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VOLUME 18, 2001

*An international journal of
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Publ. Astron. Soc. Aust., 2001, 18, 1–11

Finding Pulsars at Parkes

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Received 2000 August 31, accepted 2000 October 5

Abstract: There are many reasons why it is important to increase the number of known pulsars. Not only do pulsar searches continue to improve statistical estimates of, for example, pulsar birthrates, lifetimes and the Galactic distribution, but they continue to turn up interesting and, in some cases, unique individual pulsars. In the early days of pulsar astronomy, the Molonglo radio telescope led the world as a pulsar detection instrument. However, the Parkes radio telescope, with its frequency versatility and greater tracking ablility, combined with sensitive receivers and powerful computer detection algorithms, is now the world's most successful telescope at finding pulsars. The Parkes multibeam survey, begun in 1997, by itself will come close to doubling the number of known pulsars. Parkes has also been very successful at finding millisecond pulsars (MSPs), especially in globular clusters. One third of the known MSPs have been found in just one cluster, 47 Tucanae.

Keywords: pulsars: general — surveys — ISM: general

1 Introduction

Since the discovery of the first pulsar by Jocelyn Bell and Tony Hewish in 1967 (Hewish et al. 1968), many observatories throughout the world have undertaken searches for these fascinating objects. Prior to the commencement of the Parkes multibeam survey in mid 1997, these searches had resulted in the discovery of about 750 pulsars. All but a few of these lie within our Galaxy—the only known extragalactic pulsars are associated with the Magellanic Clouds—and all but a few have been discovered at radio wavelengths. Most are relatively close on a Galactic scale—their median distance from the Sun is only about 3·5 kpc. This is not because pulsars are clustered about the Sun. It is purely a result of the rather low radio luminosity of pulsars, which makes them difficult to detect at large distances.

It is now almost universally accepted that pulsars are neutron stars, with the basic periodicity defined by rotation of the star. The pulse period is very predictable, but it is not constant. Despite various short-term fluctuations observed to a greater or lesser extent in most pulsars, in the long term the intrinsic period of all pulsars increases with time. Pulsars are powered by the kinetic energy of rotation. They steadily lose energy, mainly in the form of a high-energy wind of charged particles and magnetic-dipole radiation, that is, electromagnetic waves at the neutron star's rotation frequency.

Pulsars may be divided into two main groups, based on the pulse period and the rate at which it increases. The first group, often called 'normal' pulsars, typically have periods of between 0·05 and 5 s, and characteristic ages, defined by $\tau_c = P/(2\dot{P})$, where P is the pulsar period and $\dot{P}$ is its secular rate of change, in the range 10^3 to 10^7 yr. The other group are the 'millisecond' pulsars (MSPs), most of which have periods of between 1·5 and 25 ms. A key property of MSPs is their great age, typically between 10^8 and 10^{10} yr. Another key property is that most MSPs are members of a binary system, in an orbit with another star. These properties suggest that MSPs are in fact 'recycled' neutron stars, spun up by accretion from a binary companion. For an extensive review of MSP formation mechanisms and their relation to X-ray binary systems, see Bhattacharya & van den Heuvel (1991).

Not long after the discovery of the first MSP by Backer et al. (1982), it was realised that the cores of globular clusters were a favourable environment for the formation of MSPs (Hamilton, Helfand & Becker 1985). Several groups began searches towards globular clusters, and this effort was rewarded by the discovery of the 3 ms pulsar PSR B1821−24 in the core of M28 by Lyne et al. (1987). Over the next few years, more than 30 MSPs were discovered in globular clusters. Of these, M15, with 8 pulsars (Wolszczan et al. 1989; Anderson 1992), and 47 Tucanae with 11 (Manchester et al. 1991; Robinson et al. 1995) stand out as the most prolific.

With 750 pulsars already known, why bother to find more? There are many good reasons. Even though 750 sounds like a large number, when you divide them into luminosity, distance and/or age bins, the numbers in some bins are not all that large. In particular, low-luminosity pulsars dominate the Galactic birthrate (e.g. Lyne et al. 1998) and yet we have a rather small sample of them, leading to large statistical uncertainties in birthrate calculations. Similarly, we know of very few pulsars at distances comparable to that of the Galactic Centre, so estimates of the Galactic population of pulsars are very uncertain except in the solar neighbourhood.

An increased sample of pulsars is also of great value to timing investigations and studies of the emission process. Young pulsars are known to suffer glitches, that is, sudden increases in spin rate, and various other forms of period irregularities. These phenomena are believed to

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result from transitions in the superfluid interior of the neutron star, and provide one of the few ways that we have of investigating the physics of ultra-dense matter (Alpar, Cheng & Pines 1989). However, the number of known glitching pulsars is relatively modest (Wang et al. 2000) and there is great variety in glitch properties. Similarly, there is a wide variety of pulse emission properties, including special groups of pulsars such as those with interpulses or wide profiles, high polarisation, drifting sub-pulses or null periods. An increased sample is very useful for studies of properties such as these.

Pulsars are also excellent probes of the interstellar medium (ISM). They are pulsed, allowing measurement of the dispersive delay due to free electrons in the ISM, and hence the column density of electrons along the path, commonly expressed as a dispersion measure (DM) in the units cm^{-3} pc. Given a model for the interstellar free-electron distribution (e.g. Taylor & Cordes 1993), pulsar distances can be estimated from their DMs. Compared to most celestial radio sources, pulsars have strong linear polarisation, and hence measurement of Faraday rotation is relatively easy. Pulsars have the unique advantage that the DM along the path is also known, so the mean line-of-sight magnetic field strength can be directly estimated, leading to models for the Galactic magnetic field (Han, Manchester & Qiao 1999). Pulsars also have the almost unique property that they are of very small angular size, making possible observation of the full range of effects due to scattering by small-scale fluctuations in the interstellar electron density (Rickett 1990). Pulsars are also excellent probes of the interstellar neutral gas (Frail et al. 1994). Most of these investigations are limited by the spatial density of known pulsars in the Galaxy, and so increasing the sample is of great value.

