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The European Pulsar Timing Array

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Abstract The timing of radio pulsars provides a tool for studying a wide range of fundamental physical and astrophysical problems. The best results are obtained by regular, frequent timing observations of a large number of sources at various frequencies. We describe a project which aims to improve on all of the above parameters by combining timing data from the pulsar timing programs of 4 European groups to form the so-called EPTA. These data will be used to study, amongst other things, relativistic binaries and gravitational waves.

Key words: techniques: radio astronomy

1 INTRODUCTION

In the past 60 years, radio astronomy has produced some of the most fundamental and exciting discoveries in physics and astronomy. Even so, the discovery potential in this research field is far from being exhausted but continues to promise new and exciting results that will provide deep insight into our understanding of fundamental physics. Questions yet to be answered with the help of pulsar observations include the validity of General Relativity (GR) in the strong-field limit, the existence and nature of a stochastic cosmological gravitational wave background and study of the interior of neutron stars which exhibit the most extreme matter density of any object in the Universe. Precise timing observations of binary pulsars have proven the existence of gravitational radiation and have provided very sensitive tests of GR. Pulsar timing resulted in the discovery of the first extra-solar planetary system, while timing observations of young pulsars allow neutron star seismology with the study of the interior of these super-dense objects from thousands of light years away.

Pulsars are still the only means to study relativistic gravity in the strong-field limit and thereby provide the best prospects for answering the question as to whether Einstein's theory of gravity is the last word in our understanding of gravity. The answer to this question relates to the quest for "quantum gravity", undertaken by modern physicists who try to unify the classical world of macroscopic gravitational interaction with the strange world of quantum mechanics.

Some unified theories predict cosmic strings, producing a stochastic gravitational wave background. This and other corresponding signals from energetic processes in the early Universe can be detected when pulsars are used as the endpoints of arms of a huge, cosmic gravitational wave detector. High-precision timing of network of pulsars, forming a "Pulsar Timing Array" (PTA), allows us to detect a gravitational wave

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background in a frequency range (∼nHz) that corresponds to the epoch of equilibrium between mass and radiation in the early Universe. This frequency range complements the much higher frequencies accessible to Advanced LIGO (∼100 Hz) and LISA (∼ mHz), and the extremely low frequencies probed by studies of the Cosmic Microwave Background and its polarization ($\sim 10^{-18}$ Hz).

2 AIMS AND ADVANTAGES OF THE EPTA

The EPTA plans ultimately to use all four telescopes available to the group, for high precision timing, in a coordinated way which allows us to make the most efficient use of observing time by coordinating schedules and source lists. It also plans to further foster relationships between the participating research groups by exchanging data, knowledge and people. Some of the advantages of using multiple telescopes to achieve the goals of a PTA are outlined below:

1. Larger total number of TOAs.
2. Commensurate scheduling will allow for improved binary and yearly phase coverage.
3. A wide range of frequencies can be sampled and then compared in quasi-simultaneous sessions.
4. Simultaneous same frequency observations can be used to check polarisation calibration and overall timing offsets.
5. Telescope, Instrumentation, or Observatory clock based errors can be quickly identified and corrected.

3 RESOURCES AVAILABLE FOR HIGH PRECISION TIMING

In Table 1 we show the characteristics of the four telescopes which make up the EPTA with specific reference to their use for high precision pulsar timing. The complementarity of the four telescopes is important as well as the frequencies where they overlap. The WSRT has excellent low frequency receivers with wide bandwidth capabilities which compliments nicely with Effelsberg in particular. All telescopes have an excellent L-band system which will provide the best frequency at which to do checks of inter-telescope stability. The bandwidth of the SRT at the high frequencies combined with a good pulsar backend means it will provide TOAs with similar precision to those of the other telescopes, and will be particularly useful at around 800 MHz.

