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Binary and Millisecond Pulsars

Abstract

Recent surveys for millisecond pulsars (MSPs) have been exceptionally productive. In particular, the recently completed Parkes southern survey discovered 17 MSPs in the Galactic disk. Results from this survey are reviewed. Precision timing results for the strongest MSP discovered in the survey, PSR J0437−4715, are described. For MSPs, the kinematic or 'Shklovskii' contribution to the period derivative is often a significant fraction of the observed period derivative, and its effect on computed ages and magnetic fields is discussed. Observed correlations between orbital period, orbital eccentricity and companion mass for binary pulsars are described.

I Introduction

Of the approximately 750 pulsars known, 73 are either members of a binary (or higher order) system or have periods in the millisecond range, defined here to be less than 30 ms, and 37 have both these properties. Of these pulsars, 28 are members of a globular cluster system. These very close relationships, well illustrated by the Venn diagram of Figure 1, strongly support the idea that millisecond pulsars are 'recycled' by mass transfer in a binary system and resultant spin-up of an old and moribund neutron star (Bhattacharya & van den Heuvel 1991, Phinney & Kulkarni 1994). Pulsars of this type are preferentially found in globular clusters because the dense cores of these clusters provide significant opportunities for an evolved star or binary system to capture a passing neutron star and subsequently to spin it up (Sigurdsson & Phinney 1995).

The study of binary and millisecond pulsars is undoubtedly the most interesting and exciting area of current pulsar research. Millisecond pulsars are extraordinarily good clocks, with a stability rivalling that of the best terrestrial clocks (Rawley et al. 1987, Kaspi, Taylor & Ryba 1994). The presence of these objects in binary systems allows the detection of many subtle effects, and these effects often have significant implications. Important examples are the verification of Einstein's general theory of relativity and detection of the effects of gravitational radiation in the PSR B1913+16

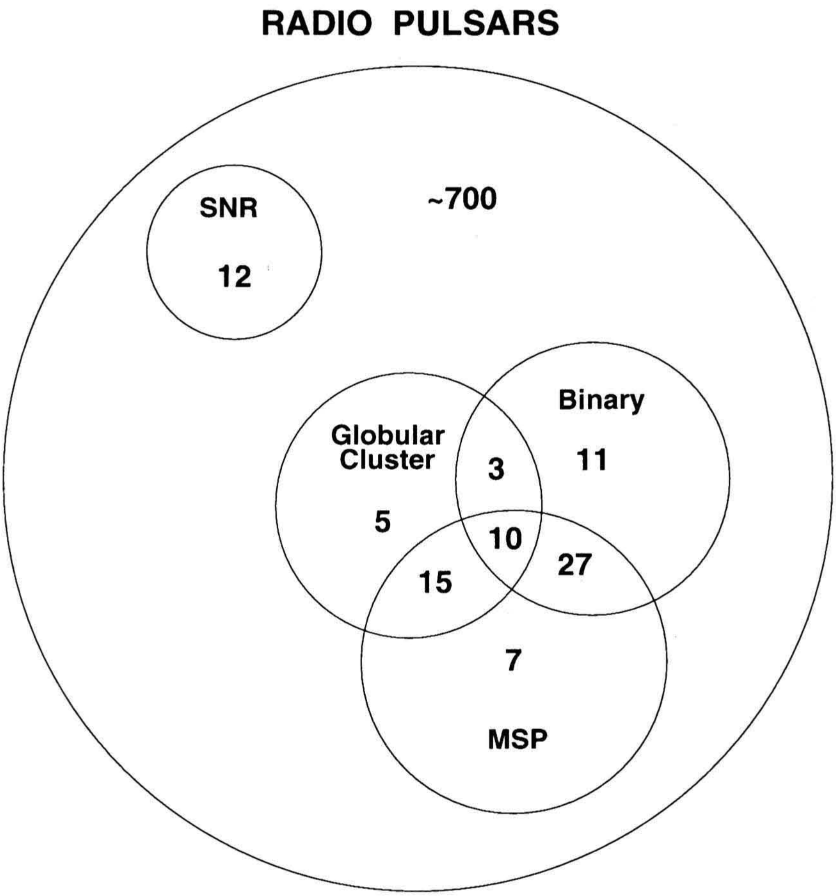

Figure 1. Venn diagram for radio pulsars showing the close relationship between binary, millisecond and globular-cluster pulsars.

system (Taylor et al. 1992) and the first detection of extra-Solar-system planets (Wolszczan & Frail 1992, Wolszczan 1994).

