Curious properties of the recycled pulsars and the potential of high precision timing.

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Abstract

Binary and Millisecond pulsars have a great deal to teach us about stellar evolution and are invaluable tools for tests of relativistic theories of gravity. Our understanding of these objects has been transformed by large-scale surveys that have uncovered a great deal of new objects, exquisitely timed by ever-improving instrumentation. Here we argue that there exists a fundamental relation between the spin period of a pulsar and its companion mass, and that this determines many of the observable properties of a binary pulsar. No recycled pulsars exist in which the minimum companion mass exceeds \( (P/10 \text{ ms}) \ M_\odot \). Furthermore, the three fastest disk millisecond pulsars are either single, or possess extremely low-mass companions \( (M_c \sim 0.02 M_\odot) \), consistent with this relation. Finally, the four relativistic binaries for which we have actual measurements of neutron star masses, suggest that not only are their spin periods related to the companion neutron star mass, but that the kick imparted to the system depends upon it too, leading to a correlation between orbital eccentricity and spin period. The isolation of the relativistic binary pulsars in the magnetic field-period diagram is used to argue that this must be because the kicks imparted to proto-relativistic systems are usually small, leading to very few if any isolated runaway mildly-recycled pulsars. This calls into question the magnitude of supernova kicks in close binaries, which have been usually assumed to be similar to those imparted to the bulk of the pulsar population. Finally, we review some of the highlights of the Parkes precision timing efforts, which suggest 10 nanosecond timing is obtainable on PSR J1909–3744 that will aid us in searching for cosmological sources of gravitational waves.

1 Introduction

The field of radio pulsar astronomy was born with the discovery of the first pulsar by Bell and Hewish [1]. Early surveys with the world’s largest radio telescopes soon swelled this number to in excess of 350 by the early 1980s[2].
Although these surveys were very successful at finding slow, high-field pulsars, the fraction of known pulsars in binaries at the time was extremely small (\(\sim 1\%\)). The discovery of the first binary pulsar\(^3\) had a profound impact on both astronomy and fundamental physics. It was soon realised that a binary pulsar could be used in tests of relativistic gravity \(^4\), but also to constrain the nature of supernovae\(^5\), the masses of neutron stars\(^3\), and how binaries evolve and die\(^6\).

In their classic paper, Bhattacharya and van den Heuvel (1991) \(^7\) documented the evolutionary scenarios that explained the expanding binary pulsar zoo. Inspired by PSR B1913+16, van den Heuvel elegantly explained the nature of binary pulsar and others such as PSR B0655+64 and PSR B0820+02 as the result of a binary evolution in a series of papers e.g.\(^8,9\). This involved several radical ideas, including binary mass transfer, common-envelope evolution, pulsar recycling, supernova kicks, tidal circularization, the widening of pulsar orbits via mass transfer, and accretion-induced collapse (AIC) of white dwarfs. Pulsars with low-mass companions were explained by either recycling or the accretion-induced collapse of a white dwarf. Bailes (1989)\(^10\) argued that it was possible to create all the recycled pulsars from recycling of neutron stars if field decay was caused by accretion, without the need for AIC, and suggestions for how this might occur have been proposed in the literature by various authors\(^11,12\).

Hobbs et al.\(^13\) and Brisken et al.\(^14\) have conclusively demonstrated that most isolated pulsars possess large velocities consistent with a large kick at birth. If all pulsars receive such kicks, then we expect general misalignment of pulsar spin and orbital angular momentum axes in binary pulsars, as well as highly eccentric orbits\(^15,16\). Recently, Dewi et al. (2005)\(^17\) have called into question the ability of a supernova from a close binary to deliver a significant (\(V > 100\) km s\(^{-}\)) kick to a proto-neutron star. Dewi et al.’s work demonstrates that some simple assumptions can reproduce the rough correlation observed between spin period and orbital eccentricity noted by Faulkner et al. (2005)\(^18\). Their work assumed that the spin period was determined by the duration of the mass accretion phase, with a timescale set by the mass of the donor. Low-mass donors could spin up pulsars to faster spin periods. Although they did not investigate the millisecond (\(P < 10\) ms) pulsars with white dwarf or low-mass companions, their work on double neutron stars showed how such a correlation was a logical consequence of small kicks and spin periods that were related to the duration of the mass transfer phase.

