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The Parkes Pulsar Timing Array

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Abstract Given sufficient sensitivity, pulsar timing observations can make a direct detection of gravitational waves passing over the Earth. Pulsar timing is most sensitive to gravitational waves with frequencies in the nanoHertz region, with the most likely astronomical sources being binary super-massive black holes in galaxy cores. The Parkes Pulsar Timing Array project uses the Parkes 64-m radio telescope to make precision timing observations of a sample of about 20 millisecond pulsars with a principal goal of making a direct detection of gravitational waves. Observations commenced about one year ago and so far sub-microsecond timing residuals have been achieved for more than half of these pulsars. New receiver and software systems are being developed with the aim of reducing these residuals to the level believed necessary for a positive detection of gravitational waves.

Key words: pulsars: general — gravitational waves — time

1 INTRODUCTION

Gravitational waves (GW) are a prediction of Einstein's general theory of relativity (and other relativistic theories of gravity) and are generated by massive objects in accelerated motion relative to an inertial frame. They are incredibly weak and, despite much effort over many decades, they have never been directly detected. Pulsars have provided strong evidence for their existence through observations of the decay of the orbit of binary pulsars, in particular for the Hulse-Taylor binary PSR B1913+16 (Taylor & Weisberg 1982; Weisberg & Taylor 2005). Current projects aimed at detecting gravitational waves include LIGO (Abbott et al. 2004), VIRGO (Acernese et al. 2004) and LISA (Danzmann 2000). All of these are laser interferometer systems. LIGO and VIRGO are ground-based and are most sensitive to GW at frequencies around 100 Hz, whereas the proposed LISA system consists of three spacecraft in orbit about the Sun and is most sensitive to GW with frequencies of about 1 mHz.

Gravitational waves in our Galaxy modulate the apparent pulse period of pulsars. Pulsar timing experiments measure pulse times of arrival (TOAs) and so they are sensitive to accumulated pulse phase offsets. Consequently, they are sensitive to long-period GW with highest sensitivity to waves which have a period comparable to the length of the data span. This is typically several years, so maximum sensitivity is achieved for GW with frequencies of about 1 nanoHertz. Pulsar timing experiments are therefore quite complementary to the laser-interferometer systems.

Observations of a single pulsar can be used to set limits on the strength of the GW background in the Galaxy at these nanoHertz frequencies. Any GW signal must be smaller than the timing residuals remaining after fitting for the pulsar model (assuming that the model terms do not absorb the GW signal). Because of their narrow pulse profiles (expressed in time units) and exceptional period stability, millisecond pulsars (MSPs) give the best limits. From an 8-year sequence of Arecibo observations of PSR B1855+09, an upper limit on the energy density of the GW background relative to the closure density of the Universe, $\Omega_g \sim 10^{-7}$, was obtained by Kaspi, Taylor, & Ryba (1994). A longer but non-uniform data set on the same pulsar was analysed by Lommen et al. (2002), reducing this limit by about an order of magnitude (see also Damour & Vilenkin 2005).

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In principle, observations of many pulsars spread across the celestial sphere, a "pulsar timing array", can make a direct detection of the GW background at the Earth (Hellings & Downs 1983; Foster & Backer 1990). GW passing over the pulsars result in period perturbations which are uncorrelated between the different pulsars. However, GW passing over the Earth produce correlated residuals which contain the quadrupolar signature of GW as a function of position on the sky. In contrast, clock errors produce a correlated signal which is independent of sky position and hence can be separated from the GW signature. Similarly, an error in the Solar-System ephemeris (effectively an error in the velocity of the Earth with respect to the Solar-System barycentre) produces a dipole signature which can be separately identified.

The Parkes Pulsar Timing Array (PPTA) project is a collaborative effort between Swinburne University of Technology, the University of Texas at Brownsville and the Australia Telescope National Facility to make precision timing observations of a sample of about 20 MSPs using the Parkes 64-m radio telescope with the ultimate goal of making a direct detection of gravitational waves. In Section 2 we give a detailed description of the goals and methods for the project, Section 3 discusses the prospects of defining a timescale based on pulsars, Section 4 describes our efforts at countering the effects of radio-frequency interference (RFI) and the current state of the project is summarised in Section 5.