One of the most fascinating things about pulsars is the fact that pulsar surveys keep turning up new and sometimes totally unexpected classes of object. Even the discovery of the first pulsar itself was serendipitious. Outstanding examples are the discovery of the Vela and Crab pulsars (Large, Vaughan & Mills 1968; Staelin & Reifenstein 1968), the first binary pulsar, PSR B1913+16 (Hulse & Taylor 1974), the first MSP (Backer et al. 1982), the first globular cluster pulsar (Lyne et al. 1987), the first eclipsing binary pulsar (Fruchter, Stinebring & Taylor 1988) and the first pulsar with a high-mass, non-degenerate companion (Johnston et al. 1992b). These objects offer valuable and sometimes profound insight into physics and astrophysics (e.g. Taylor et al. 1992). Much of the motivation for continued searches comes from the expectation of finding the unexpected.

2 The Early Years

With the announcement of the discovery of the first pulsar, the Molonglo radio telescope, operated by the University of Sydney, was ideally placed to follow up on this exciting result. The Cambridge pulsars were discovered with an array operating at 81·5 MHz, suggesting that pulsars had steep radio spectra, and the Molonglo telescope operated at the relatively low radio frequency of 408 MHz. It had large collecting area and so had high instantaneous sensitivity, necessary to record the rapidly fluctuating pulsar signals. By November 1968, it had already discovered nine pulsars, more than half of the then world total of 17 (Large, Vaughan & Wielebinski 1968). Included among these was the very important Vela pulsar, the first to be associated with a supernova remnant.

Initially, astronomers at Parkes concentrated on detailed studies of the spectra, polarisation and timing of pulsars, exploiting properties of the telescope such as frequency versatility, and polarisation and tracking capability. These observations were very successful, providing the first spectra of individual pulses (Robinson et al. 1968), the first observation of a period glitch (Radhakrishnan & Manchester 1969) and the genesis of the now widely accepted ‘magnetic-pole’ model for the emission beam (Radhakrishnan et al. 1969).

The first successful search for pulsars at Parkes, reported by Komesaroff et al. (1973), began in 1973 and discovered eight new pulsars. Because of the lower instantaneous sensitivity of the Parkes telescope, this survey was among the first to rely on digital sampling of longer datasets and signal processing techniques to obtain the necessary sensitivity. Because of its higher frequency (750 MHz) and the use of multichannel receivers, this survey was sensitive to high-DM pulsars. In particular, it discovered the highly luminous pulsar PSR B1641−45, which has a DM of about 480 cm^{-3} pc, the highest known at the time.

In a good example of synergy, the strengths of the Molonglo telescope and the Parkes telescope were combined to undertake the highly successful Second Molonglo Pulsar Survey (Manchester et al. 1978). This survey discovered 154 previously unknown pulsars, more than doubling the number of pulsars known at the time. The Molonglo telescope was used in a multibeam mode, giving eight adjacent beams in right ascension, which increased the effective integration time to $44/\cos\delta$ s. Improved front-end amplifiers and multichannel receivers were also constructed specifically for this survey. Candidates from analysis of the Molonglo data were confirmed at Parkes. The Parkes telescope tracked up the 4° declination width of the Molonglo beam with an effective 300 s integration at each point. Data were searched in real time about the candidate parameters, thereby giving an improved declination, period and DM for confirmed pulsars. As shown in Figure 1, the survey covered the whole sky south of declination +20° and detected a total of 224 pulsars, giving an excellent sample for statistical studies.

The long integration times and wide bandwidths available at Parkes make possible very sensitive surveys. One such survey was that of McConnell et al. (1991), which detected the first known extragalactic pulsars, in the Magellanic Clouds. One of these, PSR J0045−7319, until recently the only known pulsar in the Small Magellanic Cloud, was later shown by Kaspi et al. (1994) to be in a orbit about an optically identified B-star companion.

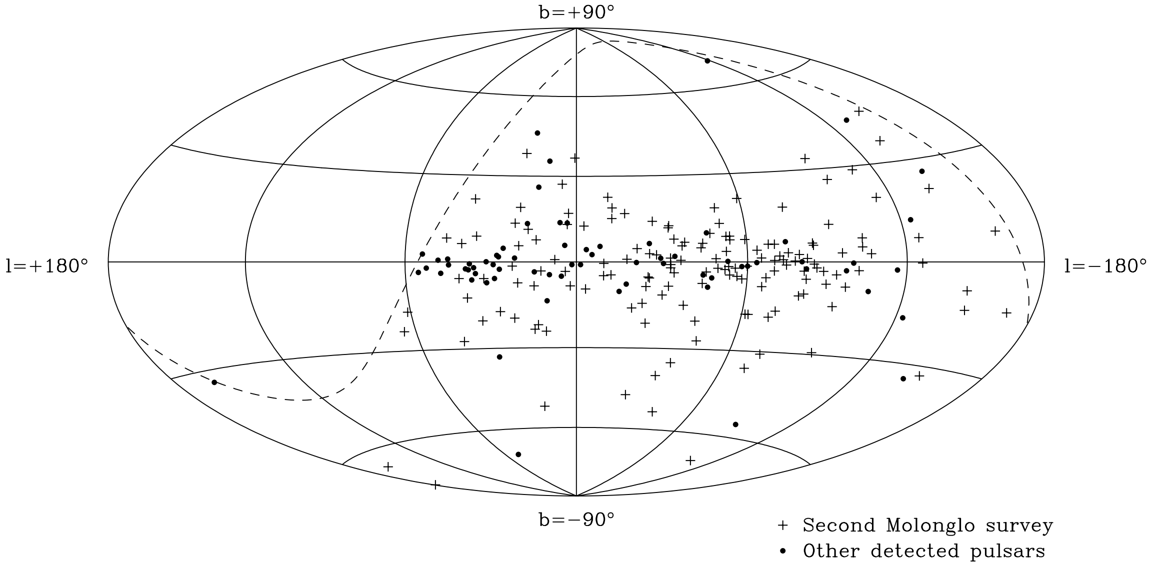

Figure 1 Pulsars detected in the Second Molonglo Survey (Manchester et al. 1978). The dashed curve marks declination +20°, the northern limit of the survey.