Pulsar astronomers have been continually improving their instrumentation and timing methodologies in order to measure quantities with astounding precision\(^19,20,21\) to reveal more and more subtle effects that allow physical constraints to be derived about their binary hosts. These measurements, and the growing millisecond pulsar (MSP) population have helped theorists de-
velop models to understand binary evolution and the nature of supernovae. The longevity of Bhattacharya and van den Heuvel is testament to the fundamentals inherent in the paper. Since its publication however, new types of binary pulsar have emerged. Whilst some of these have proven to be dramatic confirmations of the models, others require us to improve on the recipes summarised by Bhattacharya and van den Heuvel (1991).

In this paper I will review the binary and recycled pulsar population, examine some interesting correlations and trends, and suggest modifications to models that the new data appear to demand. I also demonstrate how the highest precision pulsar timing is capable of delivering arrival times down to accuracies of near 10 nanoseconds if we can eliminate sources of systematic error in pulsar timing.

2 The Binary Pulsars

2.1 General Characteristics

One of the most popular diagrams for understanding the origin and evolution of binary pulsars is the Magnetic field-Period ($B$-$P$) diagram shown in Fig 1. Although unpopular with some observers, who usually substitute the observed period derivative for the theorist’s “magnetic field”, $B^2 \propto P \dot{P}$, it shows that the binary pulsars have much weaker fields and shorter spin periods than the majority of the pulsar population. The recycling model explains their location via the “spin-up” of an otherwise normal high-field neutron star and the destruction of its field in the accretion process. This is often referred to as “recycling”.

2.2 Spin Period-Companion Mass Correlation

In simple terms, the recycling model for binary pulsar evolution predicts that recycled pulsars should have spin periods that are related to their mass accretion history, and magnetic field strength. Low-mass stars evolve more slowly than high-mass stars, and have more time to sustain mass accretion. Thus, one of the predictions of the recycling model is that there should be some relation between spin period and companion mass soon after mass accretion ceases, but only if the magnetic field does not limit the accretion through the action of a propellor phase. To explore this, in Fig 2 we plot the minimum companion mass of a binary pulsar (assumes an edge-on orbit and a pulsar $> 1.35 \, M_\odot$) against the currently observed spin period which shows good agreement with
Fig. 1. The pulsar “\(B-P\)” diagram for all pulsars not associated with globular clusters. Data are taken from the ATNF pulsar catalogue with additions from [22], [18], [23], [24]. Binary pulsars are indicated by circles with dots inside them. The relativistic binary pulsars are represented by stars and we define these by having an orbital period less than a day. Note that the double pulsar appears twice in this diagram. Improvements in pulsar search instrumentation have only made the possibility of large numbers of pulsars in the lower left of the diagram since about 1990.

From Fig 2 we can determine the handy phenomenological relation:

\[
M_c < \frac{P}{(10 \text{ms})} M_\odot
\]  

where \(M_c\) is the minimum mass of the companion.

Although we might have expected some rough relation between spin period and mass, or perhaps no \(\sim 1\) ms pulsars to possess heavy companions, what is striking is that equation 1 appears to define an exclusion region that is in effect for all recycled pulsars. The three fastest \((P < 2\text{ ms})\) millisecond pulsars in the field are either solitary (PSR B1937+21, PSR J1843–1113) or have extremely low-mass \((M_c \sim 0.02 M_\odot)\) companions (PSR B1957+20). This means that it is the companion mass, not exotic gamma-ray death-rays or the like that determine which pulsars remove or almost destroy their companion stars. The conclusion is that to be a rapidly spinning \((P < 2\text{ ms})\) pulsar, the companion...
must ultimately be of very low ($M_c < 0.2 \, M_\odot$) mass or completely destroyed. We might be tempted to conclude that all of the solitary millisecond pulsars with periods less than 10 ms were once spinning more rapidly and had low-mass companions. Certainly, if it were the magnetic field of the pulsar, and not the companion mass of the pulsar that determined the final spin period, we might not expect any such relation to hold between the spin period and companion mass.

