Pulsars: Recent Results from Parkes

R. N. Manchester

(*Australia Telescope National Facility, CSIRO, Epping NSW 1710, Australia*)

Abstract In the past few years, groups working at the 64-m Parkes radio telescope have made major contributions to the subject of pulsar astronomy. Large-scale surveys for pulsars using the Parkes multibeam receiver have discovered about 700 previously unknown pulsars, nearly doubling the number known. More directed searches toward both supernova remnants and globular clusters have discovered a significant number of pulsars, many of which are intrinsically interesting. Finally, timing and scintillation observations of some well-known pulsars have revealed a number of interesting effects.

1 Introduction

The 64-m Parkes radio telescope, operated by the Australia Telescope National Facility, CSIRO, and located near the town of Parkes in central New South Wales, has a long history of involvement in pulsar research. Just a few weeks after the announcement of the discovery of pulsars (Hewish et al. 1968), the first multi-frequency spectra of individual pulses were obtained (Robinson et al. 1968). A year or so later, the polarization of the Vela pulsar was measured, leading to the magnetic-pole model for pulsar emission (Radhakrishnan & Cooke 1969) and the first pulsar glitch was observed (Radhakrishnan & Manchester 1969). The first pulsars to be discovered at Parkes were announced by Komesaroff et al. (1973) in one of the first pulsar searches to exploit digital signal processing techniques.

Several very successful large-scale searches for pulsars followed. The Second Molonglo Pulsar survey, in which candidates from the Molonglo telescope near Canberra were confirmed at Parkes, discovered 155 pulsars and more than doubled the number of pulsars known at the time (Manchester et al. 1978). The first known extra-galactic pulsar was discovered in the Large Magellanic Cloud by McCulloch et al. (1983). The first confirmed pulsar in the globular cluster 47 Tucanae, a millisecond pulsar (MSP), was discovered by Manchester et al. (1990) and was quickly followed by the discovery of an additional ten MSPs in the same cluster (Manchester et al. 1991, Robinson et al. 1995). The first major survey of the southern Galactic plane at 1400 MHz by Johnston et al. (1992) discovered 46 pulsars, including the interesting long-period high-mass binary system PSR B1259−63. The Parkes 70 cm survey (Lyne et al. 1998) was the first extensive survey of the southern hemisphere with a system sensitive to MSPs and discovered 101 pulsars, of which 17 had millisecond periods, including the nearest and strongest MSP known, PSR J0437−4715.

By 1997, pulsar surveys at Parkes had discovered nearly one third of the 750 or so pulsars known. In this year, a major advance in the capability of the Parkes telescope for large-scale surveys at frequencies around 1400 MHz was made with the construction of the multibeam receiver (Staveley-Smith et al. 1996). This receiver gives 13 simultaneous beams on the sky, multiplying the efficiency of large-scale surveys by roughly a factor of 13. Since then, observations using this receiver have again (nearly) doubled the number of known radio pulsars to about 1500. This means that the Parkes radio telescope has *discovered twice as many pulsars as the rest of the world's telescopes put together!* Most of the new discoveries have been made by the Parkes multibeam pulsar survey, a survey of a 10° -wide strip along the southern Galactic plane, but significant numbers have been found in higher-latitude wide-area surveys as well.

The multibeam receiver has proved valuable in wide-area surveys. The low system noise and wide bandwidth of the system allowed very sensitive searches directed at specific objects using just the central beam of the receiver. Such searches have nearly doubled the number of known pulsars associated with globular clusters (and significantly increased the number of clusters with known pulsars) and discovered a number of young and interesting pulsars associated with supernova remnants. The sensitivity of the system, combined with improved data recording and analysis techniques, has also produced some interesting results from timing and scintillation studies of previously known pulsars.

2 Pulsar Surveys with the Parkes Multibeam System

The Parkes multibeam receiver has 13 beams arranged in two hexagons surrounding a central beam, each with dual polarization and system temperature of about 22 K. Pulsar searches use a filterbank receiver/digitiser system with 96×3 MHz channels, centered at 1374 MHz, on each polarization of each beam. Data are one-bit digitized and recorded on digital linear tape for subsequent analysis. Two major surveys have been made with this system: the Parkes multibeam pulsar survey and the Swinburne intermediate-latitude survey.