In this review, I first give a brief description of the recently completed Parkes southern pulsar survey, and describe some results from timing studies of pulsars detected in the survey. In Section 3, I describe some general properties of the observed population of binary and millisecond pulsars. I do not discuss in any detail the two known pulsars with massive binary companions, PSR B1259−63 and PSR J0045−7319, as these are the subject of separate presentations at this Colloquium by Simon Johnston and Vicky Kaspi, respectively.

II The Parkes Southern Survey

The Parkes southern survey was a large-scale survey of the entire southern sky for millisecond and other low-luminosity pulsars made using the Parkes 64-m radio telescope. The project was a collaboration, with the ATNF and the University of Manchester, Jodrell Bank, as principal partners. A total of nearly 45,000 beam positions were observed for about 2.5 min each. The observing frequency was 436 MHz with 256 channels across the 32-MHz bandwidth. After summing orthogonal polarizations, each channel was one-bit sampled every 0.3 ms and the data recorded on Exabyte tape. Work-station networks at the ATNF, Jodrell Bank and the Istituto di Radioastronomia del CNR, Bologna, were used to process the data; more than 600 512K-point FFTs were required for each beam position. The survey was very successful, detecting a total of 298 pulsars, including 19 millisecond pulsars. Of these, 17 millisecond pulsars and 84 'long-period' pulsars were new discoveries. Twelve of the new millisecond pulsars are members of binary systems but, so far, none of the new long-period pulsars has been shown to be binary. A more detailed description of the survey system and results from the first half of the survey are given by Manchester et al. (1996). Results from the second half of the survey and implications of the survey results for the Galactic population of pulsars are described by Lyne et al. (1998).

Figure 2 shows the clearly bimodal period distribution of the new discoveries and of all pulsars detected in the survey. The new discoveries have a much higher proportion of millisecond pulsars, reflecting the fact that most of the southern sky had not been effectively searched for this class of pulsar. This is also shown by the extraordinary discovery of PSR J0437−4715 (Johnston et al. 1993), by far the strongest millisecond pulsar known, which was detected with a signal-to-noise ratio of 510, far above the limiting value of 7.5.

Figure 3 shows the distribution of the newly discovered pulsars in Galactic coordinates. The long-period pulsars are clearly concentrated toward the Galactic equator, but the distribution of the millisecond pulsars is close to isotropic over the search area. There are several reasons for this difference. As Figure 4 shows, the detected millisecond pulsars have a much smaller range of dispersion measure (DM) than the long-period pulsars and hence are, on average, closer to the Sun. This is partly a result of sensitivity – few millisecond pulsars were detected with a DM greater than 50 cm^{-3} pc, where the instrumental broadening was two sample intervals or 0.6 ms. It is also partly a result of the generally low luminosity of millisecond pulsars – they are difficult to detect at large distances. The third factor that is important in accounting for this difference is the long lifetime of millisecond pulsars. With active lifetimes often in excess of 10^9 yr (Camilo, Thorsett & Kulkarni 1994), millisecond pulsars have plenty of time to move away from the Galactic plane.