2.3 Companion Mass of Significantly Eccentric ($e > 0.03$) Binaries

A prediction of the recycling model is that in order to have a pulsar appear in a binary with a significantly non-eccentric orbit the companion must be an inert object, like a neutron star, white dwarf or main sequence star well inside its Roche Lobe. Although it is possible to produce a pulsar in an eccentric binary with a very low mass main sequence star, none have ever been observed. This might be because these systems often disrupt during the supernova explosion, are short-lived, or the extreme initial mass ratio required is rare.

We now know of several binary pulsars orbiting massive companions like PSR
B1259–63 and PSR J0045–7319. To find a pulsar in an eccentric orbit about a white dwarf companion requires a progenitor in a system with an initial mass ratio close to unity[26], which always leaves behind a massive white dwarf such as in PSR B2303+46 or PSR J1141–6545. Finally, neutron stars are heavy objects, and appear to have minimum masses near 1.25-1.4 M⊙. As shown in Fig 2, the relativistic eccentric binaries are all consistent with reasonably massive companion stars, as we might expect.

2.4 Eccentricities of the low-e (e << 0.03) Recycled Pulsars

Fig. 3. Orbital eccentricity of all the binary pulsars with e < 0.03 that we believe have a high probability of being white dwarf companions due to their circularity and low mass. The most eccentric MSP (PSR J1618–3919) has a spin period of 11 ms and e = 0.027. Only field, as opposed to globular cluster pulsars are shown.

It takes time to spin up a pulsar to millisecond periods due to the amount of mass involved (∼ 0.1 M⊙) and the Eddington limit for mass accretion. During this time, we might expect the orbit to become highly circular. Indeed, we would expect that the shorter the spin period, and the tighter the orbit, the more circular it might become. In Fig 3 we show the orbital eccentricities (where measured) of all the binary pulsars with e < 0.03. There are many slower period pulsars with 0.00004 < e < 0.03 even at short orbital periods and no clear trends. This is consistent with the duration of the recycling phase playing a crucial role in removing eccentricity.

In Fig 4 only those pulsars with P < 10 ms are shown. A few features are immediately apparent. Firstly, all binary millisecond pulsars with P <10 ms and orbital periods (Pb) <10 d have eccentricities < 2.5 × 10^{-5}. Secondly, although there is a trace of a nice trend for pulsars with periods greater than 50 d to have a correlation of eccentricity and orbital period, Stairs et al. recently showed that PSR J1853+1303 has a small eccentricity despite a period in excess of 100 days. Clearly, long periods of mass accretion are not guaranteed
Fig. 4. Orbital eccentricity of all disk MSPs with $P < 10$ ms. Sustained recycling appears to make most of the MSPs conform to a nice orbital eccentricity orbital period relation. Pulsars with upper limits are not shown.

to iron out eccentricity, and long orbital period MSPs can still possess very small orbital eccentricities. PSR J1618–3919 is a bizarre object with a spin period of 11 ms and an orbital eccentricity of 0.027 and is clearly anomalous. Finally, there is a dearth of MSPs with orbital periods between 12 and 60 d, as first noted by Camilo[27].

2.5 The Binary Fraction of Recycled Pulsars

In Fig 5 we show the lower left region of the $B$-$P$ diagram where the recycled pulsars live. A few interesting points can be established. Firstly, as previously discussed, at short periods ($P < 2$ ms) all of the pulsars are either solitary or have very low-mass companions. Secondly, between 3 and 8 ms, the solitary and binary pulsars largely overlay each other, giving little clue as to what makes some solitary and others binary. Between 8 and 60 ms the population becomes almost 100% binary, although a recent discovery (PSR J1038+0032) has now appeared in this gap[24].