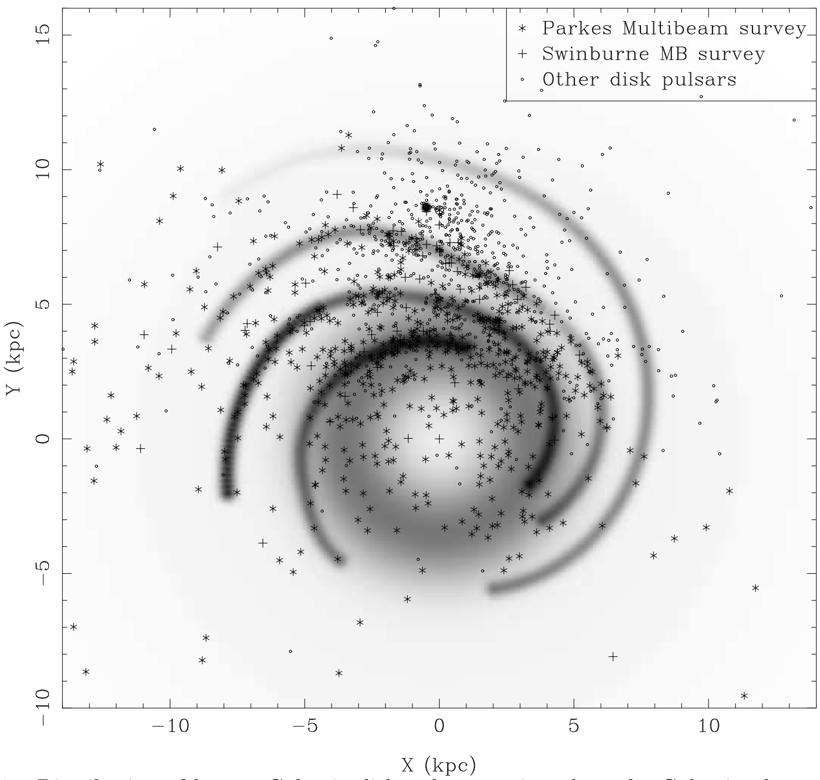

Fig. 1 Distribution of known Galactic disk pulsars projected on the Galactic plane. The underlying greyscale is the Taylor & Cordes (1993) Galactic electron density model which was used to derive pulsar distances from the dispersion measure.

The Parkes multibeam survey is a collaboration between groups from the United Kingdom, United States, Italy, Canada and Australia and covers a 10° -wide strip along the southern Galactic plane between Galactic longitudes of 260° and 50° . It has been outstandingly successful, discovering more than 620 pulsars. Descriptions of the receiver and data recording and analysis systems, details of the first 100 pulsars discovered and references to earlier papers reporting especially interesting objects are given by Manchester et al. (2001). Morris et al. (2002) and Kramer et al. (2003) report the discovery of a further 120 and 200 pulsars, respectively, and discuss some of the implications of the results. The survey has a limiting flux density of approximately 0.2 mJy, several times more sensitive than any previous large-scale survey, and uses a sampling interval of 250 μs. It achieves this high sensitivity with a combination of low system noise, wide bandwidth (288 MHz) and long integration time (35 min). Following determination of accurate periods and positions, newly discovered pulsars are listed on a website (http://www.atnf.csiro.au/research/pulsar/pmsurv/). This site currently lists parameters for 519 pulsars.

Because of the high sensitivity of the survey, most of the newly discovered pulsars are relatively distant and have high dispersion measures – the median value is about 350 cm^{-3} pc compared to 90 cm^{-3} pc for previously known pulsars. As Fig. 1 shows, many of the pulsars at distances comparable to the Galactic Center and even beyond. They therefore form an excellent sample for studies of the interstellar medium, including improvement of the electron density model and investigations of the Galactic magnetic field (e.g., Han et al. 2002).

