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Timing the Parkes Multibeam Pulsars

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Abstract. Measurement of accurate positions, pulse periods and period derivatives is an essential follow-up to any pulsar survey. The procedures being used to obtain timing parameters for the pulsars discovered in the Parkes multibeam pulsar survey are described. Completed solutions have been obtained so far for about 80 pulsars. They show that the survey is preferentially finding pulsars with higher than average surface dipole magnetic fields. Eight pulsars have been shown to be members of binary systems and some of the more interesting results relating to these are presented.

1. Introduction

The Parkes multibeam pulsar survey is proving to be extraordinarily successful, with more than 400 pulsars discovered so far (Lyne et al. 1999; Camilo et al., this volume, astro-ph/9911185). These pulsars provide a magnificent database for many different studies related to pulsar formation and evolution, the pulse emission process and the interstellar medium. The feasibility of essentially all of these studies is dependent on knowledge of accurate positions, pulse periods and period derivatives. These parameters are normally obtained from pulse timing observations made over a period of 12 months or more. Such observations also reveal the presence of various perturbations to the period, notably the effect of orbital motion. Characterisation of such orbital motion is an important part of any timing program.

Obtaining these timing parameters for the Parkes multibeam pulsars is a major task which we share between the Parkes and Jodrell Bank observatories. We first briefly describe our observational procedures and then discuss some trends in the distribution of period derivatives from the results obtained so far. Finally we highlight some of the interesting features of the eight binary pulsars so far detected.

2. Observing and Analysis Procedures

Observations to measure the basic timing parameters of the pulsars discovered in the Parkes multibeam survey are being made using both the Parkes 64-m radio telescope of the Australia Telescope National Facility, and the 76-m Lovell Telescope of Jodrell Bank Observatory. With a few exceptions, pulsars north of declination -35° are being timed at Jodrell Bank, whereas those south of this declination are being timed at Parkes. At Parkes, the centre beam of the multibeam system is used for the timing obserations. As for the survey, a 288-MHz bandwidth centred on 1374 MHz is observed in two orthogonal polarizations; the system temperature for the centre beam at high Galactic latitudes is about 21 K. At Jodrell Bank, a 96-MHz bandwidth centred on 1376 MHz is observed with a dual-polarization receiver having a system temperature of about 30 K at high Galactic latitudes. Filterbank channel bandwidths are 3 MHz at both observatories.

At Parkes, the data are one-bit digitized and written to Exabyte tape for subsequent processing. This consists of synchronously folding the data at the topocentric pulsar period to form sub-integrations of typical duration $1-2$ minutes. These are then dedispersed and stored as archive files on disk. The same procedure is followed at Jodrell Bank, except that the folding and dedispersing are done on-line. Observing times are adjusted to give signal-to-noise ratios for final average profiles which are typically between 10 and 20. For each pulsar, profiles obtained in this way are cross-correlated with a standard template to give pulse times-of-arrival (TOAs). These are then analysed using the timing programs TEMPO (see http://pulsar.princeton.edu/tempo) or, at Jodrell Bank, PSRTIME.

Observations are made over a period of $12-18$ months following confirmation at intervals typically of $4-8$ weeks, with some more closely spaced observations to resolve pulse-counting ambiguities. These observations also reveal pulsars with unusual timing behaviours, in particular, those which are members of binary systems. These are observed more intensively to determine their characteristics.

Once a satisfactory timing solution is obtained, the pulsar is given its official Jname and the parameters are entered in the pulsar catalogue. At this time, the parameters are also made available on the Parkes multibeam pulsar survey web pages (see Bell et al., this volume, astro-ph/9911321). Timing observations for these pulsars are then discontinued except in the case of binary or other pulsars of especial interest.

3. Slow-down Rates and Implications

Full timing solutions have been obtained for about 80 of the pulsars discovered so far. Fig. 1 is a plot of period derivative versus pulse period showing the multibeam pulsars, previously known radio pulsars in the Galactic disk (i.e., excluding pulsars associated with globular clusters) and anomalous X-ray pulsars (AXPs) with known period derivatives (e.g. Mereghetti, Israel & Stella 1998). Multibeam pulsars are much more concentrated toward the top of the region occupied by 'normal' (non-millisecond) pulsars on the $P-\dot{P}$ plane. Since, on average, the multibeam pulsars are much more distant than previously known pulsars (Camilo et al., this volume), this bias indicates a correlation between spin-down rate and radio luminosity.