Finally, the relativistic eccentric binaries, indicated by stars in the Figure, have larger fields than comparative period circular-orbit systems and any isolated recycled pulsars. Since they have larger mass companions we might be tempted to suggest that this left less time for mass accretion-induced accretion. Since the four relativistic binaries (defined here by coalescence times less than a Hubble time) are all above the band of circular orbit and isolated systems, we conclude they had a different origin. If the progenitor systems had had a high disruption probability during the final supernova, we would expect many isolated pulsars with similar periods and $B$-fields to populate the diagram. They do not. From this we conclude that the disruption probability is small.
In the recycling model, radio pulsars achieve their high velocities from asymmetric explosions that impart a large velocity to the pulsar. If the probability of survival is high, then there should be relatively few solitary pulsars like the eccentric binaries for every binary pulsar. If, on the other hand, the disruption probability is great, then we would expect many solitary recycled pulsars for every eccentric binary. Classical mechanics tells us that a pulsar’s orbital eccentricity is a measure of how near it came to becoming unbound in the final explosion. PSR B1913+16’s eccentricity of 0.617 suggests it came close to disruption, whereas PSR J0737−3039A/B’s $e$ of just 0.088 suggests a quiet explosion and little or no associated kick.

2.6 The Near-circularity of the Relativistic Binaries?

One of the greater mysteries under current consideration is why so many of the relativistic binaries have really very circular orbits ($e < 0.3$). Chaurasia and Bailes (2005) [16] postulated that this might be because low-$e$ systems have much longer observable lifetimes than high-$e$ ones, but this can only be part of the story. In the very young binaries PSR J1141−6545 and PSR J1906+0746 this selection effect appears unimportant and yet both have very small eccentricities (0.17 and 0.085 respectively). Large random kicks would place the majority of systems into very eccentric orbits. Indeed it has been shown[16] that if kicks are comparable to the relative orbital velocity of the stars and fill
the available phase space by chance, then only 10% of the remaining bound systems should have $e < 0.3$. Instead, of the seven relativistic binaries with orbital periods less than 2 days, an amazing 6 have $e < 0.3$. The probability of this is minute, and is very strong evidence that the sort of kicks pulsars must receive to obtain their space velocities of several hundred to 1000 km s$^{-1}$ are not commonplace in close binaries. Indeed, even if there are kicks, to get low eccentricities requires supernova masses only just above the Chandrasekhar limit, as asserted for the double pulsar by Dewi et al. (2005)[17].

Until the discovery of the solitary $P = 28$ms PSR J1038+0032 it would have been tempting to suggest that we could always map the spin period to the duration of the mass transfer phase, and hence mass of the progenitor of the exploding star, and the subsequent kick. Longer-period recycled pulsars would then have had large exploding companions, that received a large kick. This then placed them in orbits so eccentric that we had little time to observe them before they coalesced, left some in PSR B1913+16-like orbits, and disrupted many others. Stars that had longer accretion phases only did so because their companions were less massive, and exploded when the pre-supernova mass was only just above that of the Chandrasekhar limit leaving behind a young pulsar that received almost no kick. However, if PSR J1038+0032 is the result of a disrupted binary, then this is not consistent with such a simple model. To retain the model, it is then necessary to explain the existence of PSR J1038+0032 as a pulsar that destroyed its companion rather than was disrupted in the final supernova of a binary that produced two neutron stars.

In summary, in order to explain the orbital eccentricities of the binary pulsars, the kicks imparted to the last-born pulsars in a relativistic binary are small, and the mass lost in the final supernova modest.

### 2.7 Another test of the spin-companion mass correlation

How else might we test the hypothesis that the companion mass determines the spin period of a neutron star? In a relativistic binary, we can not just establish a minimum companion mass, but actually measure the companion mass. If what we have seen about spin periods being related to companion masses is true in the binary pulsar population as a whole, we might expect the longest period recycled pulsars to have the heaviest neutron star companions.