A complimentary survey, optimised for detection of millisecond pulsars, is being undertaken by a group from Swinburne University of Technology and Caltech using the multibeam receiver at Parkes. This survey is covering several strips parallel to that of the Parkes multibeam survey but at higher latitudes. It uses a smaller sampling interval, 125 μs, and just 4 min per pointing. While this survey has a lower sensitivity overall, these parameters, combined with the higher Galactic latitude of the search area, give it a relatively higher sensitivity to millisecond pulsars. The first phase of the survey (Edwards et al. 2001) covers strips with 5° ¡ —b— ¡ 15° and has been very successful, discovering 69 pulsars including eight millisecond pulsars.

One of the basic pulsar parameters is the slow-down rate, normally expressed as a dimensionless period time-derivative $\dot{P}$. Measurement of this parameter allows determination of the characteristic age of the pulsar, $\tau = P/(2\dot{P})$, and the surface-dipole magnetic field in gauss, $B_s = 3.2 \times 10^{-19} P\dot{P}$. The P — $\dot{P}$ diagram, shown in Fig. 2 for all known pulsars, is a basic tool of pulsar astronomy. Young pulsars have high surface-dipole fields and spin down rapidly, whereas millisecond pulsars have very small period derivatives, implying low magnetic fields and ages of 10^9 years or more. A large proportion of millisecond pulsars are binary. Also shown in Fig. 2 are the so-called 'anomalous X-ray pulsars' (AXPs) and 'soft gamma-ray repeaters' (SGRs) which have long pulsation periods and extremely strong implied magnetic field strengths. AXPs and SGRs are detected only at X-ray and higher energies. Some young pulsars, including the youngest known, PSR J1846−0258 which is associated with the supernova remnant Kes 75 (Gotthelf et al. 2000) are also detectable only at X-ray energies.

One of the more significant results to come from the Parkes multibeam survey is the detection of a large number of relatively young pulsars with very large implied magnetic-field strengths. Indeed, as Fig. 2 shows, the ten radio pulsars with the largest derived magnetic field strengths were all detected in this survey. Some of these pulsars have relatively long periods and are located close to the region of $P - \dot{P}$ space occupied by the AXPs and SGRs (Camilo et al. 2000a). Despite this, these are radio pulsars, so far undetectable at X-ray wavelengths (Pivovaroff et al. 2000). AXPs and SGRs, on the other hand, have no