Also shown in Table 1 are the current number of pulsars timed in the various programs and also the duration of the timing program. As can be seen Jodrell Bank Observatory (JBO) has by far the largest sample and longest time line, which nicely compliments the higher precision data from the other telescopes. It is likely that the program at the WSRT at least will be expanded to include more MSPs and where there is overlap some pulsars will be timed, on a regular basis, at one telescope only except on occasions to check for timing stability. The current timing accuracy for some of the pulsars timed at all three telescopes are given in Table 2 We note that as we accumulate more timing data with COBRA and PuMa II, discussed in detail below, these numbers will improve significantly.

Table 1 Parameters of the 4 telescopes taking part in the EPTA

Telescope	JBO	WSRT	Effelsberg	SRT
Dish	76 m	≡ 93 m	100 m	64 m
Frequency Range (MHz)	115–2300	200–2000	800–10000	290–7000
Bandwidth (MHz)	<160	<112	<100	<500
Number of Pulsars	∼35, 20 MSPs	∼1000, 100 MSPs	∼40, 20 MSPs	n/a
Program Duration (yrs)	6	30	8	n/a

3.1 Hardware Improvements

Over the last few years new pulsar processing hardware has been under development at both the JBO and the WSRT. The main aim of this instrumentation is to enable the use of coherent dedispersion on wide bands for all pulsar timing observations. As is shown below the systems are very similar with both being based, where possible, on off the shelf components such as DMA cards and linux based PCs. Another interesting feature of both systems is the use of 8-bit resolution, this provides significantly improved robustness to interference, which can otherwise, potentially cause variations in the signal which manifest themselves as changes in the

Table 2 Present timing accuracy of the three timing programs already running. These are the best-fit residuals from TEMPO in microseconds.

PULSAR	JBO	Effelsberg	WSRT
B1937+21	140	0.8	0.6
J1713+0747	$<$10	0.5	0.5
J0034-0534	60		5
J0218+4232	50	28	16
J1012+5307	20	3	1.4

pulse profile and thus have a drastic effect on pulsar timing. As well as the greatly improved time resolution provided by the use of coherent dedispersion the increased bandwidth of both systems provide also means an improvement in sensitivity which also improves timing accuracy. Initial tests with the WSRT and PuMa II have shown improvements in timing, for individual times-of-arrival, obtained simultaneously with both the old and new systems, of between a factor of 5 to 10.

COBRA:

- Up to 100 MHz Coherently Dedispersed all 4 Stokes Parameters
- Bands split into variable sized subbands
- 8 bit resolution
- Makes use of DMA cards
- Total data rate $> 400\,\mathrm{MBs}^{-1}$
- No data storage
- Processing done with a cluster of PCs

PuMa II:

- Up to 160 MHz Coherently Dedispersed all 4 Stokes Parameters
- Bands split into eight 20 MHz wide subbands
- 8 bit resolution
- Makes use of DMA cards
- Total data rate $> 640\,\mathrm{MBs}^{-1}$
- Both real time and offline data reduction possible
- Processing done with a cluster of PCs

4 PAST AND PRESENT RESULTS

Using the existing data sets it is already possible to obtain improved timing solutions which in turn reveal new properties of, in particular, binary systems. The most common case is where the often much longer time line of JBO data is combined with the higher precision data from Effelsberg and the WSRT. The former provides vital information on accurate positions and proper motions while the later two give improved binary phase coverage and precision thus revealing new binary parameters. We highlight two examples of this work below.

4.1 PSR J2145–0750

One of the first results to come out of the multi-telescope approach was for the timing of the binary pulsar J2145-0750. Combining 10 yrs of radio timing data obtained with the Effelsberg 100-m radio telescope and the Lovell 76-m radio telescope Löhmer et al. (2004) measure a significant timing parallax of 2.0(6) mas placing the system at 500 pc distance to the solar system. They also measured the secular change of the projected semi-major axis of the orbit to be $\dot{x} = 1.8(6) \times 10^{-14}$ lt-s s-1, where , $x = (a_p \sin i)/c$, is caused by the proper motion of the system. With this measurement they constrain the orbital inclination angle to $i < 61^{\circ}$, with a median likelihood value of 46° which is consistent with results from polarimetric studies of the pulsar magnetosphere. This constraint together with the non-detection of Shapiro delay rules out certain combinations of the companion mass, m_2, and the inclination, i. For typical neutron star masses