The next major survey to be undertaken at Parkes was the 20 cm survey of Johnston et al. (1992a). This survey covered a strip along the Galactic Plane with $270° < l < 20°$ and $|b| < 4°$, complementing a similar survey of the northern Galactic Plane (Clifton et al. 1992). A bandwidth of 320 MHz centred at 1520 MHz was observed with an effective integration time per point of 2·5 min, giving a limiting sensitivity of about 1 mJy for pulsars with period greater than about 50 ms. A total of 100 pulsars were detected by the survey, with 46 being new discoveries. Included among them was the very interesting eclipsing binary pulsar PSR B1259−63 (Johnston et al. 1992b). This pulsar is in a 3·5 yr, highly eccentric orbit around a $10\,M_\odot$ Be star, SS 2883, and was the first pulsar known to have a massive, non-degenerate companion. Near periastron, the pulsar passes through the circumstellar disk of the Be star and is eclipsed for about 30 days. Significant changes in DM and rotation measure are observed before and after the eclipse, giving information on the properties of the circumstellar disk (Johnston et al. 1996).

Although the Johnston et al. (1992a) survey had sensitivity to MSPs at about the 2·5 mJy level, none was detected. The main reasons for this were the high dispersion, scattering and background temperature along the Galactic Plane, coupled with the low luminosity of most MSPs. Also, because of their great age, most disk MSPs are at large Galactic z-distances, comparable to or larger than the reach of most surveys. Consequently they have a nearly isotropic distribution on the sky. These considerations suggested that a lower-frequency search covering a large area of the sky would be more likely to detect a significant number of MSPs. The Parkes 70 cm survey (Manchester et al. 1996; Lyne et al. 1998) was designed with these ideas in mind.

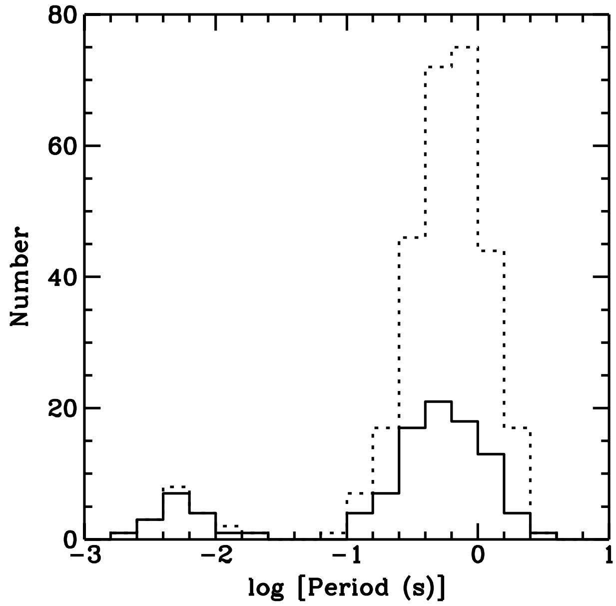

Figure 2 Period distribution of pulsars discovered (full line) and detected (dotted line) by the Parkes Southern Pulsar Survey (Lyne et al. 1998).

The survey covered the whole sky south of the equator at a frequency of 436 MHz, with a sampling interval of 300 μs and an observation time per point of 157 s, giving it a limiting sensitivity of about 3 mJy. It detected 298 pulsars, of which 101, including 17 MSPs, were previously unknown. Figure 2 shows the period distribution of these pulsars. This figure highlights the fact that MSPs comprise a different population, quite distinct from the normal pulsars. As expected, the sky distribution of MSPs was close to isotropic, whereas the normal pulsars were clustered along the Galactic Plane. The large number of pulsars

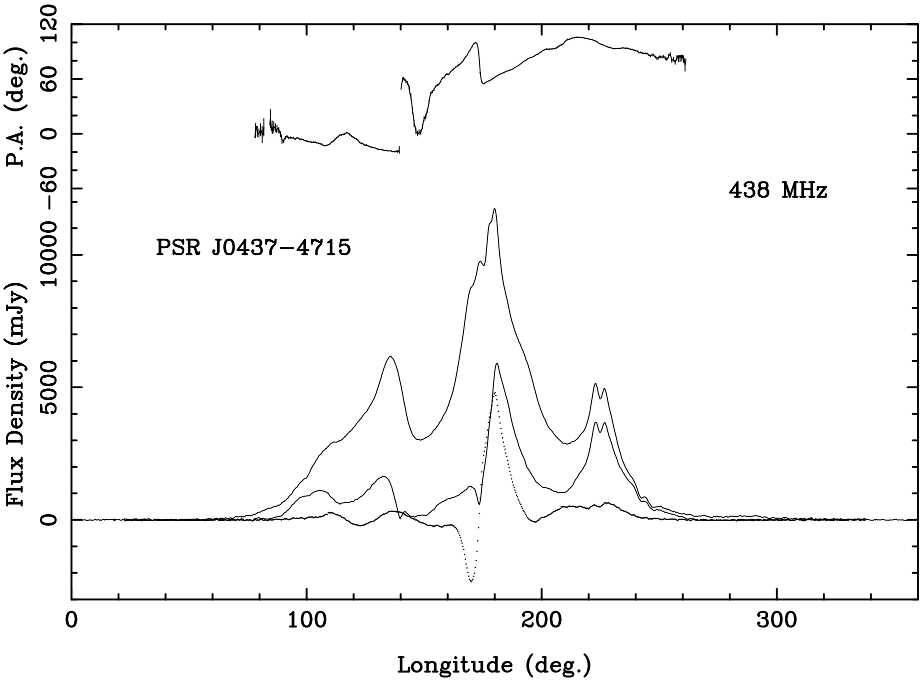

Figure 3 Mean pulse profile and polarisation parameters for PSR J0437−4715 (Navarro et al. 1997). The entire pulse period is shown. In the lower part of the figure, the upper line is the total intensity, Stokes I, the other solid line is the linearly polarised intensity, $L = (Q^2 + U^2)^{1/2}$, and the dotted line is the circularly polarised intensity, Stokes V. The line in the upper part is the position angle of the linearly polarised component.

detected and the well defined survey parameters make this an excellent database for studies of the Galactic distribution and birthrate of both normal pulsars and MSPs. Lyne et al. (1998) estimate that there are about 30,000 potentially observable MSPs with 400 MHz luminosity above 1 mJy kpc^2, and a similar number of potentially observable normal pulsars above the same luminosity limit in the Galaxy. After taking beaming into account, the corresponding birthrate for normal pulsars is one per 60 to 330 yr, and for MSPs, one per 300,000 yr.