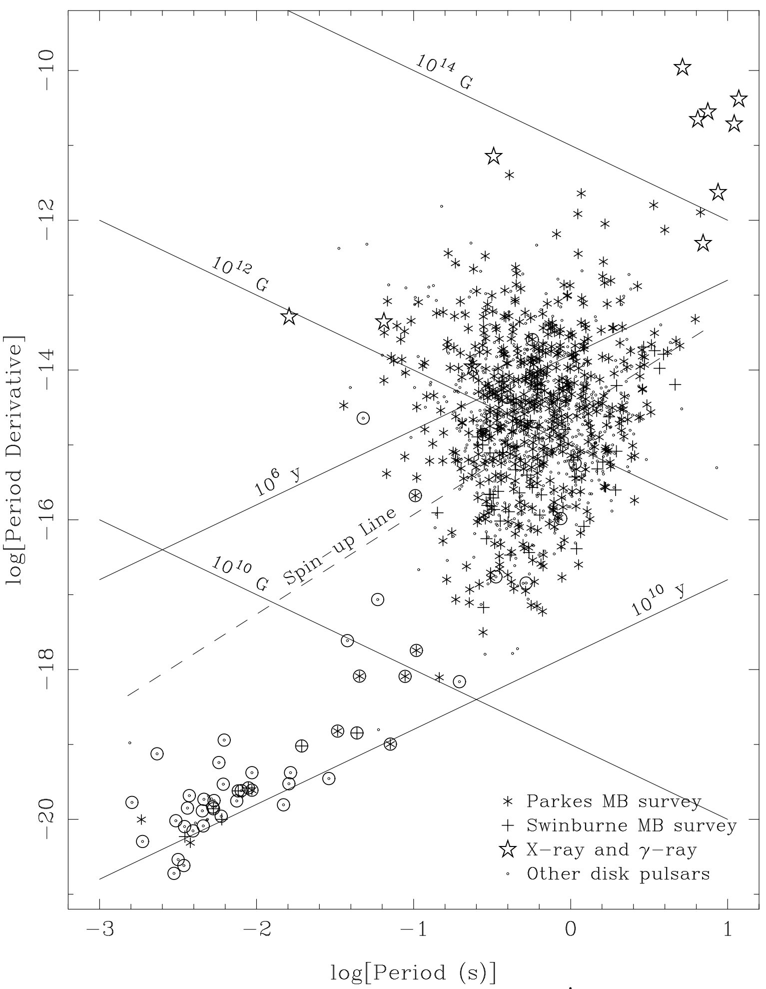

Fig. 2 Distribution of known Galactic disk pulsars in the P — $\dot{P}$ plane. Binary pulsars are indicated by circle around the point and pulsars detected only at high energies are marked with an open star. This latter group includes the anomalous X-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs) which have very long periods and high implied magnetic fields.

detectable pulsed radio emission.

3 Pulsar – Supernova Remnant Associations

The youngest pulsar so far discovered in the Parkes multibeam survey, PSR J1119−6127, has a characteristic age of only 1700 years. An associated supernova remnant might be expected for such a young pulsar, but there was no catalogued remnant at the pulsar position. A deep image at 1.4 GHz made using the Australia Telescope Compact Array (Fig. 3) clearly revealed emission centered on the pulsar which is almost certainly an associated supernova remnant (Crawford et al. 2001).

Examination of the Molonglo Galactic Plane Survey (Green et al. 1999) at the positions of several other young pulsars from the Parkes multibeam survey shows radio nebulae which may be associated supernova remnants. One of the better examples is PSR J1726−3530

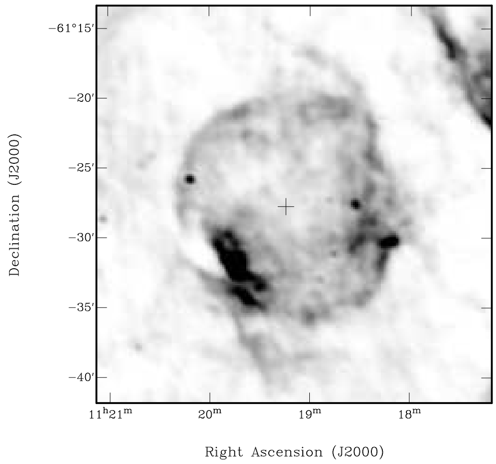

Fig. 3 (left) Image of the supernova remnant G292.2−0.5 at 1.4 GHz obtained with the ATCA. The position of the young pulsar PSR J1119−6127 is marked with a cross. (Crawford et al. 2001)

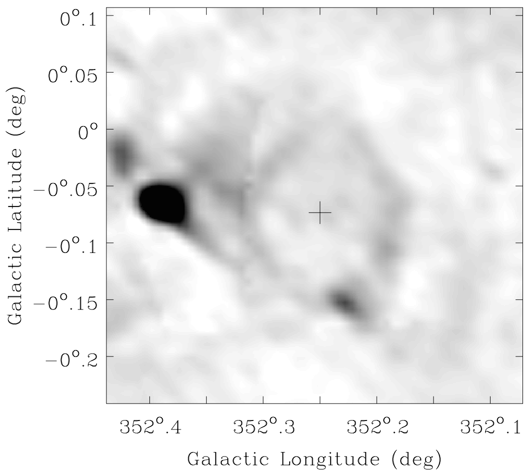

Fig. 4 (right) Image of the supernova remnant G352.2−0.1 from the 843 MHz Molonglo Galactic Plane Survey (Green et al. 1999). The cross marks the position of the young pulsar PSR 1726−3530.

which has a characteristic age of 14 kyr and a surprisingly long period of 1110 ms. As Fig. 4 shows, this pulsar is centrally located within a faint bilateral nebula. Such bilateral structures are relatively common among known supernova remnants and so it is probable that this faint nebula is a supernova remnant associated with PSR J1726−3530.

