Pulsars and Gravity

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Pulsar periods are extremely stable, making possible many interesting and important applications ranging from determining the proper motion of globular clusters to detecting gravitational waves. Many pulsars, especially millisecond pulsars, are in binary orbit with another star. The first-known pulsar binary system, PSR B1913+16, discovered by Hulse and Taylor in 1974, provided the first observational evidence for the existence of gravitational waves and verified that Einstein’s general theory of relativity is an accurate theory of gravitation. Surveys with Parkes multibeam receiver have in the past few years more than doubled the number of known pulsars. Prominent among the discoveries is the first-known double pulsar, PSR J0737−3039A/B. This system is even more relativistic than PSR B1913+16 and in just two years has provided a more stringent test of general relativity, with five post-Keplerian parameters already determined. An important prediction of general relativity is the existence of gravitational waves. Precise timing of a very stable millisecond pulsar has already put limits on the energy density of a stochastic gravitational-wave background at the Earth. Timing measurements of an ensemble of millisecond pulsars distributed over the celestial sphere can in principle make a direct detection of this stochastic background. The Parkes Pulsar Timing Array (PPTA) project is making regular timing measurements of 20 millisecond pulsars with the ultimate aim of detecting the gravitational-wave background at the Earth. With a five-year data span the PPTA should have sufficient sensitivity to detect the gravitational-wave background from binary super-massive black holes in the cores of galaxies.

§1. Introduction

Pulsars are celestial radio sources believed by most people to be rotating neutron stars. Their emission consists of a highly periodic series of pulses with a separation or period in the range 1.5 ms to several seconds. This basic periodicity is identified with the spin period of the neutron star with the pulsation due to beaming of the radiation from the star. About 1740 pulsars are now known, almost all of them located in our Galaxy. As Fig. 1 shows, the known pulsars fall into two distinct groups: so-called “normal” pulsars with periods generally between 100 ms and a few seconds and “millisecond” pulsars (MSPs) with periods in the range $1 - 100$ ms. A third group, known as Anomalous X-ray Pulsars (AXPs), have periods in the range $5 - 12$ s and in contrast to most other pulsars, only emit in the X-ray band.¹ There are about 175 MSPs now known and nearly 75% of these are members of a binary system. In contrast, only a few per cent of the normal pulsars are binary.

All pulsars slow down as a result of loss of energy to some combination of magnetic-dipole radiation and charged-particle winds. The measured period time derivative, $\dot{P}$, gives a measure of the pulsar age known as the characteristic age, $\tau_c = P/(2\dot{P})$, and the magnetic field at the neutron-star surface $B_s = 3.2 \times 10^{19} (P\dot{P})^{1/2}$ G.¹

¹) This group also includes Soft Gamma-ray Repeaters (SGRs) which show a periodic modulation.
Both of these relations assume that the external magnetic field of the neutron star is dipolar and, in addition, the characteristic age assumes that the pulsar was born with a period much less than its present value. If this is not so, the true age is less than $\tau_c$.

Normal pulsars are relatively young, with $\tau_c$ values generally between $10^3$ and $10^7$ years, and have strong surface-dipole fields of order $10^{12}$ G. About 30 of the youngest pulsars are convincingly associated with supernova remnants\(^\text{1}\) lending support to the idea that neutron stars are formed in supernova explosions as originally proposed by Baade and Zwicky,\(^\text{4}\) long before the discovery of pulsars. MSPs are distinguished not only by their short periods, but also by very small values of $\dot{P}$ and hence large values of $\tau_c$, typically between $10^9$ and $10^{10}$ years, and low magnetic fields, typically between $10^8$ and $10^9$ G. The fact that most MSPs are in binary systems gives strong support to the idea that they are old neutron stars which have been spun up or recycled by accretion of mass and angular momentum from an evolving binary companion.\(^\text{3,8,51}\) The accretion process evidently also results in a decrease in the surface dipole magnetic field by three or four orders of magnitude, but the mechanism for this is currently not well understood.