We are now fortunate enough to have four relativistic binaries where the companion mass is not just a lower limit, but a measurement. In Fig 6 we plot the spin period of the four recycled relativistic pulsars PSRs B1913+16, B1534+12, J0737–3039A, and J1756–2251 against their companion neutron star mass. Inspection of Fig 6 reveals the anticipated correlation between
pulsar mass and recycled pulsar period, providing further support for the universality of equation 1.

![Fig. 6. Companion masses against spin period for the four relativistic binary pulsars. PSR J1756–2251’s mass is an upper limit.](image)

3 Precision Pulsar Timing

Millisecound pulsars have a stability which is comparable to that of terrestrial atomic clocks. This makes them ideal targets for long-term timing to investigate cosmological sources of gravitational radiation. For many years now we have been undertaking systematic surveys for millisecond pulsars suitable for precision timing experiments with the Parkes 64 m telescope.

To be a good pulsar for timing, several characteristics are desirable. Firstly, it must be possible to obtain sub-µs residuals on a routine basis. This means the average flux density should be high, and the pulsar’s pulse should have narrow features. Secondly, the pulsar should be intrinsically stable, and not exhibit random excursions from regular rotation, often referred to as “timing noise”. Finally, it helps if the pulsar has some measureable quantity of astrophysical interest like Shapiro delay, or is close enough to measure its distance through parallax or some more subtle means.

Two pulsars stand out from the 50 or so discovered at Parkes in the last 15 years. These are PSR J0437–4715, and PSR J1909–3744.
3.1 PSR J0437–4715

PSR J0437–4715 is an otherwise unremarkable pulsar that is only $\sim 150$ pc from the Sun. This proximity to the Earth makes it very special, making its humble luminosity of $\sim 3$ mJy kpc$^{-2}$ at 20 cm result in a mean flux of 100 mJy at 20cm, two orders of magnitude above most of the MSPs known.

Early efforts on this pulsar reported its basic parameters [28]. Soon the proper motion became apparent in the timing[29] and more and more subtle effects have become measurable with new instruments. van Straten et al.[21] report the most precise timing of this pulsar with an RMS residual of just 130 ns. Recently [30] have extended the timing of this pulsar to over ten years. Almost a decade ago, it was realised that the orbital period derivative of this pulsar would be not only measurable, but lead to an independent measure of the distance via the Shklovskii effect[31]. For PSR J0437–4715, we now have a reliable measure of the period derivative and find that the implied distance is 167(1) pc. The error is the formal error from the timing model, and does not take into account any pulsar timing noise or long-term period wandering that might affect the orbital period derivative. The size of the error is comparable to the relative contribution of acceleration towards the Galaxy compared to the Shklovskii term. This result is being prepared for publication and the systematic errors investigated (Verbiest et al. 2006).

3.2 PSR J1909–3744

Discovered in Jacoby’s extension of the Swinburne Intermediate Latitude survey, PSR J1909–3744 has an extremely narrow pulse profile of just 42 $\mu$s and arrival times of astonishing accuracy. Timing of this pulsar has revealed that the companion is a well-determined 0.202(1) M$_\odot$, and the pulsar 1.44(3) M$_\odot$ [22]. The DM of only 10.34 pc cm$^{-3}$ causes the flux of this pulsar to vary by over a factor of 30 on timescales of hours. At scintillation maxima, the arrival times are of phenomenal accuracy, and in theory well below 100 ns.

In pulsar timing, systematic errors are often the limiting factor. PSR J1909–3744’s narrow pulse make it relatively immune to the disturbances in the apparent pulse shape exhibited by other pulsars from imperfect receivers and instrumentation. To try and establish if we could time pulsars at much less than 100ns accuracies, over a three week period in 2004 we observed PSR J1909–3744 almost every day for 3 weeks, trying to ensure one scintillation maxima per day. The resulting arrival times are shown in Fig 7. Now that we have extended the time baseline on this pulsar beyond 3 years, we can eliminate these three weeks of data from our fit, and see what RMS residual
we can obtain if we just take the 3 weeks of data and only fit for a DC offset. We find the 121 data points give an RMS of 122 ns. This means that we can possibly time this pulsar over any given 3 week period to an accuracy of 11 ns.