The detection by the *Chandra* X-ray observatory of an unresolved source and surrounding hard nebular emission in several well-known supernova remnants strongly suggests the presence of an energetic pulsar and surrounding pulsar wind nebula. In some of these, X-ray pulsations have been detected (e.g. Murray et al. 2002) thereby confirming the hypothesis, but in others no pulsations are detectable. This has provided a stimulus for deep radio observations in order to detect the pulsar and hence determine its properties. One such object is the supernova remnant G292.0+1.8 in which the *Chandra* image shows a region of hard emission surrounding a pointlike source about one third of the nebular radius from the center (Hughes et al. 2001). Camilo et al. (2002) made a 10-hour observation in the direction of the supernova remnant using the center beam of the multibeam receiver and analysis of these data revealed a weak 135 ms pulsar, PSR J1124−5916, with a rapid spin-down rate giving a characteristic age of 2900 years. Any doubt that this was the pulsar associated with G292.0+1.8 was subsequently removed by the detection of pulsations in the X-ray point source at the radio period.

As shown in Fig. 5, despite its youth this pulsar has a radio luminosity which is lower than that of most radio pulsars. This figure shows that there is a very wide range of radio luminosities for pulsars of all ages. Some of this is certainly due to beaming effects. Polarization properties give some information on the cut by our line of sight across the emitted beam, but these have not yet been measured for PSR J1124−5916.

With these recent detections of supernova remnants associated with young pulsars, the detection of weak radio pulsars in well-known supernova remnants and other similar discoveries in the X-ray band, the number of believable pulsar – supernova remnant associations has grown rapidly in the past few years to at least 27. For about one quarter of these, the association was first established by X-ray observations.

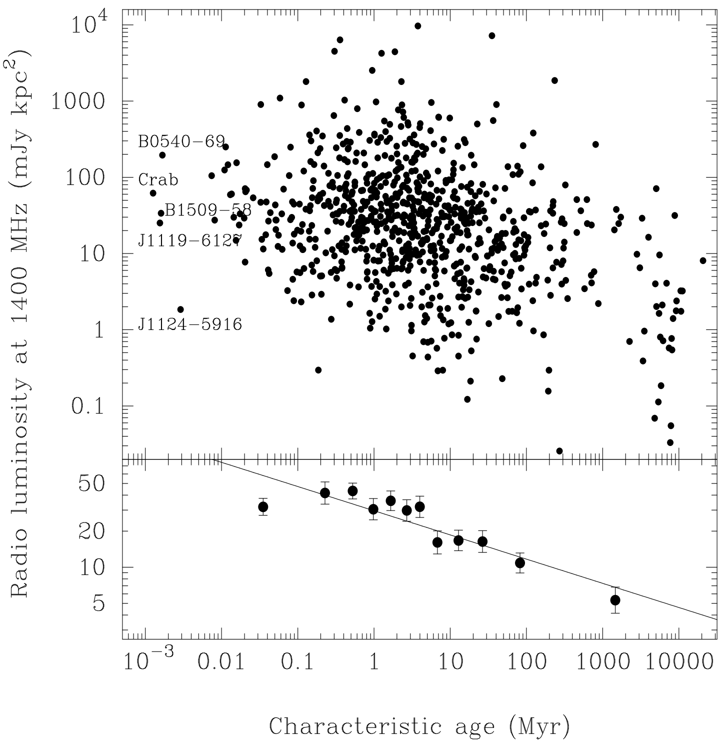

Fig. 5 Radio luminosity at 1400 MHz plotted against characteristic age for known radio pulsars. In the lower part of the figure mean values over ranges of age are plotted. (Camilo et al. 2002)

4 Pulsars in Globular Clusters

It is well known that the very dense cores of large globular clusters are an efficient breeding ground for millisecond pulsars. It is believed that exchange interactions in the cluster core result in the capture of very old and slowly rotating neutron stars into binary systems with a normal star which subsequently evolves and spins up the neutron star to millisecond periods through mass accretion (e.g. Kulkarni & Anderson 1996). The record-holder in terms of number of detected pulsars is 47 Tucanae, which now has 20 confirmed associated pulsars, all MSPs. As mentioned in the introduction, eleven of these were discovered in the period 1991 - 1995. The remainder has been found since 1998 using the central beam of the multibeam receiver (Camilo et al. 2000b). It is notable that, whereas seven of the 11 early detections are isolated pulsars, all of the recent discoveries are members of binary systems. This is largely a consequence of the use in recent searches of algorithms with improved sensitivity to pulsars in short-period binary systems and does not reflect any intrinsic difference in properties.