2 GOALS AND METHODS

The main goals of the the PPTA project are as follows:

- Detection of gravitational waves from astronomical sources
- To establish a pulsar-based timescale
- To investigate possible errors in the Solar-System ephemeris

To achieve these overall goals, a large number of secondary or intermediate goals have to be met. These include:

- Develop new instrumentation for precision pulsar timing at the Parkes radio telescope
- Make timing observations of ~ 20 MSPs at 2 – 3 week intervals for five or more years at three frequencies: 700 MHz, 1400 MHz, and 3100 MHz
- Achieve daily pulse TOA precisions of $\lesssim 100$ ns for more than 10 MSPs and < 1 μs for the rest of the sample
- Investigate and model the effect of GW signals on pulsar timing data
- Develop software for analysis of timing data from multiple pulsars with systematic errors of < 2 ns
- Develop and implement methods for detection of GW signals
- Develop and implement methods for investigating instabilities in the terrestrial timescale and establishing a pulsar-based timescale
- Develop and implement methods for investigating errors in the Solar-System ephemeris and improving the ephemeris
- Investigate the effect of signal propagation through the interstellar medium and correct for it where possible
- Develop and implement methods for mitigating the effects of radio-frequency interference (RFI) on pulsar timing data
- Develop links with international groups to foster collaboration and coordination of pulsar timing efforts

For observations at 1400 MHz, the PPTA mainly uses the central beam of the Parkes multibeam receiver (Staveley-Smith et al. 1996) although the "H-OH" receiver is used occasionally. The multibeam receiver central beam is a dual-channel system with orthogonal linear feeds. Each channel has a bandwith of 256 MHz and a system equivalent flux density on cold sky of about 30 Jy. At 700 MHz and 3100 MHz, the "10 cm/50 cm" receiver is used. This dual-frequency coaxial system with orthogonal linear feeds at each frequency allows simultaneous observations in the two bands. At 700 MHz the bandwidth is 64 MHz with a system equivalent flux density of about 70 Jy, and at 3100 MHz the bandwidth is 1024 MHz with a system equivalent flux density of about 45 Jy.

For observations at 700 MHz and 1400 MHz, data are recorded using the CPSR2 baseband recording system (see Jacoby et al. 2005) which 2-bit samples two polarisations for each of two 64-MHz wide bands

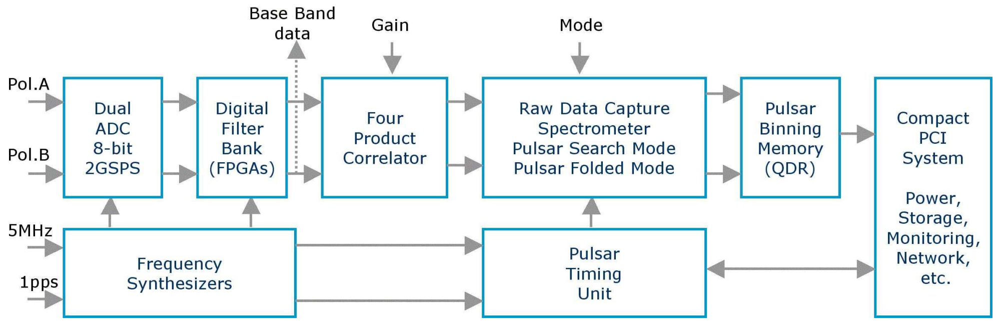

Fig. 1 Block diagram of the pulsar digital filterbank system under development at ATNF (G. Hampson, private communication).

(at 700 MHz, only one band can be used) and coherently dedisperses the data to give high time resolution. The wider bandwidths available at 1400 MHz and 3100 MHz have been observed using the "Wideband Correlator". This system, which is based on the Canaris correlator chip developed at the National Radio Astronomy Observatory, can 2-bit sample bandwidths up to 1024 MHz. It provides up to 1024 frequency channels on each of four polarisation products and synchronously integrates these at the topocentric pulsar period with up to 2048 bins per pulsar period.