It is notable that the three radio pulsars with the highest known surface dipole magnetic fields have been discovered in this survey. These pulsars have surface fields in the range $(2.3 - 5.5) \times 10^{13}$ G, beyond the point where some models predict radio emission should cease (e.g. Baring & Harding 1998). In particular, the multibeam pulsar PSR J1814−1744 (pulse period 3.97 s) lies very close to the AXP 1E 2259+586 on the $P - \dot{P}$ plane. No radio emission has been detected from this AXP (Coe, Jones & Lehto 1994). This suggests that the underlying reasons why a neutron star manifests itself as a radio pulsar or as an AXP are not simply dependent on the pulsar spin period and implied surface dipole magnetic field.

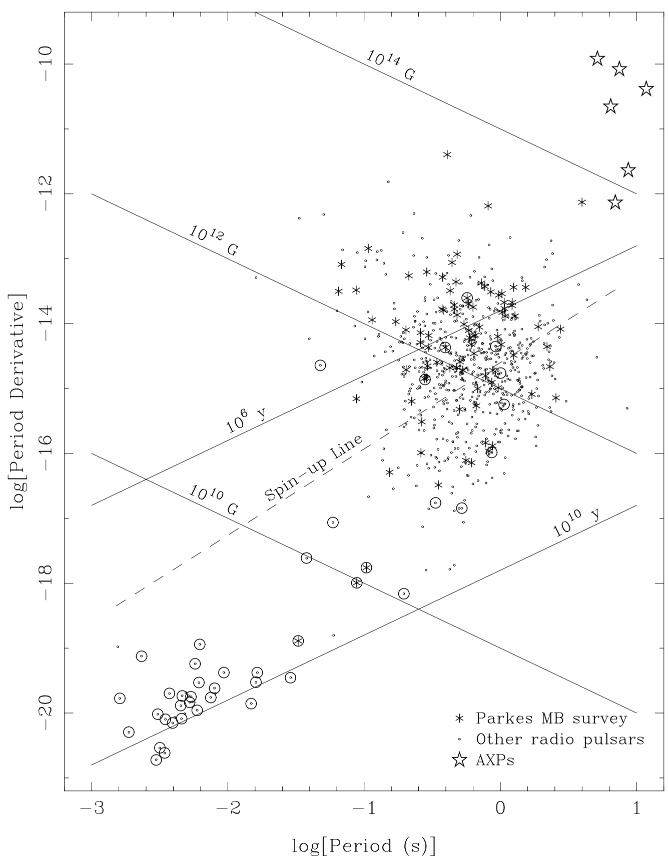

Figure 1. Plot of period derivative versus pulse period for the Parkes multibeam survey pulsars that have full timing solutions and for previously known pulsars in the Galactic disk. Pulsars that are members of a binary system are marked with a circle. The large open stars represent anomalous X-ray pulsars. Lines of constant surface dipole magnetic field and pulsar characteristic age are marked. The dashed line is the minimum period for spin-up by accretion from a binary companion (Bhattacharya & van den Heuvel 1991).

Another of these high-B pulsars, PSR J1119−6127, has the much shorter period of 0.407 s and hence is very young; its characteristic age, $\tau_c = P/(2\dot{P})$, is about 1600 years. We have already measured what appears to be a significant braking index for this pulsar, 3.0 ± 0.1. This is only the fourth measured braking index and the only one consistent with the magnetic-dipole value of 3.0. Future observations will show whether or not this value is stable and truly representative of the secular slow-down.

4. Binary Pulsars

So far, eight of the multibeam pulsars have been shown to be members of binary systems. The basic parameters for these pulsars are shown in Table 1. Distances are estimated from the dispersion measures using the Taylor & Cordes (1993) electron density model and minimum companion masses are derived from the mass function assuming a pulsar mass of 1.4 $M_\odot$. It is notable that all of these systems have relatively high-mass companions. They naturally split into three categories: low-eccentricity systems, high-eccentricity systems of intermediate mass, and high-mass systems. None of the low-eccentricity systems has a companion mass of less than 0.15 $M_\odot$ whereas about half of the previously known similar systems have minimum companion masses less than this value. Two of the multibeam pulsars have the largest known minimum companion masses for low-eccentricity systems.

Table 1. Parameters for Parkes multibeam binary pulsars

PSR J	P (ms)	τ_c (10^6 y)	Distance (kpc)	P_b (d)	Ecc.	Min. M_c ($M_\odot$)
1232−6501	88.28	1400	10.0	1.863	0.00	0.15
1904+04	71.09	–	4.0	15.750	0.04	0.23
1810−2005	32.82	4000	4.0	15.012	0.00	0.29
1453−58	45.25	–	3.3	12.422	0.00	0.88
1435−60	9.35	–	3.2	1.355	0.00	0.90
1811−1736	104.18	950	5.9	18.779	0.83	0.87
1141−6545	393.90	1.45	3.2	0.198	0.17	1.01
1740−3052	570.31	0.36	10.8	231.039	0.58	11.07

