals caused by the irregular spin-down of one pulsar will be uncorrelated with the residuals observed for a different pulsar. Irregularities in terrestrial time standards will lead to correlated residuals for all pulsars (this is only true for data sets which have the same data span; see Section 3). 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 common signal for such a background was determined by Hellings & Downs (1983) and is reproduced in Figure 2. More recently it has been shown that approximately 20 pulsars are necessary, timed with an rms timing residual of $\sim 100$ ns or better over five years with observations every week, in order to make a significant detection of a possible GW background signal [28].

Pulsar timing experiments are sensitive to GW signals in the ultra-low frequency band ($f \sim 10^{-9}$ to $10^{-8}$ Hz) as individual pulsars are typically only observed once every few weeks, have maximum data spans of years to decades and require the
fitting of a pulsar timing model. The pulsar timing method is therefore complementary to other GW detection methods such as the Laser Interferometer Space Antenna (LISA)\(^1\) and ground based interferometer systems (such as the Laser Interferometer Gravitational Wave Observatory, LIGO\(^2\)), which are sensitive to high frequency GWs. In Figure 3 we plot the sensitivity of the pulsar timing experiments, LISA and LIGO as well as some expected GW sources.\(^3\) Pulsar timing projects that aim to obtain data sets on the most stable millisecond pulsars with the aim of searching for correlated timing residuals are known as pulsar ‘timing arrays’. The first attempts to undertake such projects are described by Romani (1989) and Foster & Backer (1990).

\(^1\) [http://lisa.nasa.gov](http://lisa.nasa.gov)

\(^2\) [http://www.ligo.caltech.edu/advLIGO/](http://www.ligo.caltech.edu/advLIGO/)

\(^3\) Various authors e.g. [35, 44] have indicated that it may be possible to limit the existence of GWs with even lower frequencies \((10^{-12} \text{ to } 10^{-9} \text{ Hz})\) where the minimum sensitive GW frequency is determined by the distance to the pulsar. However, the methods required to achieve this sensitivity are different to those described in this paper. We also note that a few other methods exist that can limit the ultra-low frequency GW background. One example is reported by Gwinn et al. (1997) who obtained an upper bound on the background amplitude by analysing limits on proper motions of quasars.
3 Current data sets

The International Pulsar Timing Array (IPTA) project has the main aim of detecting GW signals using pulsar observations and is a collaboration between three separate projects. The European project (EPTA [13]) currently obtains data using the Effelsberg, Jodrell Bank, Nançay and Westerbork telescopes (a new telescope in Sardinia is currently under construction and, when commissioned, will be used as part of the EPTA). The North American project (NANOGrav [27]) uses the Arecibo and Green Bank telescopes and the Parkes project (PPTA; e.g. [22, 39, 68]) uses the Parkes radio telescope in Australia. In total approximately 37 different pulsars are being observed by these projects (see [18]). Some of the most precise timing residuals have been obtained for the brightest millisecond pulsar, PSR J0437−4715. The rms timing residuals over ∼ 1 yr obtained with the Parkes telescope at an observing frequency close to 3 GHz is ∼ 60 ns and some individual TOA uncertainties are ∼ 30 ns. Achieving such low rms timing residuals relies on removing the effects of dispersion measure variations [74], precisely calibrating the data [67] and determining many post-Keplerian binary parameters [70]. However, over longer data spans clear irregularities are observed in the timing residuals (see Figure 4; R. Manchester, private communication). These residuals differ from those published by Verbiest et al. (2008) as 1) new data have been added between the years 2006 and 2010 and 2) the time offsets between different backend systems at the observatory have been measured and subsequently not included in the fitting procedures. The cause of the observed variations is not currently known.

Pulsars exhibit two main types of timing irregularity: ‘glitches’ in which the pulsar’s rotation rate suddenly increases before undergoing a period of relaxation and ‘timing noise’ which consists of low-frequency features in the timing residuals. Hobbs et al. (2010) analysed a sample 366 pulsars and showed that the timing noise, in general, consisted of quasi-periodic oscillations with periodicities of years to decades. However, the “amount” of timing noise decreases with characteristic age and millisecond pulsars, which are used in timing array experiments, are typically extremely stable. In a few cases, timing noise and glitches are clearly seen in the residuals for millisecond pulsars. For instance, the timing residuals for PSR J1939+2134 have long been known (e.g. [33]) to be dominated by timing noise. The first glitch in a millisecond pulsar was found in PSR B1821−24 which is located in the globular cluster M28 [6]. The glitch was shown to follow the main characteristics of glitches seen in the slower pulsars. Verbiest et al. (2009) studied the timing stability for 20 millisecond pulsars included in the PPTA project, over time scales up to 10 yr. Apart from PSR J1939+2134 it was concluded that the timing of most of the other pulsars is stable enough for GW detection on decadal time scales.