Unfortunately, the processing speed of the wideband correlator system allows only a limited number of channels and bins for observations of MSPs, thereby limiting the precision of measured TOAs. To overcome this and other limitations we are developing a pulsar digital filterbank (PDFB) system with enhanced capabilities. This system will implement a polyphase filter (Ferris & Saunders 2004) using Field Programmable Gate Array (FPGA) processors and, like the wideband correlator, will have 1024 MHz maximum bandwidth. A block diagram of the system, which is being designed and constructed by Grant Hampson and Andrew Brown at the ATNF, is shown in Figure 1. It will use dual 8-bit digitisers operating at 2 Gsamples per second. The 8-bit digitisation provides higher sensitivity and better fidelity in the digitised signal as well as increased protection from strong RFI. The polyphase filter gives a superior channel bandpass shape with about 30 db of sidelobe rejection compared to 12 db for an FFT spectrometer, further reducing the effect of strong RFI. The PDFB implementation will have up to 2048 frequency channels on each of four polarisations, a pulsar binning memory with up to 2048 bins per period and a minimum bin time of 5 μs. The system will also have a "search" mode in which channel data is dumped directly to disk at a specified sampling interval and a baseband mode providing up to 16 baseband-sampled channels on two polarisations, each 64 MHz wide and contiguous across the 1024 MHz input bandwidth. These will provide the basis for a next-generation baseband system to be developed by the ATNF in collaboration with Swinburne University.

A prototype PDFB system which has 256 MHz maximum bandwidth was installed at Parkes in June, 2005, and is working well. To illustrate this, Figure 2 shows the mean pulse polarisation profiles for PSR J1713+0747 from an observation of duration 64 min at 1433 MHz which agree well with those published by Ord et al. (2004). This pulsar has a period of 4.57 ms and a dispersion measure of 15.99 cm^{-3} pc. The PDFB configuration used had 512 frequency channels and 256 pulse phase bins giving a profile resolution of 17.8 μs and a dispersion smearing of 24.2 μs. The final system will improve on these numbers, giving an effective time resolution of about 10 μs for this pulsar.

Recording data at the telescope is only the first stage in achieving the goals of the PPTA. Pulse profiles must be processed to remove the effects of bad or corrupted data, calibrated to remove instrumental effects, summed in frequency taking into account the effects of interstellar dispersion, and summed in time to form high signal/noise pulse profiles. These are then correlated with a standard pulse template to give topocentric TOAs of a reference pulse phase for each profile. The PSRCHIVE pulsar data analysis system (Hotan, van Straten, & Manchester 2004) is used for all data processing. Once a set of TOAs for a given pulsar have been obtained, a pulsar model is fitted to the data to form a set of timing residuals and give improved model parameters.

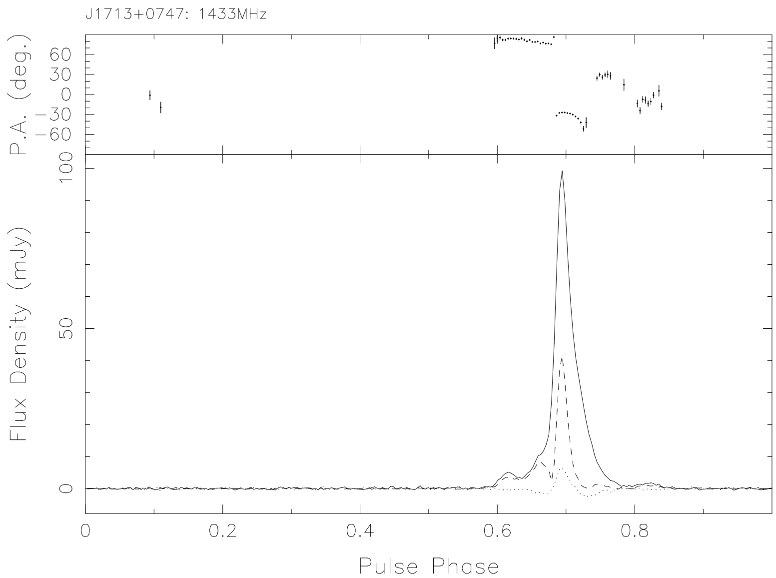

Fig. 2 Polarisation of the mean pulse profile for the MSP PSR J1713+0747 at 1433 MHz recorded with the prototype digital filterbank system at Parkes. In the lower part of the figure, the solid line is total intensity (Stokes I), the dashed line is linearly polarised intensity ($L = (Q^2 + U^2)^{1/2}$) and the dotted line is circularly polarised intensity (Stokes V). The upper part shows the position angle of the linearly polarised component.