![Timing of PSR J1909-3744 over a 3 week period.](image)

Fig. 7. Timing of PSR J1909–3744 over a 3 week period. The 121 arrival times give an RMS residual of only 122 ns, which has a standard error of the mean of just 11 ns. Arrival times of this accuracy have tremendous importance in the search for a gravitational wave “background”.

By observing this source with larger bandwidths, cooler receivers or just more often, we could potentially get this sort of arrival time accuracy in just a few days. Sensitivity to a cosmological gravitational wave background will require more pulsars like PSR J1909–3744 for success.

4 Conclusions

The observed properties of the recycled pulsars tell us that the final companion mass largely dictates the spin properties of pulsars.

There are some important consequences:

- The relativistic pulsars with the tightest orbits should have low runaway velocities, and spend most of their observable lifetimes near the Galactic plane.
- To obtain several hundred Hz spins, pulsars require a low-mass $M_c < 0.3 \, M_\odot$ companion.
- Close binaries that produce relativistic binaries eject little mass in their final supernova explosion, and have small kicks, subsequently there are few runaway isolated recycled pulsars.
• Neutron star companion masses of relativistic binaries are related to the spin period of the recycled pulsar.

Long-term precision timing can yield both extremely accurate distances and arrival times of astounding precision suitable for detecting a gravitational wave background.

Acknowledgements

I wish to thank Professor Ed van den Heuvel for his brilliant illustration of binary evolution with his beautiful cartoons that helped me enter this field, for his generous refereeing of my Ph D thesis and some early papers, his friendship, and production of an army of disciples with which to discuss interesting ideas about everything to do with binary pulsars. Joris Verbiest aided me in preparation of the 0437 data shown at the conference.

References

[1] Hewish, A., Bell, S. J., Pilkington, J. D. H., Scott, P. F. & Collins, R. A. Observation of a rapidly pulsating radio source. Nature 217, 709–713 (1968).

[2] Lyne, A. G., Manchester, R. N. & Taylor, J. H. The Galactic population of pulsars. Mon. Not. R. astr. Soc. 213, 613–639 (1985).

[3] Hulse, R. A. & Taylor, J. H. Discovery of a pulsar in a binary system. Astrophys. J. 195, L51–L53 (1975).

[4] Barker, B. M. & O’Connell, R. F. Relativistic effects in the binary pulsar psr 1913+16. Astrophys. J. 199, L25 (1975).

[5] Sutantyo, W. Asymmetric supernova explosions and the origin of binary pulsars. Astrophys. Space Sci. 54, 479–488 (1977).

[6] Flannery, B. P. & van den Heuvel, E. P. J. On the origin of the binary pulsar PSR 1913+16. Astr. Astrophys. 39, 61–67 (1975).

[7] Bhattacharya, D. & van den Heuvel, E. P. J. Formation and evolution of binary and millisecond radio pulsars. Phys. Rep. 203, 1–124 (1991).

[8] Srinivasan, G. & van den Heuvel, E. P. J. Some constraints on the evolutionary history of the binary pulsar PSR 1913+16. Astr. Astrophys. 108, 143–147 (1982).

[9] van den Heuvel, E. P. J. Models for the formation of binary and millisecond radio pulsars. J. Astrophys. Astr. 5, 209–233 (1984).
10. Bailes, M. The origin of pulsar velocities and the velocity–magnetic moment correlation. *Astrophys. J.* **342**, 917–927 (1989).

11. Romani, R. W. A unified model of neutron–star magnetic fields. *Nature* **347**, 741 (1990).

12. Srinivasan, G., Bhattacharya, D., Muslimov, A. G. & Tsygan, A. I. A novel mechanism for the decay of neutron star magnetic fields. *Curr. Sci.* **59**, 31–38 (1990).