\section*{§2. Pulsar timing}

Although pulsar periods are not constant, they are very predictable with a stability that rivals the best terrestrial clocks. It is this property, especially when combined with the fact that some of the most stable pulsars are in rapid orbital motion with another star, that makes them such valuable tools for investigation of

\(^{1}\) See the ATNF Pulsar Catalogue for associations and references.
a wide range of astrophysical problems. Quantities such as the proper motion and parallax of a pulsar or the decay of a binary orbit due to the emission of gravitational waves from the system can be precisely measured using pulsar timing.

How are these precise periods and their small perturbations measured? The first step is to form a mean pulse profile by synchronously averaging the pulsar total intensity signal, typically for a few thousand pulse periods. Mean pulse profiles formed in this way are very stable and so, by cross-correlating them with a standard template, a precise pulse time-of-arrival (TOA) at the telescope can be derived. A series of these TOAs measured over days, weeks or years is then compared with predicted values based on a model for the pulsar including its celestial position, pulse period and period derivative, and binary orbital parameters if appropriate. To avoid effects due to the accelerated motion of the Earth, TOAs are referred to the centre of mass or barycentre of the Solar System, which is assumed to be an inertial frame, and model parameters are also given in this frame. The differences between the observed and predicted TOAs are called pulsar timing residuals. Provided the pulsar model is sufficiently accurate, errors in the parameters will lead to systematic variations in the observed residuals. A least-squares fit to the residuals of functions representing the effect of errors in the various parameters can then be used to improve the estimates of these parameters. For example, a small error in the pulsar period will lead to a linear trend in the residuals, the slope of which gives the correction to the period. Similarly, an error in pulsar position will lead to an annual sinusoid in the residuals since the barycentric correction involves a projection of the vector from the Solar System barycentre to the Earth on the vector toward the pulsar position.

Residuals remaining after the model parameters have been adjusted represent unmodelled effects which can range from gravitational waves to receiver noise. Table I lists possible sources of timing “noise”, that is, effects which may contribute to observed timing residuals after fitting for the basic pulsar parameters. The size of this list illustrates the power of pulsar timing. Apart from the bottom two categories, every one of these entries is of scientific interest and some are of great significance to astrophysics and to physics in general. Even the instrumental effects are challenging problems for engineers and astronomers.

§3. The first binary pulsar: PSR B1913+16

No talk entitled “Pulsars and Gravity” would be complete without at least a short review of the wonderful results which have flowed from the discovery at Arecibo of the first-known binary pulsar by Russell Hulse and Joseph Taylor.26) This pulsar has a relatively short period of 59 ms and was quickly shown to be in a highly eccentric binary orbit with an orbital period of only 7h 45m. The orbital velocity at periastron is about 0.1% of the speed of light, so relativistic perturbations to the orbit were expected to be easily detectable and, indeed, a precession of the longitude of periastron (ω) at a rate of 4.2 deg yr\(^{-1}\) was soon observed. Interpreted within the framework of Einstein’s general theory of relativity (GR), this precession implied a total mass of the system of 2.8 M\(_\odot\), making it very likely that the companion was another neutron star. Continued observations confirmed this and also provided
Table I. Sources of pulsar timing “noise”.

| Intrinsic noise:                      |
|--------------------------------------|
| • Period fluctuations, glitches      |
| • Pulse shape changes                |

| Perturbations of the pulsar’s motion:|
|-------------------------------------|
| • Gravitational wave background     |
| • Globular cluster acceleration     |
| • Orbital perturbations: planets, 1st-order Doppler, relativistic effects |

| Propagation effects:               |
|------------------------------------|
| • Scattering and dispersion in a wind from a binary companion |
| • Variations in interstellar dispersion |
| • Interstellar scattering          |

| Perturbations of the Earth’s motion:|
|------------------------------------|
| • Gravitational wave background    |
| • Errors in the Solar-system ephemeris |

| Clock errors:                      |
|------------------------------------|
| • Timescale errors                  |
| • Errors in time transfer           |

| Instrumental errors:               |
|------------------------------------|
| • Receiver non-linearities         |
| • Digitisation artifacts or errors|
| • Calibration errors and signal-processing artifacts and errors |

| Noise sources:                     |
|------------------------------------|
| • Radio-frequency interference     |
| • Receiver thermal noise           |

