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The Population of Binary and Millisecond Pulsars

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Abstract. Recent searches for millisecond and binary pulsars are reviewed, with particular emphasis on the nearly complete Parkes southern survey. Correlations between several of the major parameters of these systems are discussed.

1. Introduction

One of the most exciting developments in astronomy in recent years has been the discovery of binary and millisecond pulsars. The first binary pulsar discovered was the famous double-neutron-star system, PSR B1913+16, found by Hulse & Taylor (1975) at Arecibo. The first millisecond pulsar, PSR B1937+21, with its spin period of 1.55 ms, still the fastest known pulsar, was discovered by Backer et al. (1982), also at Arecibo. There are now a total of 39 binary pulsars and 45 millisecond pulsars (defined to be those with period less than 25 ms) known. Of these, 27 have both a millisecond period and a binary companion, so the connection between the two classes is very close. It is generally believed that millisecond pulsars acquire their very short periods by accreting mass and angular momentum from a binary companion; see Bhattacharya & van den Heuvel (1991) for a review. The cores of dense globular clusters are a favourable environment for formation of such binary systems, and just over half of the known millisecond pulsars, 24 to be exact, are found within globular clusters.

These pulsars have proven to be a rich harvest. They provide much information on the formation and evolution of binary systems and especially binary X-ray sources, the evolution of globular cluster systems and the internal structure of neutron stars. The extraordinary stability of pulsar periods, especially in these millisecond pulsars, has made possible a wide range of significant studies. Most prominent are the verification of Einstein's general relativity and the associated detection of the effects of gravitational radiation in the PSR B1913+16 and similar systems by Taylor and his co-workers (Taylor & Weisberg 1989; Taylor et al. 1992). Another important result is the first detection of an extra-solar planetary system (Wolszczan & Frail 1992; Wolszczan 1994). Studies of millisecond pulsars have the potential to establish a long-term standard for terrestrial time, to improve our knowledge of solar-system dynamics and to detect a primordial background of gravitational radiation.

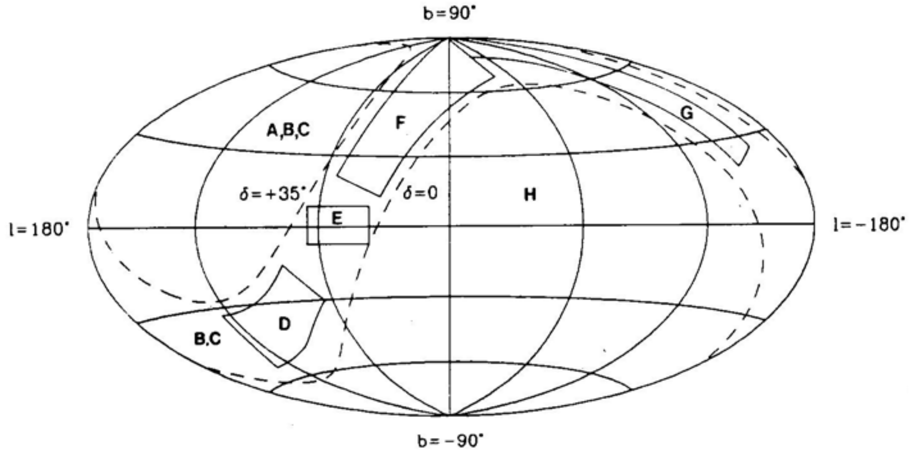

Figure 1: Sky coverage of the principal surveys sensitive to millisecond pulsars in Galactic coordinates. The dashed lines at declinations 0 and +35° delineate the approximate boundaries of the region visible to the Arecibo telescope.

2. Searches

To achieve these aims and make further progress on other studies we require a large sample of millisecond and binary pulsars which are well distributed across the celestial sphere. Over the past few years a number of very successful pulsar searches have been carried out. All of these searches have been at radio wavelengths and, since millisecond pulsars are relatively weak sources, have used large instruments, particularly the Arecibo and Parkes radio telescopes. The searches are of two types: those directed at globular clusters and those covering large areas of sky, searching for pulsars in the Galactic disc. Figure 1 shows the sky coverage of the main large-area surveys currently under way or recently completed. All of these surveys use sampling intervals close to 0.3 ms, and so are sensitive to pulsars with periods of a few milliseconds or more. Codes for the different surveys marked in Figure 1 are as follows:

- A – Jodrell Bank northern survey, 408 MHz, $\delta > +35°$
- B – Princeton/NRAO Green Bank survey, 370 MHz, $\delta > 0°$
- C – Princeton Cambridge survey, 80 MHz, $\delta > 0°$
- D – Princeton Arecibo survey, 430 MHz

Table 1. Millisecond pulsars discovered in recent searches (except the Parkes southern survey)