Probably the most interesting pulsar discovered by the Parkes Southern Survey was PSR J0437−4715, by far the nearest and strongest MSP known (Johnston et al. 1993). This pulsar has a period of 5·75 ms, is in a 5·74 day binary orbit with a companion of mass ~0·3 $M_\odot$, and has a mean flux density at 430 MHz of more than 500 mJy. The strength of this pulsar makes possible very precise measurements of its polarisation and timing properties. As shown in Figure 3, the pulsar has a very wide and complex profile covering more than 80% of the period with at least 12 identifiable pulse components and high polarisation, both linear and circular (Navarro et al. 1997). The position angle variation is complex, suggesting that the usual assumption of dipole magnetic field lines in the pulsar magnetosphere is not valid. Timing observations (Sandhu et al. 1997) have given the pulsar position with a precision of 50 μas, the proper motion at the 2000σ level, and a value for the annual parallax of 5·6 ± 0·8 mas. This parallax corresponds to a distance for the pulsar about 30% larger than the value derived from the DM. The large proper motion (~140 mas yr^{-1}) results in an apparent acceleration of the pulsar, accounting for about 80% of the observed period derivative. It also changes the inclination of the pulsar orbit to the line of sight, resulting in a secular change in the projected size of the orbit. This change has been detected at the 20σ level, enabling a limit to be placed on the inclination angle of the orbit, $i < 43°$, and hence improving the determination of the mass of the companion.

With hindsight, another very interesting pulsar discovered in this survey was PSR J2144−3933, originally believed to have a pulse period of 2·84 s. In the course of a study of the pulse-to-pulse fluctuation properties of pulsars, Matthew Young realised that the true period of this pulsar was 8·51 s, by far the longest period known (Young, Manchester & Johnston 1999). This long period places the pulsar beyond the 'death line' of most models for the pulse emission mechanism. The pulsar also has a very narrow pulse, less than 1° of longitude. If this is typical of such long-period pulsars, they could form a large fraction of the total Galactic population.

3 The Parkes Multibeam Pulsar Survey

The Parkes multibeam receiver, while primarily designed for H I surveys (Staveley-Smith et al. 1996), is a superb instrument for pulsar surveys. Its 13 beams allow the sky to be covered roughly 13 times as fast, or much longer to be spent on a given point. Also, its receivers have excellent sensitivity, with an average system noise of only 21 K. With major contributions from Jodrell Bank Observatory and Osservatorio Astronomica di Bologna, a filterbank

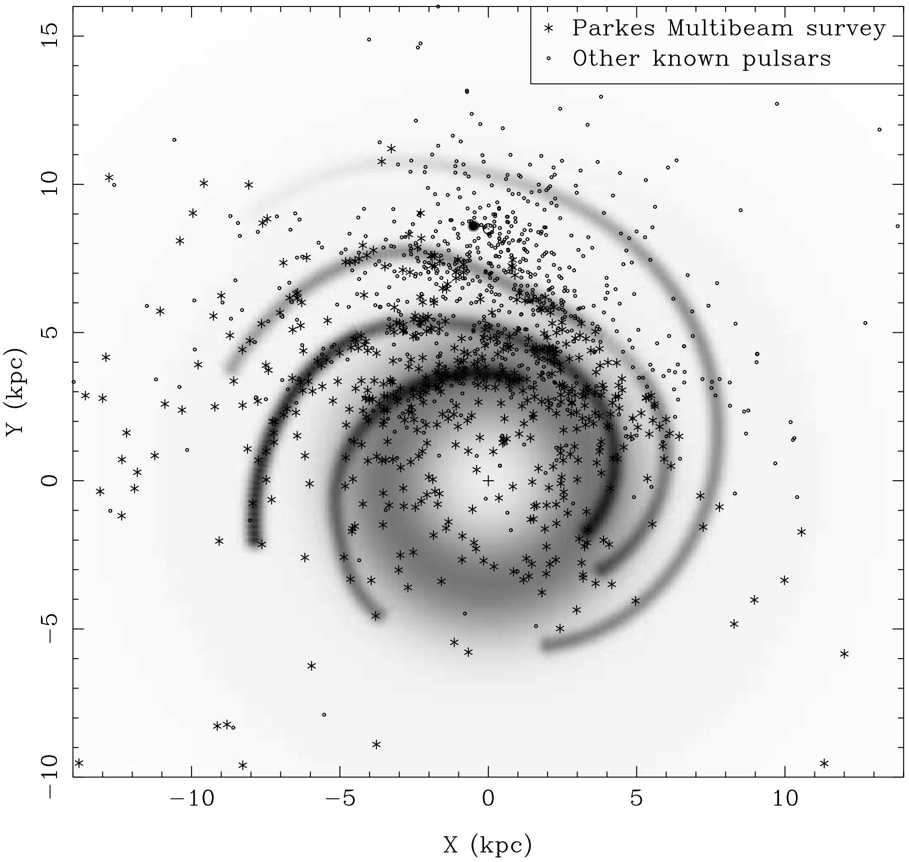

Figure 4 Distribution of known pulsars projected on to the Galactic Plane. The position of the Sun is marked by ⊙ and the Galactic Centre by +. The distribution of interstellar free electrons according to the Taylor & Cordes (1993) model is shown as a grayscale. The dark spot near the Sun is the Gum Nebula.

system capable of handling the data from the 13 beams was installed at Parkes in early 1997 and the Parkes Multibeam Pulsar Survey commenced in August 1997. The survey is covering the region $260° < l < 50°$ with $|b| < 5°$. The filterbank has 96 3-MHz channels for each polarisation of each beam, and all outputs are one-bit digitised at 250 μs intervals and recorded to tape. Each pointing of the 13 beams is of 35 min duration, giving a sensitivity for long-period pulsars away from the hot regions of the Galactic background of about 0·15 mJy. This is about seven times better than the previous best survey of this type (Johnston et al. 1992a), and so a large increase in the number of detected pulsars was expected.