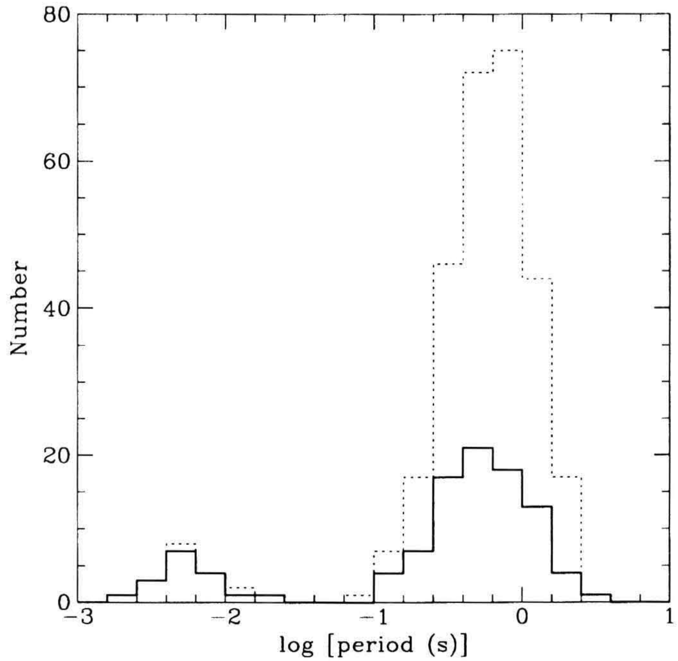

Figure 2. Period distribution of pulsars discovered in the Parkes southern survey (full line) and all pulsars detected by this survey (dotted line).

PSR J2051−0827 — an eclipsing binary pulsar

One of the more interesting pulsars discovered in the Parkes southern survey is PSR J2051−0827. This pulsar has a pulse period of 4.5 ms and is a member of a binary system with the very short orbital period of 2.38 h (Stappers et al. 1996). The companion is a low-mass white dwarf which is evidently being ablated by the pulsar wind, creating a gaseous envelope which, at least at low radio frequencies, eclipses the pulsar every orbit. At 1.4 GHz, the pulsar can frequently be seen through the whole orbital period. There are substantial variations in the column density of electrons in the eclipsing plasma both as a function of orbital phase for one orbit, and at the same orbital phase on different orbits (Stappers et al. 1996). Typical column densities are $\sim 4 \times 10^{17}$ cm^{-2} which, for reasonable values of outflow velocity, correspond to mass-loss rates $\sim 10^{-14}$ M$_\odot$ yr^{-1}. Even though the companion mass is only ~ 0.03 M$_\odot$, it is clear that mass loss at this rate is never going to destroy the companion.

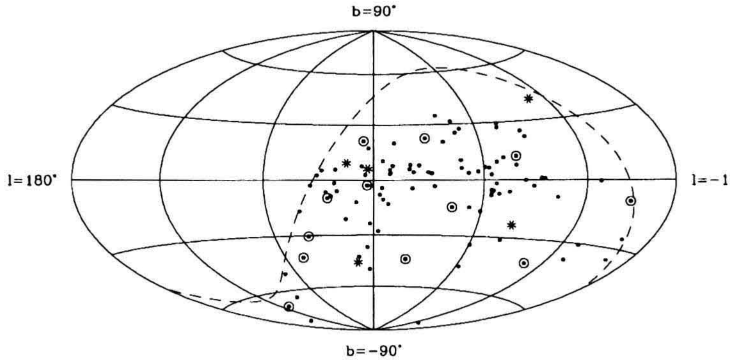

Figure 3. Galactic distribution of the 101 pulsars discovered in the Parkes southern survey. Binary MSPs are marked by $\odot$ and single MSPs by $*$. The dashed line is the celestial equator and the northern limit of the survey.

Either substantial mass loss occurs in the form of neutral gas or in directions not traversed by the line of sight to the pulsar. If neither of these possibilities is true, ablation is not a viable mechanism for creating single millisecond pulsars.

PSR J0437−4715 — recent timing results

As part of a collaborative program with Shri Kulkarni and his group at Caltech, the Caltech correlator (Navarro 1994) has been used at Parkes to obtain timing data for PSR 0437−4715 from 1994 January to 1996 August. For these observations, the correlator system recorded two bands, each of width 128 MHz and normally centered at 1410 and 1660 MHz. Auto-correlation functions were folded with 1024 bins across the period for 90 s and then transferred to a work-station for subsequent processing. After transforming to the frequency domain, the data were dedispersed and pulse times of arrival (TOAs) computed by cross-correlation with a standard template. Over the 2.5 yr, a total of nearly 5000 TOAs were recorded. Times were referred to UTC(NIST) using GPS links.