Up to now, the program TEMPO[1] has been widely used for this purpose. However, TEMPO contains a number of approximations which preclude the very high precision required for the PPTA and other similar projects. To overcome these problems and to provide a more user-friendly and versatile interface to the program, a new program, TEMPO2, is being developed at the ATNF. This program, described by Hobbs et al. (2006) in these proceedings, will also allow simultaneous fitting of data from many pulsars, a vital step in the process of achieving the goals of the PPTA.

3 A PULSAR TIMESCALE

The standard of terrestrial time, TT(TAI), is defined by a weighted average of more than 200 caesium clocks at time standard laboratories around the world. The unit of TT(TAI) is the SI second on the rotating geoid and the rate of TT(TAI) is adjusted from time to time to conform to this definition. TT(TAI) is defined essentially in real time and has a fractional frequency stability of order 10^{-15}. With reassessment of errors in individual clocks and improved averaging techniques, it is possible to retroactively define an improved timescale. A number of such improved timescales have been defined by the BIPM in Paris, e.g., TT(BIPM2003) (Petit 2003).

Soon after the discovery of the first MSPs, it was recognised that pulsars could be used to define a timescale independent of terrestrial clocks (e.g., Taylor 1991). This timescale is relative in the sense that there is no standard "pulsar frequency" and so can only be used to investigate the stability of terrestrial timescales. Furthermore, these comparisons are insensitive to linear changes in rate (since pulsars have an intrinsic period derivative) and to annual terms since pulsar positions are not known a priori to sufficient accuracy. From an analysis of 7 years of Arecibo timing data, Kaspi, Ryba, & Taylor (1994) showed that PSR B1855+09 has a fractional frequency stability $\sim 2 \times 10^{-15}$ averaged over timescales of several years.

By averaging over many pulsars and with improved technology, timing array observations should be able to improve significantly on this limit and potentially detect variations in the best available terrestrial timescale, in effect defining a "pulsar timescale" (Foster & Backer 1990; Petit & Tavella 1996). As an illus-

[1] See http://www.atnf.csiro.au/research/pulsar/tempo.

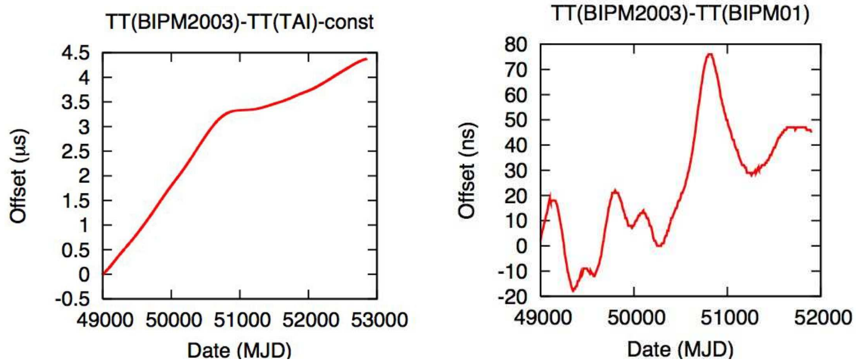

Fig. 3 (a) Difference between TT (BIPM2003) and TAI from 1993 to 2003 after removal of a constant term. (b) Difference between TT (BIPM2003) and TT (BIPM2001) from 1993 to 2001. (R. Edwards with data from Petit 2003.)

tration of the magnitude of the effects that a pulsar timescale might reveal, the left panel of Figure 3 shows the difference between TT (BIPM2003) and TAI. Even after the trend is removed, there are deviations of order 1 μs which will be easily detectable by the PPTA. As an indication of the base-level uncertainty in the best available terrestrial timescales, the right panel shows the difference between TT (BIPM2003) and TT (BIPM01). Peak deviations are of order 50 ns. If the PPTA is able to meet its goal of sub-100 ns timing for more than 10 MSPs, the pulsar timescale should be defined to 10–20 ns with an averaging time of a few weeks, sufficient to detect fluctuations in the best terrestrial timescales.

4 RFI MITIGATION

RFI is a problem for all radio astronomy observations. Furthermore, with increasing use of the RF spectrum and increasing sensitivity of radio astronomy systems, it is a problem which is rapidly becoming more serious. Because of their high time resolution and high sensitivity, demanding wide bandwidths, pulsar observations are especially susceptible to contamination by RFI. The problem is especially acute for the 50 cm (700 MHz) receiver at Parkes where digital TV transmissions have recently commenced within and adjacent to the receiver bandpass. In this case, it is possible to obtain a reference spectrum of the contaminating signal with high signal/noise ratio using a 3.5-m parabolic reflector directed at the TV station which is approximately 200 km south of the Observatory.