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4 The exact number of pulsars varies as new pulsars are discovered and added to the IPTA sample. Radio pulsar surveys are being carried out (Keith et al., submitted to MNRAS, [7]) and the Fermi gamma-ray spacecraft, has recently discovered numerous previously unidentified gamma-ray sources. Many of these have now been shown to be millisecond pulsars (P. Ray, these proceedings) some of which are likely soon to be included in the IPTA.
The basic method to detect a GW background signal in pulsar data is to search for correlated timing residuals between different pairs of pulsars. However, we note that these correlations only hold in the case where all pulsar data sets are processed using the same fitting procedure and have the same data span. In Figure 5, post-fit timing residuals are shown that include simulated clock irregularities. Even though the same signal has been added to each data set, the residuals are not highly correlated because of the differing data spans and the model fits that have been carried out. The following need to be taken into account when attempting to detect or limit GW signals in pulsar timing data:

- Pulsar timing residuals are irregularly sampled, have large gaps and different pulsars have different sampling and data spans.
- The uncertainty on each TOA for a given pulsar can vary by an order-of-magnitude because of interstellar scintillation, different observing durations for different observations and when combining data sets obtained from different observatories. For an unknown reason it is often found that the TOA uncertainties are under- or over-estimated (by factors of $\sim 2$).
- Timing residuals are always related to a pulsar timing model for which various fits have been carried out to determine the pulsar’s spin, astrometric and orbital parameters.
- Arbitrary offsets can exist between TOAs measured with different instruments or at different observatories.
- The timing residuals may be affected by timing noise or glitch events.
4 Potential sources of gravitational waves

Theoretical models predict that pulsar timing experiments are sensitive to individual, periodic sources of GWs, burst sources and a background of GWs. This section describes the various possible sources that have been discussed in the literature.

4.1 Single sources

GWs are generated by the acceleration of massive objects. For a two-body orbital system the GW frequency is twice the orbital frequency implying that supermassive binary black-hole systems can produce GW signals that are strong enough, and are in the correct frequency regime, to be detectable by pulsar timing experiments. An estimate of the timing residual for a massive black-hole binary system can be obtained from [27]:

![Fig. 5 Post-fit timing residuals for three simulated pulsars. Each pulsar data set consists of white noise plus a clock irregularity that is the same for each pulsar. The post-fit residuals are not correlated because of model fitting and because each data set has a different data span.](image)
\[ t \sim 10\text{ns} \left( \frac{1\text{Gpc}}{d} \right) \left( \frac{M}{10^9\text{M}_\odot} \right)^{5/3} \left( \frac{10^{-7}\text{Hz}}{f} \right)^{1/3} \]  

(3)

where \( d \) is the distance to the black-hole binary which has a total mass of \( M/(1+z) \) and emits GWs at frequency \( f \).

Sesana, Vecchio & Volonteri (2009) showed that it is likely that the maximum timing residuals induced by such a system will be in the \( \sim 5 \sim 50 \text{ns} \) range. Any such source is likely to be from a massive system (with a chirp mass \( M_c > 5 \times 10^8 \text{M}_\odot \)) and at a redshift between \( 0.2 < z < 1.5 \). More recently Sesana & Vecchio (2010) showed for a “fiducial” timing array project containing 100 pulsars uniformly distributed in the sky that, if a source is detected with a signal to noise ratio of 10, the source position could be determined to within \( \sim 40 \text{deg}^2 \) with a fractional error on the signal amplitude around 30% and the source inclination and polarisation angles could be recovered to within \( \sim 0.3 \text{rad} \).

Unfortunately there has not yet been any clear detection of a supermassive binary black hole system where the black holes are close enough, and massive enough, for the system to be emitting detectable GW emission. Rodriguez et al. (2006) discovered a system in the radio galaxy 0402+379, which has a projected separation between the two black holes of just 7.3 pc. However, this is still too wide to be emitting detectable GWs. Sudou et al. (2003) reported the possible detection of a supermassive black hole binary in the radio galaxy 3C 66B and provided the orbital parameters for the postulated system. Jenet et al. (2004) showed that such a system should have produced detectable GW emission and managed to rule out its existence with high confidence. Lommen & Backer (2001) unsuccessfully searched for GW emission from Sagittarius A* which had also been suggested to be part of a binary system. Sillanpaa et al. (1996) have identified a candidate supermassive black hole binary system in the blazar OJ287 with member masses of \( 1.3 \times 10^8 \text{M}_\odot \) and \( 1.8 \times 10^{10} \text{M}_\odot \). However, Yardley et al. (2010) showed that this system will require the sensitivity of future telescopes (such as the Square Kilometre Array, SKA) for detection. Searches for more supermassive binary black hole candidates are ongoing. Wen, Liu & Han (2009) selected 1209 pairs of galaxies from the Sloan Digital Sky Survey and searched for features indicative of merging events. More recently Burke-Spolaor (submitted to MNRAS) used archival VLBI data to search 3114 radio-luminous active galactic nuclear for binary supermassive black holes. Only one such source (the same as that previously discovered by Rodriguez et al. 2006) was detected.