a measurement of another “Post-Keplerian” (PK) parameter, $\gamma$, representing the combined effects of gravitational redshift and second-order Doppler shift (i.e., special relativistic time dilation) on the observed pulsar period. Again within GR, the measurements of $\dot{\omega}$ and $\gamma$ determined the masses of the two stars separately, showing they were both close to $1.4 \, M_\odot$ and likely to both be neutron stars. Given the Keplerian orbital parameters and the two masses, it was then possible to make a prediction of the rate at which the orbit should decay due to the emission of gravitational waves. After several years of observation, the orbital decay was measured and shown to be in excellent agreement with the predictions of GR.\(^\text{56}^\) Figure 2 is a recent plot showing the measured and predicted orbital decay. The masses used in this prediction, derived from the measured periastron advance and time dilation terms, were $M_p = 1.4408 \pm 0.0003 \, M_\odot$ and $M_c = 1.3873 \pm 0.0003 \, M_\odot$ and the ratio of observed to predicted orbital period decay was $\dot{P}_b(\text{obs})/\dot{P}_b(\text{pred}) = 1.0013 \pm 0.0021$.\(^\text{58}^\) The value of $\dot{P}_b$ has to be adjusted to take into account the differential acceleration of the binary system and the Solar System in the gravitational field of the Galaxy and its uncertainty is now dominated by the uncertainty in this term. Never-the-less, the agreement of the observed and predicted values is an outstanding confirmation of GR as a theory of gravity.

In summary, PSR B1913+16 was not only the first binary pulsar discovered, it has given the first accurate determinations of neutron-star masses, provided the first observational evidence for the existence of gravitational waves and shown that gen-
eral relativity gives an accurate description of strong-field gravitational interactions — truly a set of results which fully justifies the 1993 award of the Nobel Prize in Physics to Taylor and Hulse.

§4. Parkes multibeam pulsar searches

Many search efforts on various (mostly radio) telescopes over the past 38 years have contributed to the sample of known pulsars. The 64-m Parkes radio telescope is by far the most successful instrument in discovering pulsars, having found more than twice as many pulsars as the rest of the world’s telescopes put together. Much of this success has come in the past eight years with the Parkes multibeam receiver, a 13-beam system operating at 1.4 GHz which is a very efficient search instrument. The Parkes Multibeam Pulsar Survey\textsuperscript{19,44} and other surveys using this receiver have discovered more than 850 pulsars, or nearly half of all known pulsars.

Figure 3 is a $P$-$\dot{P}$ diagram for all known pulsars. Different pulsar types are easily distinguished on this diagram, with most normal pulsars lying in the “pulsar island” with intermediate values of $\dot{P}$, whereas all MSPs lie in the lower left of the diagram with $\dot{P}$ values typically five orders of magnitude less than those of most
normal pulsars and correspondingly small implied magnetic fields. The group of X-ray pulsars in the upper-right corner of the diagram are the AXPs and SGRs which are often termed “magnetars” because of the very strong surface dipole magnetic fields, typically $10^{15}$ G, implied by their rapid spin-down rates. As well as discovering a large sample of relatively “normal” pulsars, the Parkes multibeam survey was notable in finding a new sample of long-period but relatively young radio pulsars with very high implied magnetic fields. The most extreme of these, PSR J1847–0130, has a pulse period of 6.7 s and a $B_s$ value of just under $10^{14}$ G, placing it within the region of the $P$–$\dot{P}$ diagram occupied by the magnetars. There are no confirmed detections of pulsed radio emission from AXPs or SGRs and, conversely, pulsed X-ray emission has not been detected from the high-$B_s$ radio pulsars, leaving us with a puzzle as to why these strong-field pulsars appear in two different manifestations.

The Parkes multibeam surveys have also been very successful at finding intermediate period (20 – 100 ms) binary pulsars, filling in what was something of a gap between the MSPs and the tail of the normal pulsar population. The intermediate pulsar periods and low magnetic fields suggest that these pulsars are mildly recycled. They tend to be high-mass systems and most of the double-neutron-star (DNS) binaries lie in this region. Of the eight DNS systems now known, three were found using the Parkes multibeam system: PSR J1811–1736, the double-pulsar system PSR J0737–3039A/B and PSR J1756–2251. PSR J1141–6545, a relatively young pulsar with a high-mass white-dwarf companion in a short-period and eccentric orbit for which relativistic orbit perturbations are detectable, was also found in the Parkes Multibeam Survey.