TOAs were analyzed using TEMPO (Taylor & Weisberg 1989) and the DE200 Solar system ephemeris (Standish 1990). The position of PSR J0437−4715 relative to the DE200 reference frame is determined to a precision of about 50 micro-arcsec. This allows a precise determination of the proper motion of the system, which is quite large, ~ 140 mas yr^{-1} (Bell et al. 1995a) and, more importantly, a significant measurement

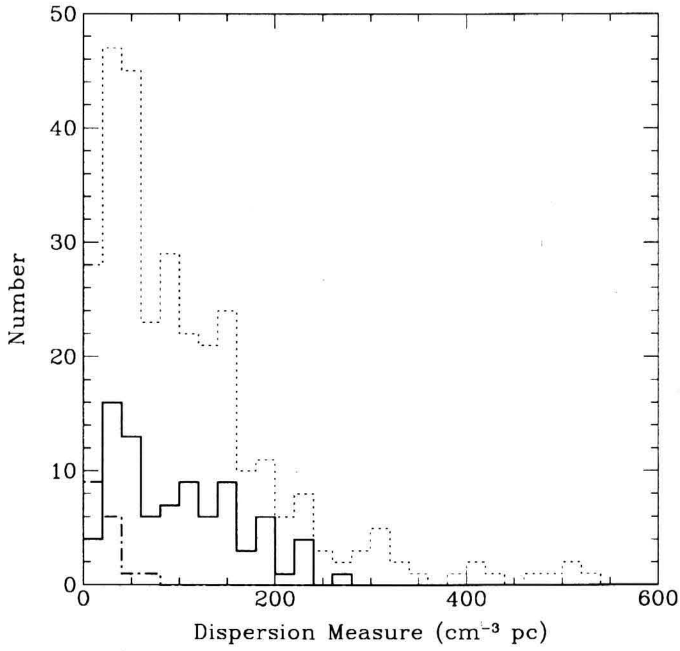

Figure 4. Distribution in dispersion measure of newly discovered millisecond pulsars (dot-dash line), long-period pulsars (full line) and all pulsars detected in the Parkes southern survey (dashed line).

of the annual parallax. The derived value, 5.6 ± 0.8 mas, corresponds to a distance of 180 ± 25 pc. This compares with 140 pc based on the DM and the Galactic electron density model of Taylor & Cordes (1993).

As was first described in the context of pulsars by Shklovskii (1970), the changing Doppler shift resulting from transverse motion of the pulsar makes a positive contribution to the observed period derivative,

$$\begin{aligned} \dot{P}_s &= \frac{P\mu^2 d}{c} \\ &= 2.43 \times 10^{-27} \left(\frac{P}{\rm ms}\right) \left(\frac{\mu}{\rm mas\ yr^{-1}}\right)^2 \left(\frac{d}{\rm pc}\right) \end{aligned}$$

where P is the pulsar period, μ is its proper motion and d is the pulsar distance. Actually, this kinematic effect has been known for a long time in classical astronomy as *secular acceleration* – the first reference given by van de Kamp (1981) is to Bessel (1844)! If we assume that the observed period derivative for PSR J0437−4715 is entirely due to this kinematic effect, we can place an upper limit on the distance of 204 pc, consistent with the parallax distance. Alternatively, if we take the parallax distance as correct, the kinematic effect contributes 85% of the observed period derivative and the intrinsic period derivative is very small, $\sim 7 \times 10^{-21}$. The implied surface magnetic field is also very small, $B_0 \sim 2 \times 10^8$ G, and the characteristic age is very large, $\tau_c \sim 2.5 \times 10^{10}$ yr.

As pointed out by Bell & Bailes (1996), the changing Doppler shift also affects the binary orbital period. If the expected intrinsic orbital period derivative is negligible (as is the case for the PSR J0437−4715 system), then a further and potentially accurate distance estimate can be obtained from the observed orbital period derivative. For PSR J0437−4715, $\dot{P}_b = (5.3 \pm 0.9) \times 10^{-12}$, giving a distance in the range 180 to 255 pc, also consistent with the parallax value.

The large proper motion of the system has another observable effect: the plane of the orbit remains fixed in space as the system moves across the sky, but our view of it changes. This change in orbit inclination angle i results in a change in the projected semi-major axis of the pulsar orbit $x \equiv a_p \sin i$. The observed value of $\dot{x} = (8.0 \pm 0.4) \times 10^{-14}$ sets a limit on $\cot i$ (Kopeikin 1996) and implies $i < 43°$ and a companion mass $m_2 > 0.2$ $M_\odot$.