Wen et al. (submitted to ApJ) described the basic methods in which existing pulsar timing observations can be used to place constraints on the coalescence rate of binary supermassive black holes in the Universe. Yardley et al. (2010) determined the sensitivity of the Verbiest et al. (2008, 2009) data sets to individual GW sources and obtained a sky-averaged constraint on the merger rate of nearby \( (z < 0.6) \) black-hole binaries in the early phases of coalescence with a chirp mass of \( 10^{10} \text{M}_\odot \) of less than one merger every seven years. This work is summarised in Figure 6 which plots the current sensitivity to single sources and predicted future sensitivity (with the Square Kilometre Array, SKA, telescope).
4.2 Burst sources

Sources of detectable burst GW emission include 1) the formation of supermassive black holes which leads to a day-long burst of radiation [63], 2) highly eccentric supermassive black hole binaries [12], 3) close encounters of massive objects [34] and 4) cosmic string cusps [8]. Pshirkov & Tuntsov (2010) constrained the cosmological density of cosmic string loops using photometry and from pulsar timing showing that the pulsar timing data provides the most stringent constraints on the abundance of light strings.

Seto (2009), Pollney & Reisswig (2010), van Haasteren & Levin (2010) and Pshirkov, Baskaran & Postnov (2010) all considered GW bursts “with memory”. In general such events consist of a rise in the GW field, followed by an oscillatory behaviour for a few cycles and finally convergence to a non-zero value. The permanent change is known as the burst’s “memory”. Such events can occur during close encounters of massive bodies on hyperbolic trajectories or in an asymmetric supernova. Pshirkov, Baskaran & Postnov (2010) showed that one such event could be detected from distances of up to 1 Gpc (for the case of equal mass supermassive binary black hole systems of $M = 10^8 M_\odot$). A similar event can occur if the line of sight to a pulsar passes a cosmic string (Pshirkov & Tuntsov 2010). Such an event would instantaneously change the apparent frequency, $\nu$, of the pulsar by a small amount $\Delta \nu$ in the same way as that of a GW burst with memory although the
memory phenomenon would apply to all observed pulsars whereas this line-of-sight effect is specific to an individual pulsar.

Amaro-Seoane et al. (2010) discussed the possibility that supermassive black holes do not coalesce before the merger with a third galaxy. This leads to orbits with high eccentricity leading to an intense burst of GWs. They showed that, for reasonable supermassive black-hole evolution models, a few bursts will induce timing residuals $>1\,\text{ns}$, however, if pulsar timing were sensitive at the nanosecond level, most of these bursts would be undetectable because of confusion with the GW background.

A detection of a burst source using pulsar timing would provide the ability to localise the position of the source with the hope of identifying an electromagnetic counterpart. The angular resolution of a given timing array experiment depends upon the number of pulsars in the array, the timing precision and the distribution of the pulsars on the sky.

### 4.3 Stochastic background

A stochastic background of GWs is expected from the early phases of coalescence for supermassive black holes [47, 26, 72, 111], cosmic strings or relic GWs from the big bang [38]. In most models, the GW strain spectrum, $h_c(f)$, is represented by a power-law in the GW frequency, $f$. 

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**Fig. 7** Upper bounds from Jenet et al. (2006) for stochastic backgrounds with various values of the GW spectral exponent $\alpha$ (solid line). The dotted lines indicate regions predicted by various GW background models. The dashed line indicates potential future limits from the PPTA project. The star symbol provides the upper bound given by Kaspi, Taylor & Ryba (1994). Figure from Jenet et al. (2006).
where the spectral exponent, $\alpha = -2/3$, -1 and $-7/6$ for likely GW backgrounds caused by coalescing black hole binaries, cosmic strings and relic GWs respectively. The energy density of the background per unit logarithmic frequency interval can be written as

$$\Omega_{GW}(f) = \frac{2}{3} \frac{\pi^2}{H_0^2} f^2 \left(\frac{f}{yr^{-1}}\right)^2$$

where $H_0$ is the Hubble constant. Sesana, Vecchio & Colacino (2008) showed that the expected form of the stochastic background is not simply $h_c \propto f^{-2/3}$, but the frequency dependence becomes steeper above $\sim 10^{-8}$ Hz. They showed that the major contributors to the background come from massive $>10^8 M_\odot$ binary black hole systems that are relatively nearby ($z < 2$).