A number of mostly longer-period systems with near-circular orbits and white-dwarf companions have also been found in the Parkes multibeam surveys. These systems find application to tests of relativistic equivalence principles, giving limits on Parameterised Post-Newtonian (PPN) parameters which are comparable to the best Solar System limits but in the strong field regime with $GM/(rc^2) \sim 0.1$ compared to $\sim 10^{-5}$ for Solar System tests. One pulsar which is particularly useful for such tests is PSR J1853+1303, a 115-d binary with a very small eccentricity ($\sim 2 \times 10^{-5}$) and a white dwarf companion of probable mass $\sim 0.3$ M$_\odot$. This system provides a good test for the existence of the Nordvedt Effect where differential acceleration between the two stars in the gravitational field of the Galaxy induces a eccentricity in the orbit.

§5. The double pulsar PSR J0737–3039A/B

Without doubt, the most exciting discovery to come from the Parkes multibeam surveys is that of the first-known double pulsar, J0737–3039A/B. This system was first discovered as a 22 ms pulsar in a highly relativistic orbit of period only 2.4 h, with eccentricity about 0.088 and minimum companion mass 1.25 M$_\odot$. With these parameters, the system was very likely to consist of two neutron stars and strong supporting evidence for that was quickly obtained with the measurement of a relativistic periastron advance of 16.9 deg yr$^{-1}$ (four times that of the Hulse-Taylor binary!), implying a total system mass of about 1.59 M$_\odot$. However, the
clinching evidence came with the discovery by Lyne et al.\cite{39} of pulsations from the companion star, making this the first and so far only double pulsar known. PSR J0737−3039B has a long pulse period, 2.77 s, and a relatively strong magnetic field, $B_s \sim 1.2 \times 10^{12}$ G, making it the younger of the two neutron stars. The discovery of this system not only provided a marvellous testbed for relativistic theories of gravitation and pulsar emission physics, it also provided strong confirmation of the recycling process for MSP formation. Furthermore, it increased by nearly an order of magnitude the expected rate of neutron-star coalescences in the Galaxy and, by implication, in the rest of the Universe.\cite{31} Such DNS coalescences are a prime target for laser-interferometer gravitational-wave detectors such as LIGO\cite{1} and VIRGO.\cite{2}

We now have two years of timing data on this system and already five PK
parameters plus the ratio of masses of the two stars, $R = M_A/M_B$, have been measured. The mass ratio, which is uniquely measurable for the double pulsar, and the GR constraint from the periastron advance are nearly orthogonal on the mass-mass diagram, and precisely determine the two masses: $M_A = 1.338 \pm 0.001 \, M_\odot$ and $M_B = 1.249 \pm 0.001 \, M_\odot$.35) Both of these masses are rather low compared to other pulsar masses,55) especially that of the B pulsar, which is the lowest well-determined value known. Table II lists the observed mass ratio and post-Keplerian parameters for PSR J0737−3039A/B, the predictions of GR for these parameters based on the Keplerian orbit parameters and the masses of the two stars, and the dependence of the accuracy (i.e., signal/noise ratio) of each parameter on data span $T$. Figure 4 illustrates these constraints on a mass-mass diagram.35)

Of the six PK constraints, only two are independent since (in GR) all depend on just only the two masses (and the Keplerian parameters). The consistency of these constraints with a single small region on the mass-mass diagram again shows that GR is an accurate theory of gravity. In particular, the measurement of the Shapiro shape $s$ confirms GR at the 0.1% level, more accurately than is possible with PSR B1913+16. Currently the measurement of orbit decay is less accurate than that for PSR B1913+16. However, it will improve rapidly, as the 2.5-power of the length of the data span (Table II), so that within 5 or 6 years it should surpass PSR B1913+16. Furthermore, since PSR J0737−3039A/B is relatively close to the Sun, the accuracy of its $\dot{P}_b$ measurement will not be limited by the uncertainty in the Galactic acceleration as is the case for PSR B1913+16. Currently the main uncertainty comes from the Shklovskii acceleration.50) An improved measurement of proper motion (and a parallax measurement) from timing or VLBI will reduce this uncertainty.