The next category of binary system, with high eccentricity and companion mass about 1 $M_\odot$, has two members in the multibeam sample. The first, PSR J1811−1736, has all the hallmarks of a double neutron-star system (Lyne et al. 1999). It has a very large characteristic age, suggesting a history of recycling, a moderately long pulse period, high eccentricity and parameters consistent with a 1.4 $M_\odot$ companion. The other system, PSR J1141−6545, only recently discovered, is superficially similar, but has some important differences. Its orbital period is very short, only 4.8 h. An accurate position has been obtained for the pulsar using the Australia Telescope Compact Array and this has allowed a measurement of the period derivative from the $\sim$ 5-week data span presently available. Significantly, the characteristic age is relatively short at $\sim$ 1.5 My. We

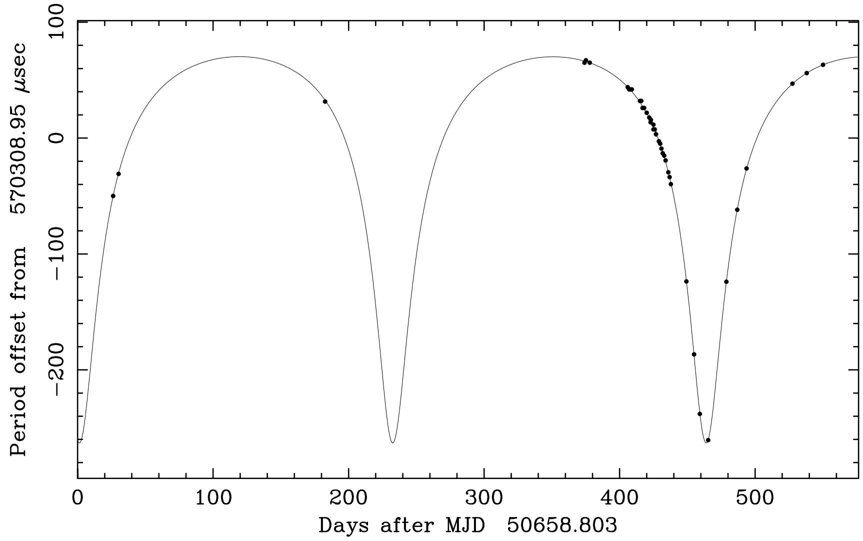

Figure 2. Period variations for PSR J1740−3052 over a 500-day interval. Observed points are marked by dots; the period uncertainty is less than the size of the dot. The smooth curve represents a fit to the data of an orbit with period of 231 days.

have also already obtained a significant measurement of the orbital precession, 5.5±0.4 °/y, the highest known value. If general relativistic precession is the only significant effect, this implies a total mass for the system of $2.4 \pm 0.2 M_\odot$. These are certainly preliminary results, but they suggest that the companion may be a heavy white dwarf, similar to the PSR B2303+46 system (van Kerkwijk & Kulkarni 1999), rather than a neutron star.

The final system in the list, PSR J1740−3052, is distinguished by its very massive companion, with a minimum mass $\sim 11 M_\odot$. As Fig. 2 shows, the orbit is highly eccentric. The very large mass restricts the possible types of companion star to a massive 'normal' (i.e. non-degenerate) star or a black hole. We are currently attempting to determine which of these two possiblities is correct. Unfortunately, the pulsar lies at low Galactic latitude within 2.2° of the Galactic Centre, and is probably at least as distant. Optical searches are therefore futile, even for an O-B star. We have obtained infrared K-band images of the region using the 2.3-m telescope at Siding Spring Observatory and the 3.9-m Anglo-Australian Telescope which show that the pulsar is coincident within $0\rlap{.}''4$ with a star having a K-band magnitude of about 11. Infrared spectra of the star are consistent with its being a K5 supergiant, which could be sufficiently massive to be the pulsar companion. They also show Brackett-γ in emission, which suggests irradiation of the star, for example, by a pulsar companion.

However, if this star is the companion, it is surprising that there is no evidence for any eclipse of the pulsar emission – the pulsar passes within 1.25 nominal stellar radii at periastron. Fig. 2 shows that the pulsar was detectable at several times very close to periastron passage. We plan further observations to search for the expected effects of a close encounter of the pulsar with a supergiant companion.

5. Conclusions

The Parkes multibeam pulsar survey is living up to its promise. It is finding large numbers of pulsars, many of which are young and hence especially interesting for studies of neutron star evolution and related topics. It is also finding some very interesting binary pulsars, the study of which will have a significant impact on our understanding of binary and stellar evolution. The survey is currently only about 50 per cent complete and timing solutions have been obtained for only about 15 per cent of the expected final complement of pulsars. We certainly hope and expect that many more interesting and important objects will be uncovered by this survey.

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