These expectations have already been fully realised. With about 80% of the survey completed, more than 570 previously unknown pulsars have been discovered, making this by far the most successful pulsar survey ever. When finished, the survey will come close to doubling the number of known pulsars. Figure 4 shows the distribution of known pulsars projected on to the Galactic Plane, where distances have been computed using the Taylor & Cordes (1993) electron density model. In contrast to the previously known pulsars, which are clustered around the Sun, many of the multibeam pulsars are at large distances, with some apparently on the other side of the Galactic Centre. There is some indication of a deficit of detected pulsars within a couple of kpc of the Galactic Centre. The electron density model is not well determined at these large distances though, and the distances may have systematic biases. Also, many of the multibeam pulsars are concentrated in spiral arms, but this may simply be a result of the increased model electron density in the arms. The multibeam sample will be important in helping to refine the electron density model.

As shown by Figure 5, pulsars detected by the multibeam survey are on average much younger than previously known pulsars. They include the three pulsars with the strongest known surface dipole magnetic fields (Camilo et al. 2000a). One of these pulsars, PSR J1119−6127, has a characteristic age of only 1700 years and is associated with what appears to be a previously uncatalogued supernova remnant (Crawford et al. 2001). Another, PSR J1814−1744, has the relatively long period of 3·97 s, but a very rapid spin-down rate, giving it an implied surface field strength of $5{\cdot}5 \times 10^{13}$ G. These parameters place the pulsar near the so-called ‘anomalous X-ray pulsars’ (AXPs) on the P–$\dot{P}$ plane (Figure 5). AXPs are believed to be slowly rotating neutron stars, but they have no detectable radio emission. On the other hand, PSR J1814−1744 has no detectable X-ray emission (Pivovaroff, Kaspi & Camilo 2000). The reason(s) for these very different properties are not well understood.

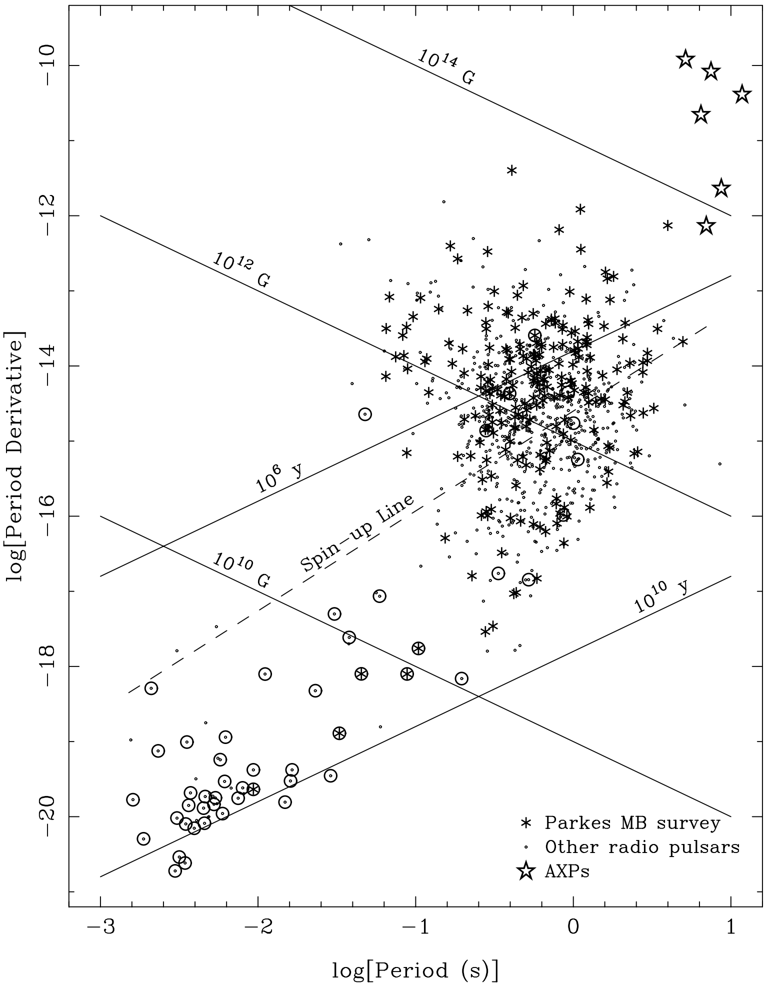

Figure 5 Distribution of pulsars and anomalous X-ray pulsars (AXPs) in the P–$\dot{P}$ plane. Binary systems are indicated by a circle around the point. Lines of constant pulsar characteristic age, $\tau_c = P/(2\dot{P})$, and surface dipole magnetic field strength, $B_s \propto (P\dot{P})^{1/2}$, are indicated. The spin-up line, representing the minimum period attainable by accretion from a binary companion, is also shown.

Only one MSP has been discovered so far. Although this is somewhat surprising given the parameters of the survey, there are several possible contributing factors. The search so far has been concentrated at low Galactic latitudes, where dispersion and scattering are large. This limits the maximum distance at which typical MSPs can be detected, so the volume of the Galaxy searched so far is relatively small. Another contributing factor is that only ‘unaccelerated’ searches have been performed so far. Especially with the rather long observation time of this survey, this limits our senstivity to MSPs, most of which are in binary systems. A third factor is that the algorithms for dealing with interference were not optimal in the early stages of processing. This mainly affects MSP detections, since most of the searched frequency space corresponds to millisecond periods. All of these factors are being overcome and we expect to detect more MSPs with future observations and data processing.

Eight of the newly discovered pulsars are members of binary systems. Five of these are in near-circular orbits with companions which are probably white dwarfs (Camilo et al. 2001). These systems differ from most known white-dwarf binaries. Except for the one MSP detected, the pulsar periods are relatively long, lying between 45 and 90 ms, and the companions are heavy, with minimum mass between 0·15 and 0·9 $\mathrm{M}_\odot$.

One of the binary pulsars, PSR J1811−1736, is in a highly eccentric 18-day orbit and is very probably a double neutron-star system, the first to be discovered in the southern hemisphere (Lyne et al. 2000). In contrast to PSR J1811−1736, which has a characteristic age of $\sim 10^9$ yr, PSR J1141−6545 is a young pulsar ($\tau_c \approx 1{\cdot}5 \times 10^6$ yr) in a much tighter ($P_b \approx 4{\cdot}1$ h) and eccentric orbit (Kaspi et al. 2000). Precession of the longitude of periastron has been observed for this system, and interpreting this as due to the effects of general relativity gives a value for the total mass of the system of $2{\cdot}300 \pm 0{\cdot}012\,\mathrm{M}_\odot$. The pulsar and orbit properties suggest that the companion is a heavy white dwarf formed *before* the supernova explosion that created the pulsar. This is unusual—in most binary systems the neutron star is formed from the heavier binary companion, which evolves faster.