After fitting for these parameters, the final rms residual was 500 ns. While this is close to the best timing precisions so far obtained (e.g., Kaspi et al. 1994), it is many times the formal TOA uncertainties based on the cross-correlation analysis. With further observations and the elimination (or at least reduction) of remaining systematic errors, there is potential for refining these results and detection of even more subtle effects.

These results and their implications are discussed in more detail by Sandhu at this Colloquium and by Sandhu et al. (1997).

III The binary and millisecond pulsar population

Over the past few years, there has been a large increase in the number of known millisecond and binary pulsars, especially in the Galactic disk. Mostly as a consequence of this, there has also been an increase in the number of pulsars with significant measurements of parameters such as proper motion and orbital eccentricity. This allows a more thorough examination of various correlations suggested on the basis of either empirical evidence or models for stellar or binary evolution.

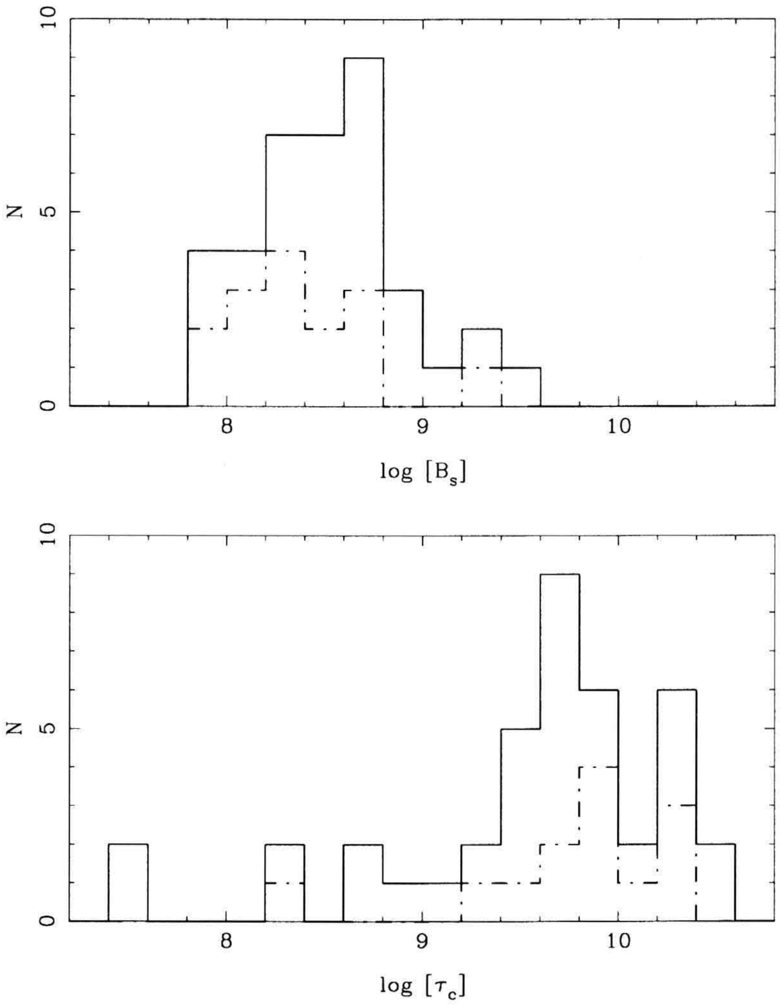

Figure 5. Distributions of dipole surface magnetic field B_s and characteristic age τ_c for millisecond pulsars ($P < 30$ ms). For pulsars with known and significant proper motions, the intrinsic period derivative $\dot{P}_i$ has been used to compute B_s and τ_c. The distributions for those pulsars where this correction has been made are marked with dot-dash lines.