In contrast to backgrounds formed from supermassive black-hole binary systems, Saito & Yokoyama (2009) showed that the formation of intermediate-mass ($\sim 600 M_\odot$) black holes at the end of the inflationary era will lead to a potentially detectable background of GWs. Current pulsar upper bounds already limit the process for the formation of such black holes.

Both “kinks” and “cusps” on cosmic string loops can also contribute to a background of GWs. Olmez, Mandic & Siemens (2010) showed that both phenomena contribute at the same order to the background. The most recent constraints, and their implications, on the cosmic string tension using pulsar timing experiments have been provided by Battye & Moss (2010).

A background of GW radiation from the early universe is also expected, if detected, to provide a unique view of the physics of the very early universe (e.g. [15]). Boyle & Buonanno (2007) showed that combinations of cosmic microwave background experiments and GW detection experiments lead to strong constraints on the existence and properties of various energy components that may have dominated the universe at the end of the inflationary era.

One of the first limits on a GW background was placed by Stinebring et al. (1990). Kaspi, Taylor & Ryba (1994) used observations of PSRs J1857+0943 and J1939+2134 from the Arecibo observatory to provide an upper bound on the GW background. Their data sets were made publically available allowing other algorithms to be applied to their data sets [40, 29]. Jenet et al. (2006) developed a method that took into account all the effects of fitting a pulsar timing model to data sets of different data spans and applied the technique to carefully selected PPTA data sets as the technique can only be applied to data sets that are statistically “white”. Van Haasteren et al. (2008) developed a Bayesian algorithm which has been applied to EPTA data sets [13]. Anholm et al. (2009) developed an independent method which currently does not address some issues relating to real pulsar data. Work is ongoing to develop a method that correctly detects the GW background or limits its amplitude and can easily be applied to the IPTA data sets.

The most stringent limits published to date on the amplitude of a background caused by these various phenomena were obtained using observations from the
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The IPTA pulsar data sets contain some of the most precisely measured observations yet made of radio pulsars. These data sets can be used to search for GW sources and for numerous other purposes. Details of the only currently publically available data sets are provided in Kaspi, Taylor & Ryba (1994). Hobbs et al. (2009) provided a sample of simulated data sets for comparison of GW detection algorithms that are available for download. In the near future it is expected that all observations from Parkes Observatory (after an embargo period of 18 months) will be available for download providing access to most PPTA data. A few data sets relating to the PPTA project are also available as part of the PULSE@Parkes outreach project[20, 24].

The TEMPO2 package provides a few “plugin” packages and routines suitable for GW analysis:

- **GW SIM.H**: a library that implements the mathematics described by Hobbs et al. (2009). The routines in this library can be used to create new TEMPO2 plugins easily.
- **FAKE**: plugin that simulates pulsar TOAs given a timing model.
- **GWSINGLE**: plugin that simulates a single non-evolving GW source and produces a file of site-arrival-times that can be used for subsequent processing.
- **GWEVOLVE**: plugin that simulates a single evolving GW source.
- **GW BKGRD**: plugin that simulates a background of GW sources.

A new plugin is currently under development that will either provide limits on the amplitude of the GW background or give the significance of any detection by searching for correlations in the timing residuals of multiple pulsars.

6 The future

It is likely that the signature of a GW background will be discovered in IPTA data sets shortly. However, any such initial “detection” will only have a low significance (e.g. $\sigma \sim 2$ to 3). How this significance will increase with time will depend upon the intrinsic pulsar timing noise, the amplitude and spectral exponent of the background, whether new pulsars are discovered and whether observing systems are improved. A very high significance detection, enabling detailed studies of the astro-
physical objects that form the background and the physics of the GWs themselves (e.g. [35]), will require large numbers of pulsars to be observed with high precision. Various new telescopes are being developed that should detect a large number of new pulsars or be able to observe pulsars with high precision (e.g. the Australian Square Kilometre Array Pathfinder [31, 32], MeerKAT [4] and FAST [41]). These telescopes are pathfinders to the Square Kilometre Array which should be fully operational by 2024. This telescope should revolutionise pulsar and GW astronomy by allowing almost all pulsars in our Galaxy to be detected and GW detection using pulsar observations should become commonplace.

7 Conclusion

Pulsar timing experiments can detect gravitational wave signals. The most likely detectable source is an isotropic, stochastic background from a large number of coalescing supermassive binary black hole systems. It is possible that a detection of such a background could be made with existing data, but it will require a further 5-10 yr to have a definitive, highly significant detection. It is expected that GW astronomy using pulsars will become a standard astronomical tool during the Square Kilometre Array era when the background will be analysed in detail and individual binary black-hole systems and burst GW sources will be detectable.

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