With such a reference signal, it is possible to generate an adaptive filter to effectively remove time-varying RFI contamination from the telescope observation without affecting the underlying astronomy signal (Barnbaum & Bradley 1998; Kesteven et al. 2005). The results of a test of this procedure are shown in Figure 4, with the left panels showing the unfiltered data for one receiver channel and the right panels showing the effect of the adaptive filtering. These data are from a 16.7-s observation of PSR J0437−4715 and the reference signal, both recorded using the CPSR2 recording system. They were processed off-line making use of PSRCHIVE. The upper panels show the receiver bandpass, the second panel shows the pulsar mean pulse profile, the third panel shows the power spectrum of the pulsar signal and the bottom panel shows the signal-to-noise ratio of the pulsar signal. These plots clearly show that the adaptive filtering removes the effect of the RFI without affecting the astronomy signal either under the RFI or in the rest of the bandpass. Processing of the other (orthogonal) receiver channel (recorded simultaneously) gave similar results and analysis of the two channels together showed that the polarisation properties of the pulsar signal were preserved.

Given the success of these trials, we are developing a hardware implementation of the adaptive filter that will be able to operate in real time for the 64-MHz bandwidth of the 50 cm receiver. This will be based on the same FPGA processors as used in the PDFB and will act as a preprocessor for it or other data recording systems. We expect to commission this system during 2006.