Future pulse timing measurements also should lead to the determination of additional PK parameters, none of which has previously been measured. General relativity predicts an apparent deformation of the orbit described by the parameters $\delta_r$ and $\delta_\theta$.12) $\delta_r$ is absorbed by other terms, but $\delta_\theta$ should be measurable in a few years and will improve as $T^{2.5}$. Higher-order terms in the PPN expansion predict small secular changes in the periastron advance $\dot{\omega}$, some of which are dependent on the spins of the two pulsars. These terms are a factor of 2 – 5 below current uncertainties but should be measurable in 5 – 10 years. In principle, such measurements could constrain the moment of inertia of the pulsars, leading to significant constraints on the equation of state for neutron-star (or quark-star) material.13), 36), 47)

Another GR effect which should produce observable changes is geodetic preces-
Fig. 4. Mass-mass diagram for the PSR J0737–3039A/B binary system based on interpretation of the Post-Keplerian parameters within general relativity. The shaded regions are excluded by the mass-function constraint \( \sin i \leq 1 \) for each pulsar. The mass ratio \( R \) and the periastron advance \( \omega \) are both accurately measured and give nearly orthogonal constraints on this diagram. Other constraints come from measurement of the Shapiro shape \( s \) and range \( r \) and the orbit decay \( \dot{P}_b \). The inset shows that all constraints are consistent with a very small region in the \( M_A-M_B \) plane.

Secular changes in the mean pulse profiles for PSR B1913+16,\(^{34,57}\) PSR B1534+12\(^{53}\) and PSR J1141-6545\(^{24}\) have been interpreted as evidence for geodetic precession of the pulsar spin axis. Similar effects should be even more pronounced in PSR J0737–3039A/B where the precessional periods are only 75 years for A and 71 years for B.\(^{39}\) Surprisingly, measurements show no significant change in the mean profile for PSR J0737–3039A over an 18-month interval,\(^{43}\) perhaps implying that the misalignment angle of the A spin axis is very small. This in turn implies that the B pulsar received a small natal kick, which may be related to its small mass and the relatively low eccentricity of the system.\(^{48}\)

On the other hand, significant secular changes have been observed in the orbital modulation and mean pulse profile of PSR J0737–3039B.\(^{11}\) The B pulsar is only bright for two short intervals of orbital phase, each about 10 minutes in duration. These two bright intervals are each getting shorter and the whole pattern is slowly moving toward later orbital phases. At the same time, the mean pulse profile in each of the two bright phases is changing from a two-component profile to a single broad
component, probably due to the growth of a central component. It is not clear if these changes result from periastron precession or geodetic precession of the B spin axis.

§6. Detection of gravitational waves

The existence of gravitational waves (GW) propagating at the speed of light is an important prediction of GR and other relativistic theories of gravity. While the relativistic binary pulsars have provided strong evidence that GW exist, despite much effort over several decades, so far there has been no direct detection of these waves. GW are generated by the acceleration of any mass. Significant astrophysical sources of GW include events in the early Universe, such as inflation and oscillations of super-strings. Many galaxies are believed to contain binary supermassive black holes at their core, formed as a result of earlier mergers, and these will emit strong GW as they evolve and eventually coalesce. At coalescence, depending on the mass, the wave frequency is of order a milliHertz. Similarly, coalescing DNS binaries will emit intense GW at higher frequencies, up to a kiloHertz. Finally, X-ray binaries in our Galaxy will dominate the GW background at frequencies around a milliHertz.

A gravitational wave passing over a pulsar or the Earth will induce a time-varying gravitational redshift and hence a modulation of the apparent pulsar period or frequency. Detection of this signal relies on the presence of a significant timing residual or pulse phase offset, the integral of the frequency modulation. Hence, pulse timing is most sensitive to low-frequency GW, with maximum sensitivity for frequencies $\sim 1/T$, where $T$ is the data span. Since pulsar timing observations typically have data spans of several years, this technique is most sensitive to GW in the nanoHertz region. In contrast, ground-based laser interferometer systems such as LIGO and VIRGO are most sensitive to GW with frequencies around 100 Hz, whereas LISA, a space-based system with arms $5 \times 10^6$ km long, is most sensitive in the milliHertz region. Pulsar timing is therefore complementary to the laser interferometer systems.