Intrinsic period derivatives

As mentioned above, the 'Shklovskii' or kinematic term makes a positive contribution $\dot{P}_s$ to the observed period derivative, $\dot{P}$. When computing characteristic ages and surface magnetic fields, the intrinsic period derivative, $\dot{P}_i = \dot{P} - \dot{P}_s$ should be used. This correction is especially important for MSPs because of their small $\dot{P}$; it is significant for a few longer-period pulsars, but it makes an insignificant contribution to the observed period derivative. Distributions of B_0 and τ_c for MSPs are plotted in Figure 5 showing that many have weak surface magnetic fields, $\sim 10^8$ G, and characteristic ages of greater than 10^{10} yr. The low magnetic fields have implications for pulse emission models and the large characteristic ages have implications for stellar and binary evolution. In particular, the large characteristic ages, many greater than the age of the Galaxy, mean either that magnetic fields of isolated or non-accreting binary pulsars decay on timescales of gigayears or that many millisecond pulsars are born with periods not too much less than their current value. In turn, this latter conclusion would mean that many millisecond pulsars are born (or reborn) with periods well below the conventionally defined spin-up line (Bhattacharya & van den Heuvel 1991). Even ignoring the more radical alternative, that millisecond pulsars are formed directly and not by spin-up in an accreting binary system (e.g., Michel 1987), there are many assumptions in the definition of the spin-up line (Ghosh & Lamb 1992, Arons 1993) and hence considerable room for movement in it.

Binary evolution

Probably the clearest of the various relationships between binary parameters is the correlation between orbital eccentricity and orbital period for binary systems with low-mass white dwarf companions (Phinney 1992, Phinney & Kulkarni 1994). For these systems, if the companion was a red giant filling its Roche lobe during the spin-up phase, there is a coupling between convective instabilities in the red-giant envelope and the orbital motion. The predicted relationship between orbital eccentricity and orbital period agrees well with recent discoveries and improved measurements (Figure 6), confirming that Roche-lobe overflow was indeed the spin-up mechanism. Systems with companions of intermediate mass, most likely CO white dwarfs, have followed a different evolutionary path, probably involving common-envelope evolution and spiral-in (van den Heuvel 1994). All of the high-mass systems have high eccentricity. Two of them (PSRs J0045−7319 and B1259−63) have main-sequence companions and at least four and probably all six of the others are double-neutron-star systems. Eccentricities are generally higher for systems in globular clusters, reflecting interactions with other cluster stars (Phinney 1993).

As first pointed out by Joss, Rappaport & Lewis (1987), if Roche-lobe overflow is maintained during spin-up, then a relationship is expected between the final orbital period and the final mass of the companion star. This relationship was further refined by Rappaport et al. (1995). Figure 7 shows the current correlation between these two quantities.

Pulsars with CO white-dwarf companions lie well to the right of the line, reflecting their different evolutionary history as mentioned above. There is now a significant