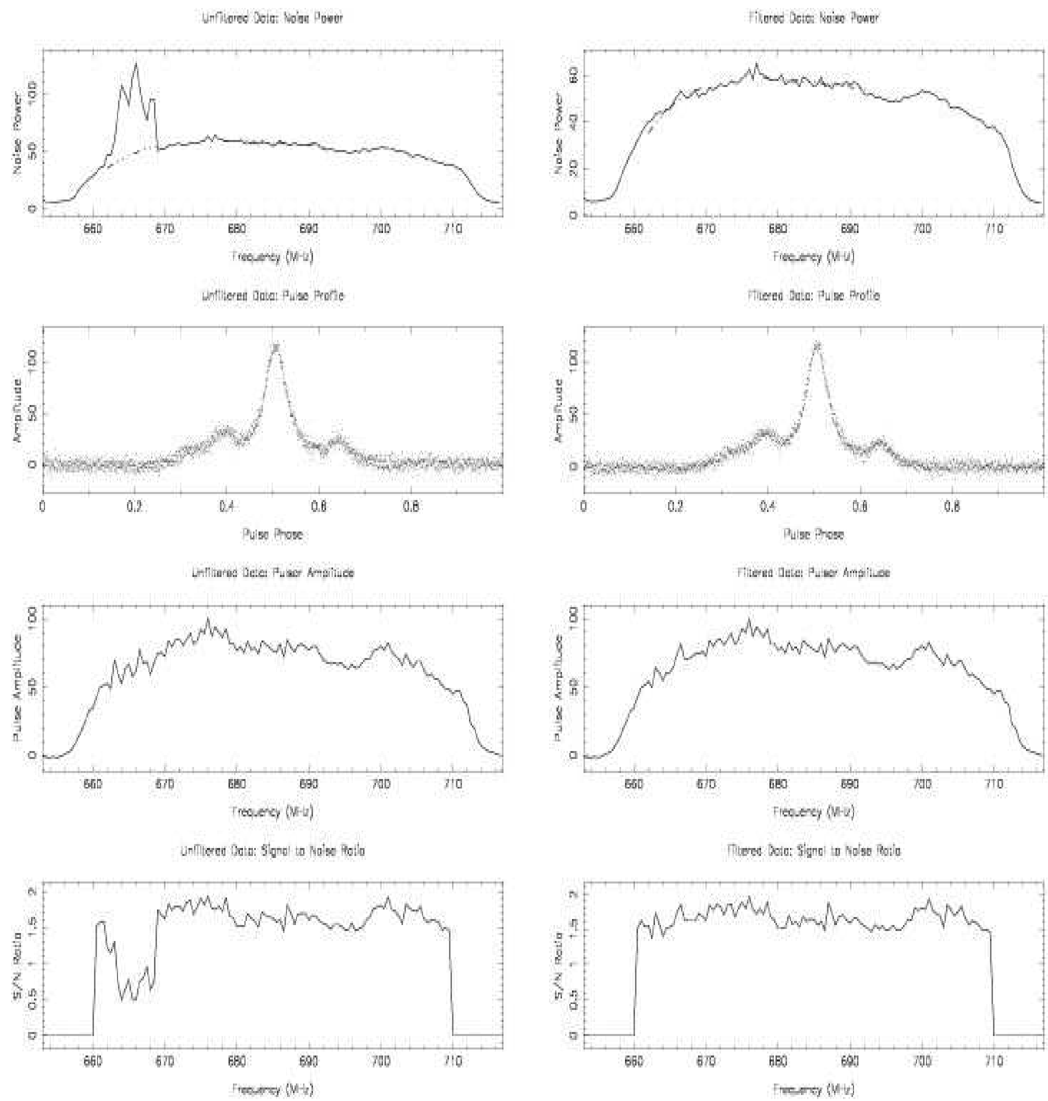

Fig. 4 Results of adaptively filtering data from the 50 cm receiver at Parkes to remove the effects of digital TV in the bandpass. The left panels show properties of the signal before filtering and the right panels show results after filtering (Kesteven et al. 2005). See text for further details.

5 CURRENT STATUS OF THE PPTA

Systematic observations of the 20 MSPs chosen for the PPTA commenced about one year ago. Figure 5 shows the sky distribution of these and other MSPs with periods less than 20 ms (excuding those in globular clusters). PPTA pulsars are generally those with relatively narrow pulses and high flux densities as these give the most precise TOAs, but in some cases pulsars have been included to improve the sky distribution. This figure highlights the fact that there are few suitable MSPs known north of the Parkes northern declination limit ($+24°$). Further searches of the northern sky for MSPs are clearly warranted. Additional searches of the southern sky at high Galactic latitudes would also be useful.

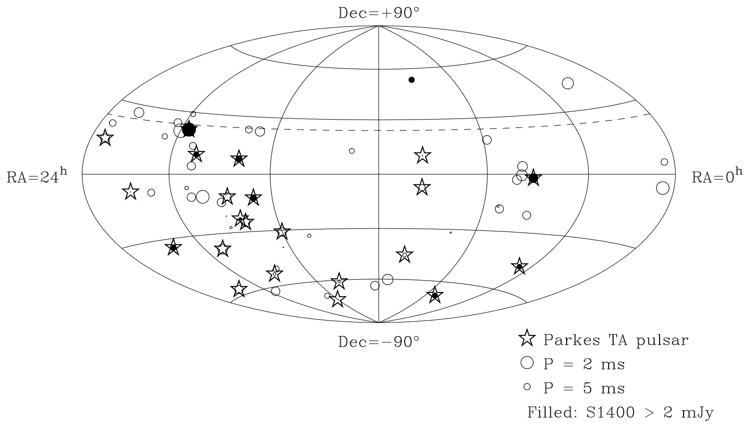

Fig. 5 Galactic disk MSPs with periods less than 20 ms plotted in celestial coordinates. The size of the circle is inversely related to the pulsar period and for stronger pulsars the circle is filled. The dashed line is the northern declination limit of the Parkes telescope. Pulsars chosen for the PPTA are marked by a star.

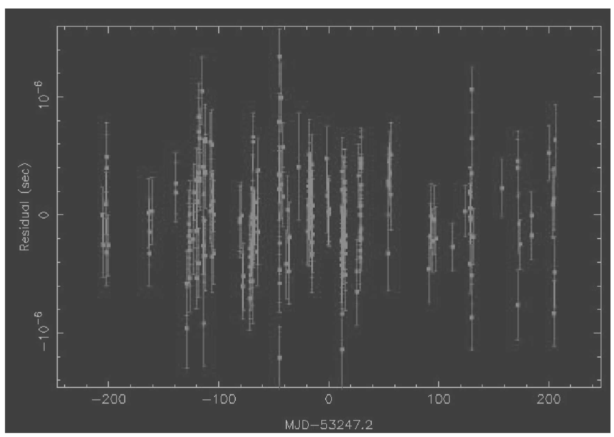

Fig. 6 Timing residuals from observations of PSR J0437−4715 at 3100 MHz using the wideband correlator.