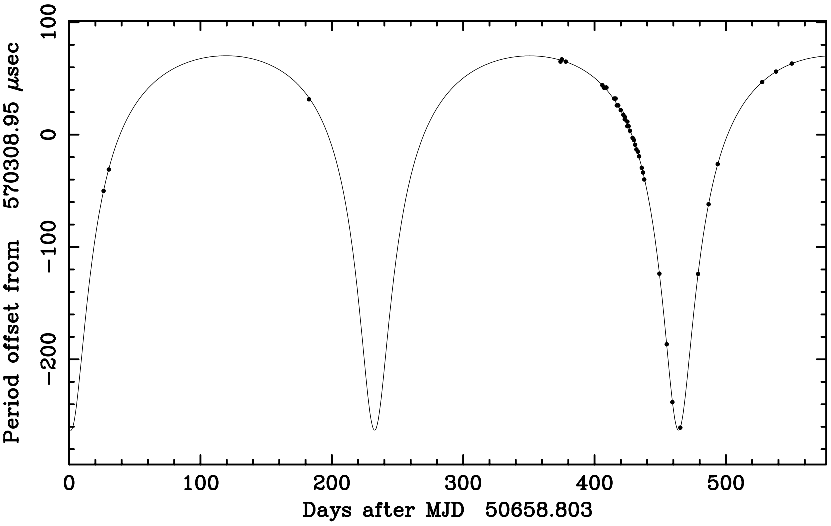

Figure 6 Variations in apparent solar-system barycentric period of PSR J1740−3052. The fitted curve is for a binary model with orbital period 230·0 day and eccentricity 0·579 (Stairs et al. 2001).

As shown in Figure 6, PSR J1740−3052 is in a highly eccentric long-period orbit. The interesting thing about this system is that the minimum companion mass is 11 $M_\odot$, implying that the companion is either a massive star or a black hole. Unfortunately the pulsar lies close to the direction of the Galactic Centre and probably at about the same distance, so optical searches for the companion are unlikely to be productive. However, 2·2 μm infrared observations with the Siding Spring 2·3 m telescope and the Anglo-Australian Telescope have revealed a K-supergiant star whose position agrees with that of the pulsar to better than 0·3 arcsec (Stairs et al. 2001). The infrared spectrum of this star shows Brackett-γ emission, consistent with the presence of a compact binary companion, and the star's colours are consistent with a distance comparable to that of the pulsar. Furthermore, DM and rotation measure changes were observed over the last periastron passage, in February 2000. All of these observations point towards this star being the binary companion. However, there a couple of puzzling features. The pulsar comes to within 1·25 stellar radii of the companion star at periastron. One might expect the radio emission to be eclipsed by the stellar atmosphere or wind, but no eclipses are observed. Also, it should raise large tides on the companion, causing a large precession in the longitude of periastron. This is also not observed. Either we do not understand winds and tides in supergiant stars very well, or all the other observations are misleading and the companion is really a black hole. Although the latter is an attractive option (this would be the first known neutron star–black hole system), the former is more likely.

4 Millisecond Pulsars in 47 Tucanae

In terms of finding MSPs, the globular cluster 47 Tucanae has proven to be a goldmine. The cluster is massive ($\sim 10^6$ $M_\odot$), relatively nearby with a distance from the Sun of about 5 kpc, and has a very dense core with a central density of $\sim 10^5$ $M_\odot$ pc^{-3}. These properties are favourable for the formation of neutron-star binary systems by exchange interactions in the core (e.g. Rasio, Pfahl & Rappaport 2000) and the detection of MSPs formed by subsequent accretion spin-up of the captured neutron stars. Parkes searches at 430 and 640 MHz in the early 1990s (Manchester et al. 1990, 1991, and Robinson et al. 1995) resulted in the detection of 11 MSPs in 47 Tucanae, already a record number of pulsars for one cluster. These pulsars all had very short periods, in the range 2·1 to 5·8 ms, and three of them were known to be members of binary systems. One, 47 Tuc J, had the very short orbital period of 2·9 h and showed evidence for eclipses of the pulsar signal. Most of these pulsars are very weak and several were only detected occasionally, when interstellar scintillation raised their flux density to a detectable level. Because of this, only two of the 11 pulsars, C and D, both isolated (non-binary) pulsars, had coherent timing solutions and hence accurate positions, periods and slow-down rates.

Matters remained like this for several years, until Camilo et al. (2000b) exploited the high sensitivity of the multibeam system and sophisticated data processing techniques to discover a further nine MSPs in the cluster, all members of binary systems! The complete dominance of binary pulsars in these latest discoveries shows that the low proportion of binary systems in the earlier results was purely a selection effect, and that most pulsars in globular clusters (at least in 47 Tucanae, but probably in all clusters) are binary. Again, all of these pulsars had very short periods, the longest being 7·6 ms. 47 Tuc R has the shortest orbital period known for any radio pulsar, 96 min, and also shows evidence for eclipses. All of the known binary systems in 47 Tucanae have very low-mass companions, $\lesssim 0{\cdot}2$ $M_\odot$.

Not only has the multibeam system allowed detection of more pulsars in 47 Tucanae, it has also given us a much higher detection rate on the previously known pulsars.