With observations of one or two pulsars, because of the presence of other sources of timing noise (Table I), it is only possible to put a limit on the strength of the stochastic GW background in the Galaxy. Analysis of an 8-year dataset from observations of PSR B1855+09 at Arecibo gave an upper limit on energy density of GW relative to the closure density of the Universe, $\Omega_g \sim 10^{-7}$. An extended 17-year dataset for this pulsar including Green Bank data was analysed by Lommen but the non-uniformity makes the analysis difficult — we adopt a conservative upper limit on $\Omega_g$ of $10^{-8}$.

Although there can be no positive detection of the stochastic GW background with observations of only a few pulsars, it is possible in principle to detect GW from an individual source with such data. Perhaps the most likely astrophysical sources of GW to be detected with pulsars are super-massive binary black holes in the cores of galaxies. Lommen and Backer used Arecibo observations of three pulsars to place upper limits on the mass ratio of such binary systems in six nearby galaxies assuming
an orbital period of order 2000 days. Recently, a claim based on VLBI observations was made for the existence of a $10^{10} M_\odot$ binary system of orbital period close to one year in the core of the nearby galaxy 3C 66B. Using the PSR B1855+09 dataset referred to above, Jenet et al. showed that the existence of such a binary system in 3C 66B could be ruled out at the 98% confidence level.

Pulsar timing observations of a larger sample of pulsars widely distributed on the celestial sphere can in principle be used to make a direct detection of the stochastic GW background at the Earth. This concept, often termed a “pulsar timing array”, was first discussed by Foster and Backer. The pulsar timing signals from GW passing over the individual pulsars are uncorrelated since the pulsars are widely distributed in the Galaxy. However, GW passing over the Earth produce a signal which is correlated between pulsars in different directions. Because of the quadrupolar nature of GW, signals from pulsars separated by about 90 deg on the sky will be anti-correlated, whereas those on opposite sides of the celestial sphere will be correlated. Figure 5 shows the results of a simulation of the effect of an isotropic and stochastic GW background at the Earth from binary black holes in galaxies on observations of 20 pulsars accessible to the Parkes radio telescope. The maximum correlation for pulsars with small angular separation is 0.5 because of the presence of an equally strong but uncorrelated signal from GW passing over the pulsars. The thick line is the theoretical expectation for the correlation.

Only MSPs can provide TOAs with sufficient precision to have any chance of making a significant detection of the GW background. Precision timing of a large sample of MSPs has many other applications besides the detection of gravitational waves. For example, irregularities in the terrestrial timescale, which is based on a weighted average of a world-wide network of caesium clocks, should be detectable.

Fig. 5. Correlation of timing residuals between 20 pulsars as a function of the angular separation of the pulsars on the sky for an isotropic and stochastic gravitational-wave background at the Earth. Based on a simulation by F. A. Jenet and G. B. Hobbs, private communication.
This has a monopolar signature in the residuals, that is, the apparent periods of all pulsars increase or decrease in unison regardless of sky position. It will be possible to establish a “pulsar timescale” which may be the most stable timescale over intervals of months and years. Similarly, it is possible in principle to detect errors in the Solar System ephemeris which is used to correct observed TOAs to the barycentre of the Solar System. Errors in the predicted Earth velocity will result in a dipole signature on the sky with its axis in the direction of the error. Finally, of course, a host of investigations of the properties of the pulsars themselves and of interstellar effects are possible (Table I).