13. Hobbs, G., Lorimer, D. R., Lyne, A. G. & Kramer, M. A statistical study of 233 pulsar proper motions. *Mon. Not. R. astr. Soc.* **360**, 974 (2005).

14. Brisken, W. F., Benson, J. M., Goss, W. M. & Thorsett, S. E. Very long baseline array measurement of nine pulsar parallaxes. *Astrophys. J.* **571**, 906–917 (2002).

15. Hills, J. G. The effects of sudden mass loss and a random kick velocity produced in a supernova explosion on the dynamics of a binary star of arbitrary orbital eccentricity - Applications to X-ray binaries and to the binary pulsars. *apj* **267**, 322–333 April 1983.

16. Chaurasia, H. K. & Bailes, M. On the Eccentricities and Merger Rates of Double Neutron Star Binaries and the Creation of “Double Supernovae”. *Astrophys. J.* **632**, 1054–1059 October 2005.

17. Dewi, J. D. M., Podsiadlowski, P. & Pols, O. R. The spin period-eccentricity relation of double neutron stars: evidence for weak supernova kicks? *Mon. Not. R. astr. Soc.* **363**, L71–L75 (2005).

18. Faulkner, A. J. *et al.* PSR J1756–2251: A New Relativistic Double Neutron Star System. *Astrophys. J.* **618**, L119–L122 (2005).

19. Taylor, J. H., Fowler, L. A. & McCulloch, P. M. Measurements of general relativistic effects in the binary pulsar PSR 1913+16. *Nature* **277**, 437 (1979).

20. Kaspi, V. M., Taylor, J. H. & Ryba, M. High-precision timing of millisecond pulsars. III. Long-term monitoring of PSRs B1855+09 and B1937+21. *Astrophys. J.* **428**, 713–728 (1994).

21. van Straten, W. *et al.* A test of general relativity from the three-dimensional orbital geometry of a binary pulsar. *Nature* **412**, 158–160 (2001).

22. Jacoby, B. A., Hotan, A., Bailes, M., Ord, S. & Kulkarni, S. R. The Mass of a Millisecond Pulsar. *Astrophys. J.* **629**, L113–L116 August 2005.

23. Stairs, I. H. *et al.* Discovery of Three Wide-Orbit Binary Pulsars: Implications for Binary Evolution and Equivalence Principles. *Astrophys. J.* **632**, 1060–1068 October 2005.

24. Burgay, M. *et al.* The parkes high-latitude pulsar survey. *Mon. Not. R. astr. Soc.* (2006). in press.
[25] Bailyn, C. D. & Grindlay, J. E. Neutron stars and millisecond pulsars from accretion–induced collapse in globular clusters. *Astrophys. J.* **353**, 159–167 (1990).

[26] Tauris, T. M. & Sennels, T. Formation of the binary pulsars psr b2303+46 and psr j1141-6545. young neutron stars with old white dwarf companions. *Astr. Astrophys.* **355**, 236–244 (2000).

[27] Camilo, F. in *The Lives of the Neutron Stars (NATO ASI Series)* (eds Alpar, A., Kiziloğlu, Ü. & van Paradis, J.) 243–257 (Kluwer, Dordrecht, 1995).

[28] Johnston, S. *et al.* Discovery of a very bright, nearby binary millisecond pulsar. *Nature* **361**, 613–615 (1993).

[29] Bell, J. F., Bailes, M., Manchester, R. N., Weisberg, J. M. & Lyne, A. G. The proper motion and wind nebula of the nearby millisecond pulsar J0437–4715. *Astrophys. J.* **440**, L81–L83 (1995).

[30] Hotan, A. W., Bailes, M. & Ord, S. M. High precision baseband timing of 15 millisecond pulsars. *Mon. Not. R. astr. Soc.* (2006). submitted

[31] Bell, J. F. & Bailes, M. A new method for obtaining binary pulsar distances and its implications for tests of general relativity. *Astrophys. J.* **456**, L33–L36 (1996).