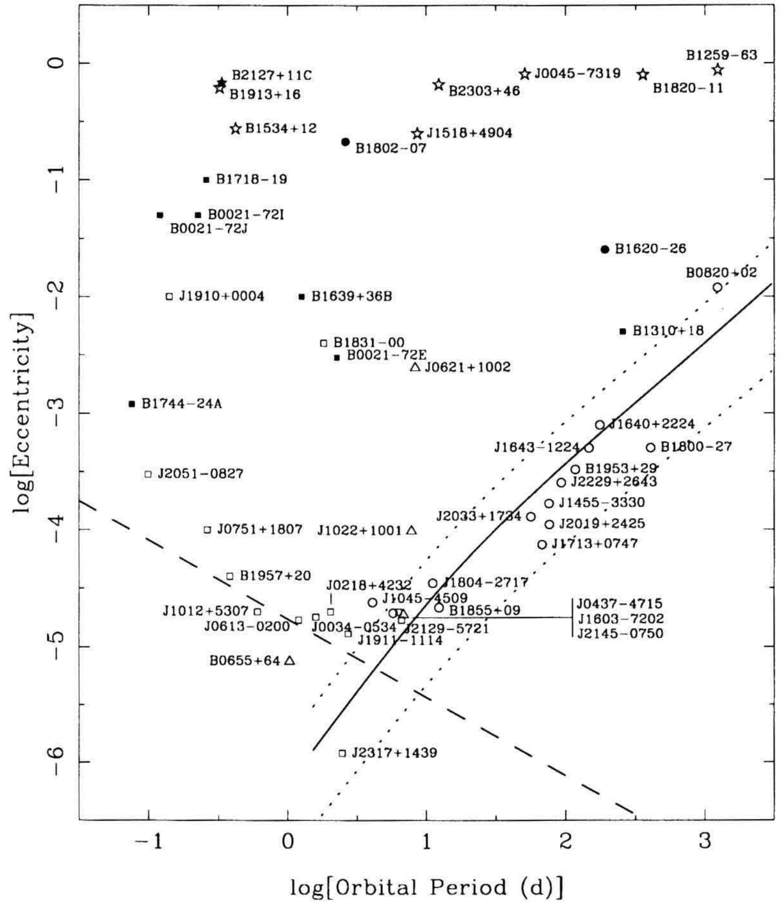

Figure 6. Orbital period versus orbital eccentricity for known binary pulsars. Systems with low-mass white dwarf companions are marked with a circle, other low-mass companions by squares, intermediate-mass companions by a triangle and high-mass companions by a star. Upper limits on the eccentricity are marked by a square. Systems in globular clustersre marked by filled symbols. The approximate limit on eccentricity for pulsars with TOA uncertainties of 10 μs is indicated by the dashed line. (After Bell et al. 1997)

group of pulsars with long orbital periods which lie well to the left of the line. It is statistically unlikely that all of these pulsars have the low inclination angles necessary to allow them to fit on the predicted correlation.

Fig. 7 also shows that the orbital-period 'gap' at around 50 d, first mentioned by Camilo (1995), persists with the latest data. This suggests that it represents a real difference in evolutionary paths. A possible mechanism is discussed by Tauris (1996).

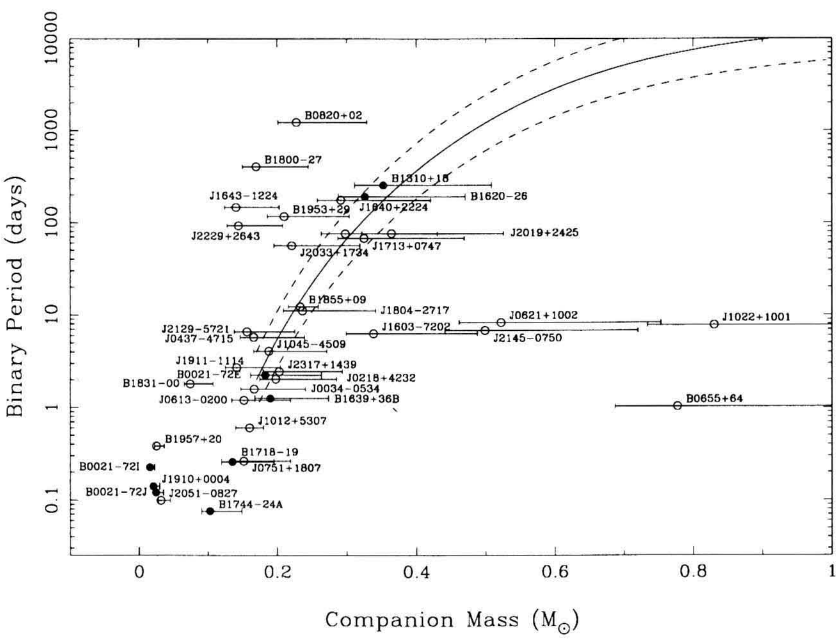

Figure 7. Binary period versus companion mass for binary pulsars. For all pulsars except PSR B1855+09 (Ryba & Taylor 1991) and PSR J1012+5307 (van Kerkwijk, Bergeron & Kulkarni 1996) where direct measurements of companion mass exist, error bars are plotted for $1 - \cos i = 0.2$ and 0.8, that is, the points where the probability of an inclination less than i is 20% and 80% respectively. The line is the predicted relationship according to Rappaport et al. (1995), valid for companion masses $\gtrsim 0.2$ $M_\odot$.

IV Conclusions

Recent discoveries of binary and millisecond pulsars have greatly enriched the subject of pulsar astronomy and astrophysics. With planned surveys and follow-up observations of both newly discovered and previously known pulsars, many new and interesting results can be expected in the next few years.

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