Accurate positions as well as proper motions, period derivatives and dispersion measures can be obtained from pulse timing measurements extending over a few years (Freire et al. 2001a). All of the known pulsars in 47 Tucanae lie within two arcmin of the cluster center, reflecting the mass segregation resulting from energy equipartition in this relaxed cluster. Measured proper motions are dominated by the motion of the cluster as a whole, rather than by the motion of individual pulsars within the cluster. The mean proper motion is close to that determined from *Hipparcos* observations of stars in the cluster (Odenkirchen et al. 1997) and now has a smaller uncertainty than that measurement.

Freire et al. (2001b) noticed the interesting correlation between period derivative and dispersion measure for pulsars in 47 Tucanae shown in Fig. 6. Observed period derivatives are dominated by acceleration of pulsars in the cluster gravitational field – those on the far side of the cluster are accelerated toward us and hence have a negative period derivative. These pulsars also have a higher than average dispersion measure, clearly indicating the presence of ionized gas in the cluster. This is the first clear detection of gas associated with a globular cluster. The total mass of gas is quite small, only about 0.1 $M_\odot$, and much less than expected on the basis of evolution of stars within the cluster. It is likely that the pulsars themselves are blowing most of the stellar-wind gas from the cluster.

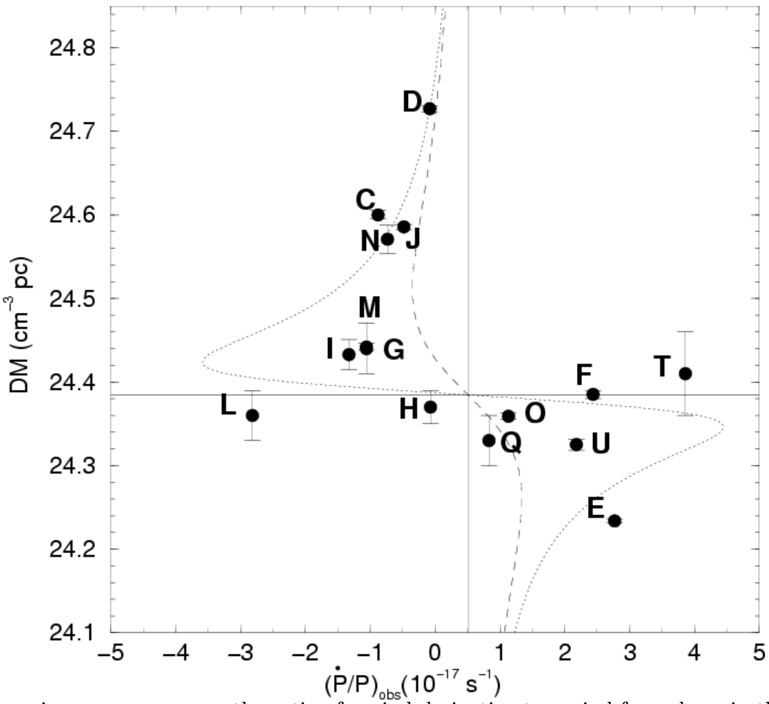

Fig. 6 Dispersion measure versus the ratio of period derivative to period for pulsars in the globular cluster 47 Tucanae. The strong correlation between these quantities indicates the presence of ionized gas within the cluster. The dotted and dashed lines indicate the expected correlation for lines of sight passing through the cluster core and 2 pc from it, respectively. (Freire et al. 2001b)

The central beam of the Parkes multibeam receiver has also been used to search for pulsars in other globular clusters. This search has recently produced dividends, with a total of 11 pulsars, all with millisecond periods and most members of binary systems, being found in four globular clusters, none of which had known associated pulsars prior to this search (D'Amico et al. 2001a, 2001b). For one of these clusters, NGC 6752, D'Amico et al. (2002) find that two pulsars lying close to the cluster core have large negative period derivatives, implying a strong gravitational acceleration toward the core. These results suggest that the mass-to-light ratio (in solar units) in the core region is greater than ten, and that the central density is $> 7 \times 10^5$ $M_\odot$ pc^{-3}. These values are more extreme than those estimated from optical measurements and suggest the presence of one or more black holes at or near the centre of the cluster core.