§7. The Parkes Pulsar Timing Array

Several groups around the world have embarked on pulsar timing array projects. We have established the Parkes Pulsar Timing Array (PPTA) project, a collaboration between groups at the Australia Telescope National Facility, Swinburne University of Technology and the University of Texas at Brownsville. We are using the Parkes 64-m radio telescope to observe 20 MSPs at three frequencies, 680, 1400 and 3100 MHz, with observations at approximately 2-weekly intervals. Figure 6 shows the distribution of the PPTA sample in celestial coordinates. Three different data acquisition systems are being used. At 680 MHz, the 64-MHz bandwidth is sampled using a baseband recording system (CPSR2) developed by Swinburne University in collaboration with Caltech.\textsuperscript{27} The 256-MHz bandwidth at 1400 MHz and the 1024-MHz bandwidth at 3100 MHz are each recorded using a wide-band correlator developed at ATNF. This system has limited time and frequency resolution for observations of MSPs and is being replaced by a polyphase digital filterbank system with improved performance. Currently a prototype system with a bandwidth of 256 MHz is in operation at Parkes. A final system with 1024 MHz bandwidth is expected to be commissioned in early 2006. Off-line data processing uses the \texttt{psrchive} suite of programs\textsuperscript{25} and \texttt{tempo2}, a development of the widely used \texttt{tempo} program with improved precision and a user-friendly graphical interface.\textsuperscript{23}

Figure 7 shows the results of simulations of the projected PPTA performance in detection of a stochastic GW background from supermassive binary black holes believed to exist in the cores of many galaxies\textsuperscript{28,61} for a variety of observational scenarios and data processing techniques.\textsuperscript{29} Unless otherwise stated, the predictions are for 250 observations of 20 pulsars over a 5-year interval with rms timing residuals of 100 ns. In panel A, the solid line is for the simple correlation technique discussed above. Clearly, the detection significance is marginal with this set of parameters. Low-pass filtering of the residual curves gives a small improvement as shown by the dashed line. Timing residual variations for a GW background from binary black holes have a very “red” spectrum, i.e., they are much stronger at low frequencies corresponding to longer orbital periods. Flattening or “pre-whitening” of this spectrum before correlation leads to an improved detection significance as shown in panel B of Fig. 7. The solid line has the same parameters as the curves in panel A, showing that pre-whitening increases the detection significance, especially for stronger GW signals. The dashed line refers to a sample having 10 pulsars with 100-ns residuals.
Fig. 6. Sky distribution of Galactic disk MSPs with periods less than 20 ms. The size of the circle is logarithmically related to the pulsar period and stronger pulsars have filled symbols. Pulsars selected for the Parkes Pulsar Timing Array are indicated.

Fig. 7. Detection significance of the Parkes Pulsar Timing Array as a function of the strength of a stochastic background of gravitational waves generated by supermassive binary black holes. The vertical lines delimit the range in which the predicted signal strengths lie. See text for further details.

and 10 with 500 ns, the dot-dashed line has just 10 pulsars each with 100 ns residuals, and the triple dot-dashed line has 20 pulsars, each with 100 ns residuals and 500 observations over 10 years. Clearly it is of benefit to have a large sample of pulsars, even if some of them have a larger scatter in their residuals.

Figure 8 compares the GW energy density of the principal astrophysical sources over 17 orders of magnitude in frequency with the sensitivity of LIGO, LISA and PPTA detectors. For the supermassive binary black holes, the two lines represent the
range of estimated strengths for the GW background at the Earth. At low frequencies the signal rises due to the formation of these systems in the early Universe, then increases gradually as energy loss to GW causes them to spiral in to shorter periods. At the peak in the curve, the most massive systems ($\sim 10^9 \text{ M}_\odot$) are beginning to coalesce with only the less massive systems able to spiral in to periods of less than a few days. The PPTA will improve on the current limit in the nanoHertz region by about two orders of magnitude in $\Omega_g$ (one order in gravitational strain) and should be able to detect these signals even if they are at the more pessimistic end of the predictions.

Observations for the PPTA commenced about a year ago. Currently we are achieving $\sim 100$ ns residuals for four MSPs and sub-microsecond residuals for a further eight. We are improving our instrumentation and data processing techniques and hope to achieve our design goals in another 6 – 12 months. Radio-frequency interference is an important factor in limiting TOA precisions and we are developing techniques to reduce its effect. With these efforts and some luck we may have a positive detection of gravitational waves in five years or so. Even if we do not achieve this goal, we will have an excellent dataset for investigation of MSP and interstellar medium properties and the terrestrial timescale. We will also have laid the foundation for what will surely be a positive detection of GW by the Square Kilometre Array using pulsar timing.
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