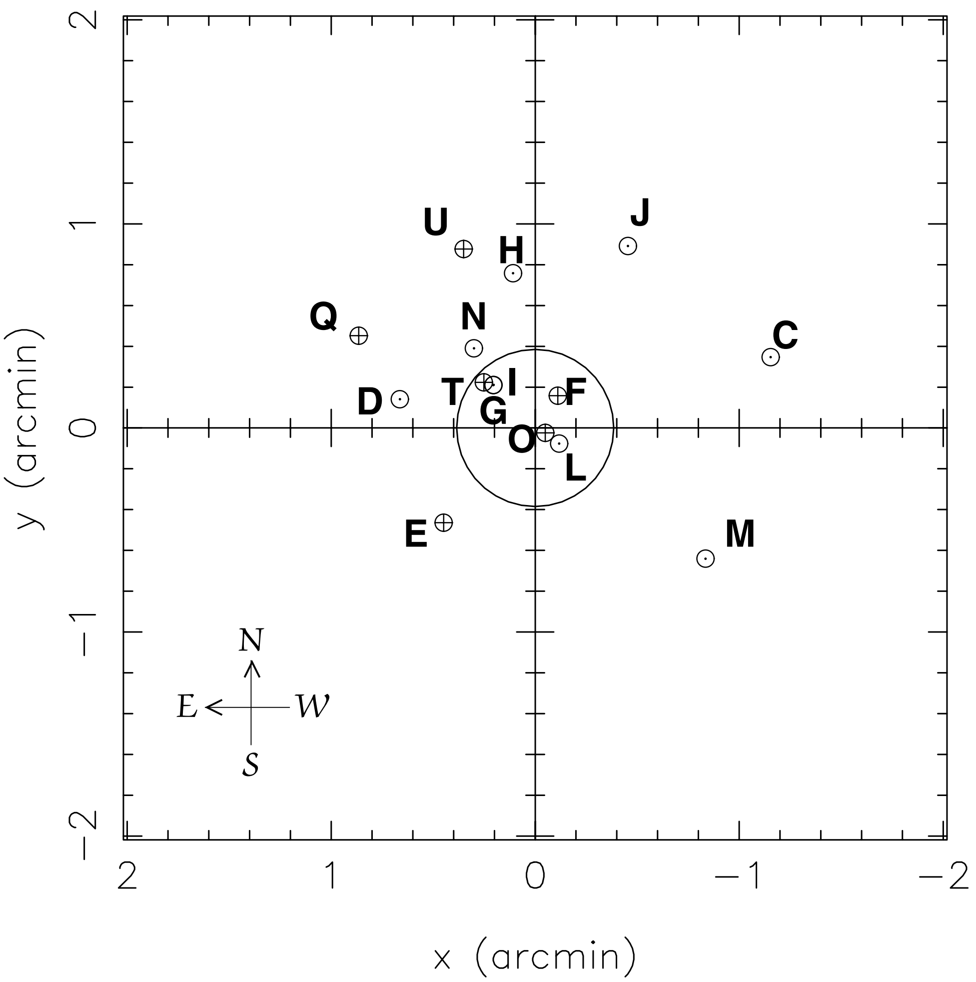

Figure 7 Positions relative to the cluster centre of the 15 pulsars in 47 Tucanae with coherent timing solutions. The large circle indicates the size of the cluster core (cf. Freire et al. 2000).

This has allowed timing solutions to be obtained for a further 13 pulsars, giving us a much improved knowledge of the pulsar parameters (Freire et al. 2000). This in turn makes possible a number of interesting studies of cluster properties. Figure 7 shows that the pulsars are concentrated in the central region of the cluster; the core radius is 23 arcsec but the tidal radius is much larger, about 40 arcmin. This indicates that they are in dynamical equilibrium with other cluster stars, their larger-than-average mass giving them a smaller-than-average velocity in the cluster and hence confining them to the central region. Interestingly, a cumulative histogram of number of pulsars versus perpendicular radius from the cluster centre is linear within the uncertainties. This implies that stars with mass similar to that of a neutron star are the dominant stellar species in the core region. Since the maximum mass of main-sequence stars is about 0·8 $M_\odot$, these may be unseen neutron stars or binary systems consisting of two heavy main-sequence stars. The existence of such binary systems is suggested by the observation of 'blue straggler' stars in the cluster core (Gilliand et al. 1998); these stars are believed to be formed by the coalescence of such binary systems.

The positions obtained from timing observations have very small uncertainties, typically $\lesssim$1 mas. Given the improved parameters for cluster pulsars obtained from the recent observations, Freire et al. (2000) were able to go back and reanalyse the data from the early 1990s to obtain two more coherent timing solutions, giving four in all. Comparison of positions from these solutions with those from analyses of recent data allowed determination of the proper motions of the four pulsars. These results are shown in Figure 8. The observed proper motions are dominated by the motion of the cluster as a whole, not by motions of pulsars relative to the cluster. Their weighted mean already gives a more precise value for the cluster proper motion than that obtained from Hipparcos data, and future observations will further improve the reliability of this value.

As mentioned in the Introduction, the long-term or secular intrinsic period derivative of all pulsars is believed to be positive. However, observed period derivatives for MSPs near the core of globular clusters are sometimes negative. This is attributed to an acceleration of the pulsar in the cluster's gravitational potential dominating over any intrinsic period derivative. Pulsars on the far side of