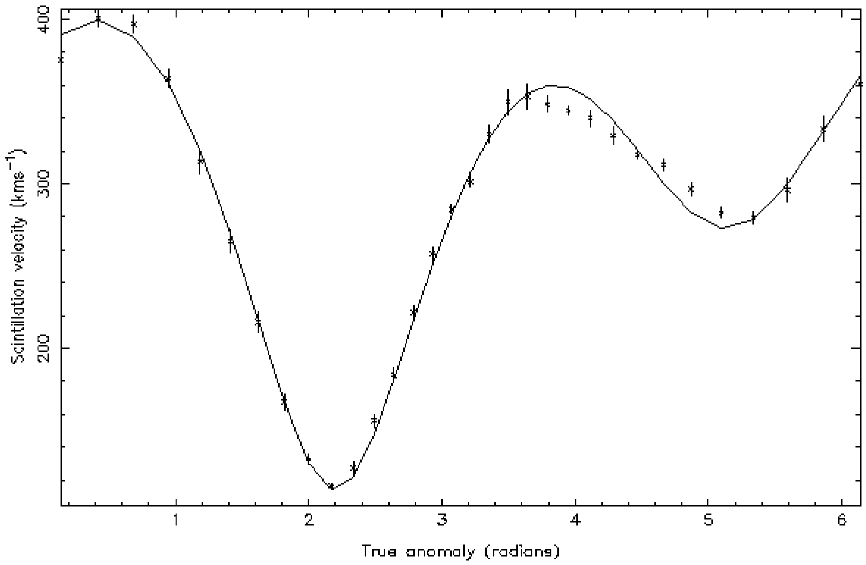

Fig. 7 Scintillation velocity for PSR J1141−6545 as a function of true orbital anomaly – slightly less than the full orbital period is shown (Ord et al. 2002).

5 Some Recent Timing and Scintillation Results

Two especially interesting recent results from Parkes observations are described here. The first concerns timing observations of PSR J0437−4715, the nearest and strongest millisecond pulsar known. The strength of this pulsar – its peak flux density is often several Jy at 1400 MHz – allows measurement of mean pulse profiles with very high signal-to-noise ratio and hence highly accurate pulse timing. Observations made over a two-year interval with a baseband recording system (van Straten et al. 2001) have given an accurate value for the annual parallax of the pulsar, 7.19 ± 0.14 mas, implying a distance of 140 pc, and the first detection of an effect known as annual orbital parallax – the change in the projected pulsar orbit diameter resulting from the annual orbital motion of the Earth. This detection allowed an accurate determination of the pulsar orbit inclination, $42^\circ.75 \pm 0^\circ.09$, and hence a prediction of the size of the Shapiro delay – the delay resulting from the gravitational bending of the ray path as it passes near the binary companion. The observations agree well with the prediction, with an rms deviation from the predicted curve of only 35 ns. These results not only provide an independent test of general relativity, but also are the most accurate pulsar timing measurements ever made.

Another nice result obtained using the same baseband observing system is the detection of an orbital variation in the timescale of diffractive interstellar scintillation in the pulsar PSR J1141−6545 by Ord et al. (2002). This pulsar, discovered in the Parkes multibeam survey, is in an eccentric binary orbit with the short period of 4.75 hours, allowing more than two complete orbits to be observed in one transit of the Parkes telescope. These showed a clear variation in the timescale for diffractive scintillation as a function of orbital phase. Modelling of the implied scintillation velocity (Fig. 7) gave measurements of the pulsar space velocity ($115\,\mathrm{km\,s^{-1}}$), the orbit inclination ($76^\circ \pm 2^\circ.5$) and the pulsar and companion masses, $1.29 \pm 0.02\,\mathrm{M}_\odot$ and $1.01 \pm 0.02\,\mathrm{M}_\odot$, respectively. The derived space velocity is lower than that expected on the basis of simulations (Tauris & Sennels 2000), suggesting that the birth kick was weaker than average.

5 Conclusions

The Parkes radio telescope has made a remarkable contribution to pulsar astronomy, especially over the past few years. Its huge successes in increasing the number of known pulsars, both in the Galactic disk and in globular clusters, are especially noteworthy. It has made significant contributions in other areas as well, such as pulsar timing and scintillation studies. The large database provided by the new discoveries opens up many opportunities for further studies.

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