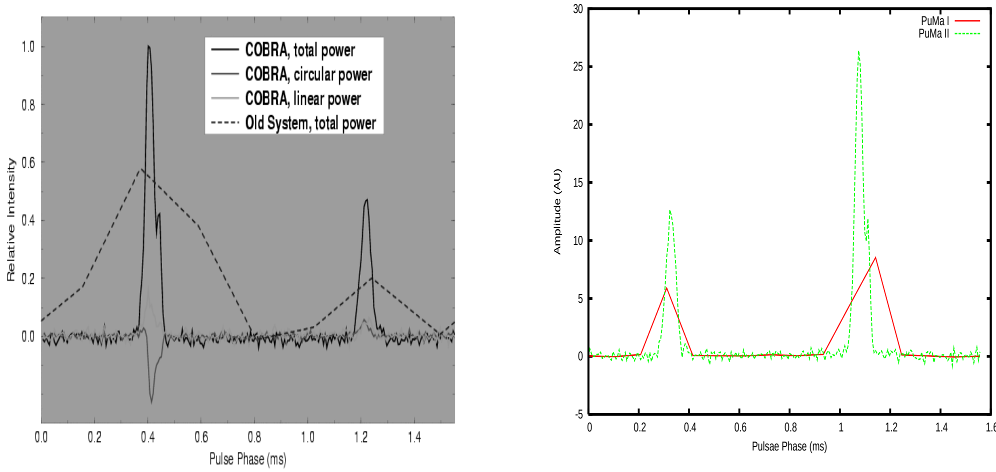

Fig. 1 Observations of PSR B1937+21 showing the improvements in the time resolution possible with the new pulsar instrumentation at both JBO and the WSRT. In both cases the pulse profile as observed with the original systems and the new systems are shown. The JBO data were obtained with a bandwidth of 5 MHz and the WSRT data with a bandwidth of 20 MHz. Both observations were obtained at L-band and the coherently dedispersed data (COBRA, PuMa II) are not shown with the full time resolution, but with a resolution chosen to maximise both resolution and signal-to-noise.

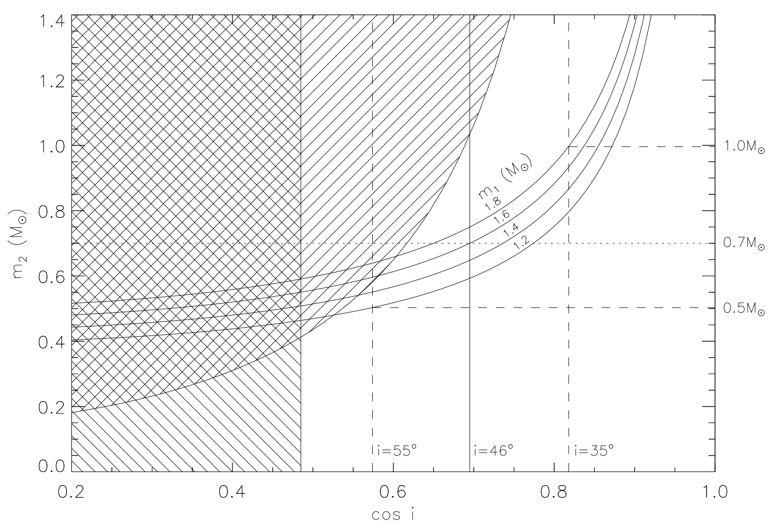

Fig. 2 Constraints on orbital inclination, i, and WD mass, m_2, from $\dot{x}$-measurement and limits on Shapiro delay. Points inside the hatched rectangle are excluded by measured $\dot{x}$, points inside the curved hatched area are excluded by the non-detection of Shapiro delay. From the mass function we calculated the contours for constant neutron star masses, indicated by the solid curves. The vertical lines denote the median value ($i = 46^\circ$, solid) and its 1σ errors (at 35° and 55°, dashed) for the distribution of inclination angles derived from the observed $\dot{x}$. From these uncertainties we derive the companion mass limits $0.5\,M_\odot \leq m_2 \leq 1.0\,M_\odot$ displayed by the horizontal dashed lines. Photometric studies of the WD companion (see Section. 4.1) result in a lower mass limit of $0.7\,M_\odot$ (horizontal dotted line).