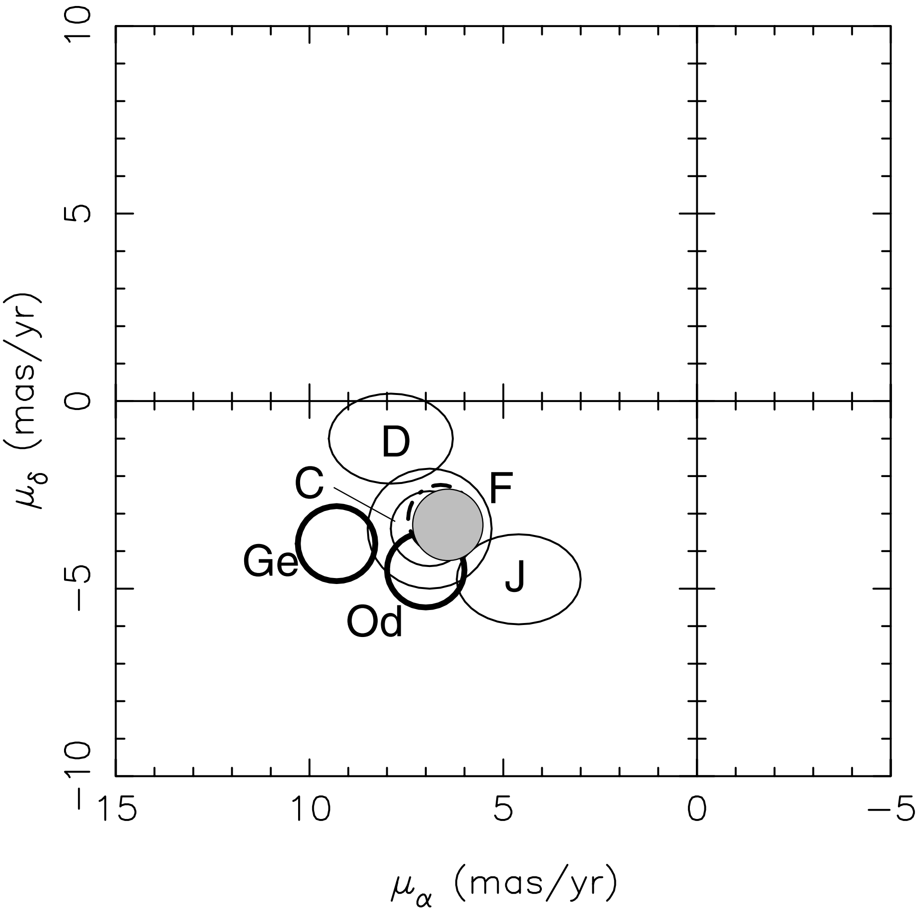

Figure 8 Proper motions of four pulsars in 47 Tucanae (cf. Freire et al. 2000). The filled ellipse represents a weighted average of the pulsar results and its uncertainty. Also shown are two determinations of the cluster proper motion from Hipparcos data by Geffert et al. (1997) and Odenkirchen et al. (1997).

the cluster will be accelerating towards us and hence will appear to be speeding up. Figure 9 shows the observed $\dot{P}/P$ ratios along with a model prediction of the probability of a given acceleration being observed. The observed points are consistent with these predictions, provided that the central velocity dispersion in the cluster is more than $12\,\mathrm{km\,s^{-1}}$ (Freire et al. 2000).

These results are already impressive. However, with continuing observations using (already installed) filterbanks giving higher time resolution, new and improved results can be expected from the Parkes observations of 47 Tucanae. Already, two more pulsars have been discovered, bringing the total known in the cluster to 22. Existing timing solutions will improve and new timing solutions will be obtained, giving improved proper motions and cluster accelerations. There is no doubt that further study of 47 Tucanae will be rewarding.

5 Conclusions

In this review, I have highlighted the major pulsar searches undertaken using the Parkes 64 m radio telescope. Numerous other smaller-scale searches have taken place over the years, many of which have produced important results. A recent notable example is the survey being undertaken by Russell Edwards and his colleagues from Swinburne University of Technology using the multibeam receiver. The Swinburne survey complements the Parkes multibeam survey, covering higher latitudes with $5° < |b| < 15°$, and has discovered 55 pulsars including eight MSPs (Edwards 2000).

All in all, the Parkes telescope has discovered just under two thirds of all known pulsars, nearly twice as many as all the other telescopes in the world combined! And the most successful of these surveys, the Parkes multibeam survey, is not yet finished. By a large margin, the Parkes telescope is the most successful telescope in the world at finding pulsars. This success is due to several factors, principally the large size of the telescope, its southern location (making it ideal for Galactic surveys) and the excellent performance and innovative design of the receiver systems installed on it. I have to say that the stamina of the astronomers responsible for these surveys is also a significant factor.

Acknowledgments

There are two very important acknowledgments to be made. The first is to the people who designed, built,

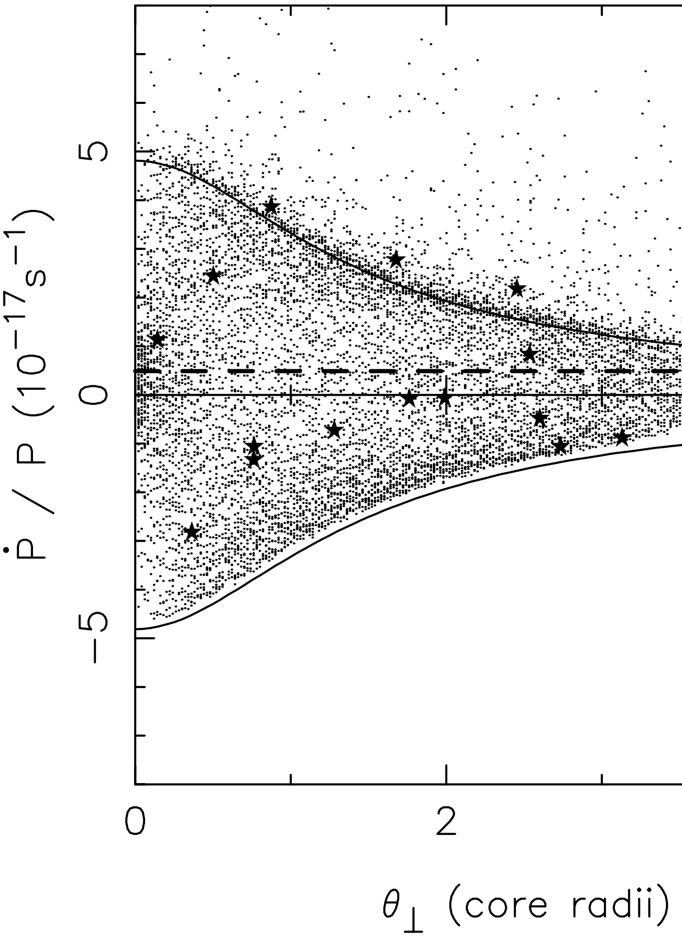

Figure 9 Observed $\dot{P}/P$ ratios for pulsars in 47 Tucanae as a function of their radial distance from the cluster core (cf. Freire et al. 2000). The dashed line is the mean observed value of $\dot{P}/P$. The solid curves give the maximum acceleration based on a King model for the cluster density distribution, and the dots represent accelerations of a random sample of pulsars having the mean acceleration and distributed through the cluster with an r^{-2} density distribution.

maintained and developed the Parkes telescope and its receivers over its 40-year history. The second is to my colleagues who have played a major role in most of the work described here. Without the skill and dedication of these people, this review could never have been written. I also thank Simon Johnston for a careful reading of the manuscript and several helpful suggestions. The Parkes radio telescope is part of the Australia Telescope, which is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO.

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