Regular observations of the PPTA sample commenced in mid-2004, although as discussed in Section 2, development of the observing systems has continued since then. Typically we have a 2–3 day observing session every 2–3 weeks where we observe the 20 pulsars in the sample at 700, 1400, and 3100 MHz. CPSR2 observations at 1400 MHz are currently giving the best results, especially when combined with previous Swinburne timing observations. Currently we have sub-microsecond timing residuals for seven pulsars and residuals of a few microseconds for an additional seven. The best timing is for PSR J1909–3744 for which daily observations give an rms residual of 74 ns (Jacoby et al. 2005). Despite the limited time and frequency resolution of the wideband correlator, sub-microsecond residuals have been obtained for four pulsars at 1400 or 3100 MHz. Figure 6 shows post-fit residuals to observations of PSR J0437−4715 at 3100 MHz using the wideband correlator which have an rms value of 0.32 μs. The prototype PDFB is producing high quality data and has convincingly demonstrated the viability of the technique. However, it still has some limitations in maximum bandwidth and minimum sampling time which will be overcome in the final PDFB system. We anticipate that this will be commissioned in early 2007.

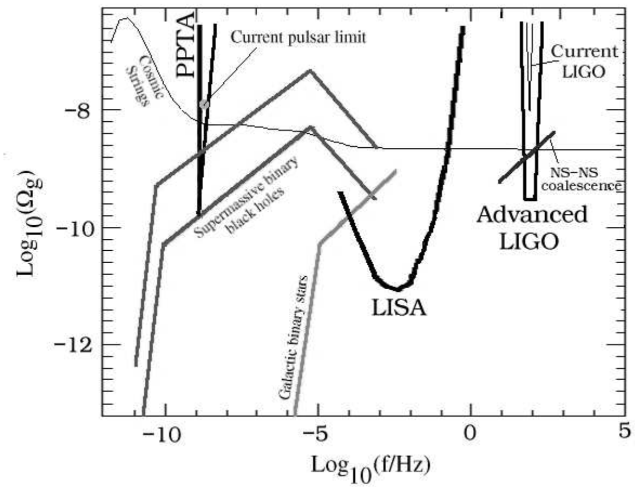

Fig. 7 Energy density of gravitational waves relative to the critical mass density of the Universe as a function of frequency. Sensitivity limits of the LIGO laser interferometer system, both current and projected, the proposed LISA space interferometer system and the projected sensitivity of the PPTA after 5 years of observation are shown. The current limit on from pulsar timing and the expected spectrum from several classes of astronomical sources are also given. The two lines for supermassive binary black holes show the upper and lower bounds of the predictions. (After Maggiore (2000), with help from S. Phinney, F. Jenet and G. Hobbs)

Simulations of the PPTA (Jenet et al. 2005) show that, with timing residuals of 100 ns or better for at least 10 of the MSPs and 500 ns or better for the remainder with 250 observations over 5 years, the predicted levels of the stochastic GW background from binary black holes in galaxies (Jaffe & Backer 2003; Wyithe & Loeb 2003) should be detectable. Since the expected timing residuals from GW have a very "red" spectrum, i.e., are dominated by slow fluctuations, filtering of the data is necessary to obtain the highest sensitivity. Optimal techniques for doing this "pre-whitening" are being investigated. Figure 7 shows the sensitivity curves for LIGO (both current and Advanced LIGO, the latter expected to be completed about 2010), LISA (proposed launch in 2017) and the PPTA after five years, as well as the expected level of the stochastic GW background at the Earth for a range of astronomical sources. The current limit on the energy density from pulsar timing (Lommen et al. 2003) is also shown. This figure highlights the complementarity of pulsar timing to the other GW detection efforts and shows that the PPTA should be able to detect GW from supermassive black holes in galaxies if the technological goals are achieved.

6 CONCLUSIONS

The Parkes Pulsar Timing Array (PPTA) project aims to obtain high-precision timing data on a sample of 20 of the brightest short-period MSPs accessible to the Parkes 64-m telescope. The principal goal of the project is the direct detection of gravitational waves with frequencies in the nanoHertz region. Simulations show that, with a relatively modest improvement in current timing precision, this should be possible with observations over a 5-year data span. In any case, the data will permit a range of interesting investigations including establishment of a pulsar-based timescale, studies of the interstellar medium and studies of the pulsars themselves. New receiver and software systems, including a versatile digital filterbank, an RFI mitigation system and a timing analysis program are being developed to help us achieve these goals.

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