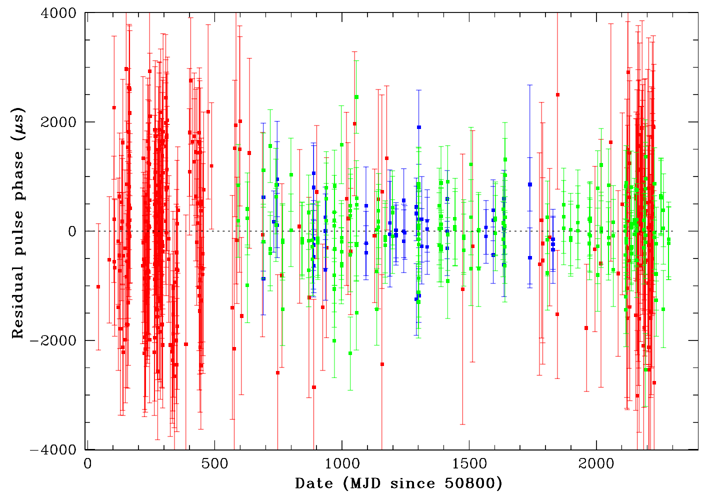

Fig. 3 Residuals for Jodrell Bank, Effelsberg and Westerbork joint data sets. The Effelsberg data were obtained at 1.3–1.7 GHz with 28 MHz bandwidth, the WSRT data at a central frequency of 1380 MHz and a bandwidth of 80 MHz and the Jodrell data at 1404 MHz with a bandwidth of 32 MHz. The overall RMS of the fit is 850 μs.

and using optical observations of the carbon/oxygen-core white dwarf they are able to derive a mass range for the companion of $0.7M_\odot \leq m_2 \leq 1.0M_\odot$. By applying evolutionary white dwarf cooling models to revisit the cooling age of the companion they find that the companion has an effective temperature of $T_{\rm eff} = 5750 \pm 600$ K and a cooling age of $\tau_{\rm cool} = 3.6(2)$ Gyr, which is roughly a factor of three lower than the pulsar's characteristic age of 10.4 Gyr. The cooling age they derive implies an initial spin period of P_0=13.0(5) ms, which is very close to the current period.

4.2 PSR J1811–1736

A more recent work presents a new timing solution for the binary pulsar PSR J1811–1736, obtained combining data taken with the Lovell telescope at Jodrell Bank, with the 100 m telescope at Effelsberg and with the WSRT (Corongiu et al. 2005). The timing solution agrees with a previous one presented by Lyne et al. (2000), but improves the precision of the measured spin parameters, Keplerian orbital parameters and the relativistic periastron advance. These firmer constraints, in particular on the total mass of the system and on the minimum mass of the so far unseen companion (Mignani 2000), provide strong support for the double neutron star nature of this system. Despite the quite long data span, timing precision is still heavily limited by the interstellar scattering, whose effects at 1.4 GHz are visible in the pulse profile at this frequency. We carried out simulations on the results that could be achieved if observations were carried at 3 GHz, finding encouraging results and indicating that at least one of the observatories of the three should move to timing at that frequency or higher.

5 CONCLUSIONS

The European Pulsar Timing Array will ultimately combine the pulsar timing data from 4 telescopes. These data will be used to obtain better timing results for a large number of millisecond pulsars. As well as allowing us to better understand the individual systems and use them to probe theories of gravity, neutron star formation and binary evolution, this array of pulsars will be used to attempt to detect gravitational waves in the nHz regime. The detection of such waves will help place constraints on the nature of the stochastic background of gravitational waves expected to be generated in the early stages of the universe. The current and future improvements in pulsar hardware planned by the EPTA collaboration will greatly improve the pulsar timing accuracy and thus bring us closer to this goal.

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