PSR J	Pulse Period (ms)	Binary Period (d)	Min. Comp. Mass ($M_\odot$)	Survey	Ref.
0024−72N	3.05	–	–	–	1
0218+4232	2.32	2.03	0.16	–	2
0751+18	3.48	0.26	0.12	–	3
1015+53	5.26	0.60	0.11	A	4
1640+22	3.16	175	0.30	F	5
1713+0747	4.57	67.82	0.28	F	6
2019+2425	3.93	76.51	0.32	E	7
2229+2643	2.98	93.02	0.12	D	8
2317+1439	3.44	2.46	0.18	D	9
2322+2057	4.81	–	–	D	7

Refs. 1. Robinson et al. (Submitted to MNRAS, 1994) 2. Navarro (1994) 3. Lundgren et al. (1993), Lundgren (1994) 4. Lyne (Unpublished, 1994) 5. Wolszczan (Unpublished 1994) 6. Foster et al. (1993) 7. Nice et al. (1993) 8. Camilo (Unpublished, 1994) 9. Camilo et al. (1993)

- E – Princeton Arecibo low-latitude survey, 430 MHz
- F – Penn State/ NRL Arecibo survey, 430 MHz
- G – Caltech Arecibo survey, 430 MHz
- H – ATNF/Jodrell Bank/Bologna Parkes survey, 436 MHz, $\delta < 0°$

The Jodrell Bank northern survey, using the Lovell 76-m telescope, started about a year ago and, as shown in Table 1, has discovered one millisecond pulsar so far. Parameters of the survey are similar to those of the Parkes southern survey, with a limiting flux density of approximately 3 mJy at long periods. The Princeton group is undertaking two surveys covering the whole northern sky; both started about a year ago. The first uses the 43-m telescope at Green Bank, while the second uses the 80-MHz Cambridge array with a somewhat more sophisticated data analysis system than was used to find the original pulsars. So far these two surveys have yet to yield positive results. The sky visible to Arecibo has been divided into several sections, with different groups searching each section. Because of the huge collecting area of Arecibo, these searches have very good sensitivity, with a minimum detectable flux density of < 1 mJy, but they take a long time to cover a given area of sky because of the small beam area. They have been very successful, so far discovering six millisecond pulsars, as listed in Table 1.

Three pulsars in Table 1 were not discovered in large- area surveys. PSR J0024– 72N was discovered in our continuing observations of the globular cluster 47 Tucanae (cf. Manchester et al. 1991) and is the 11th pulsar known in the cluster. It is not a member of a binary system. PSR J0218+4232 was discovered by the Caltech, Leiden and Jodrell Bank groups, based on observations at Westerbork at 327 and 1400 MHz which revealed a highly polarized and steep-spectrum point source. It is notable that this is only the third pulsar discovered in this way, despite several intensive searches following the discovery of the first millisecond pulsar, PSR B1937+21, by this method. (The second was the millisecond pulsar in M 28; Lyne et al. 1987) Finally, PSR J0751+18 was discovered at Arecibo in a search of error boxes of unidentified gamma-ray point sources from the EGRET survey. As with the other Arecibo searches, this search was at 430 MHz, but it was somewhat more sensitive with a limiting flux density of about 0.5 may. It now seems unlikely that this pulsar is associated with a gamma-ray source (D. J. Thompson, private communication).

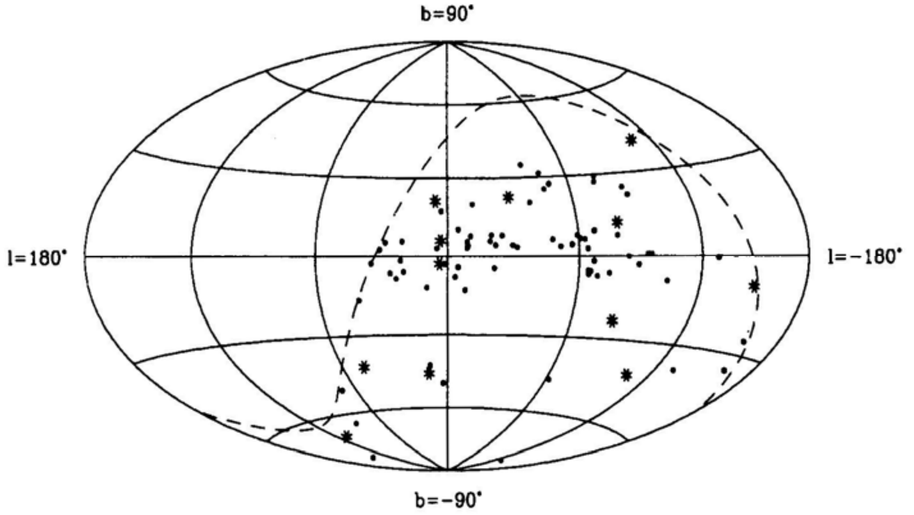

Figure 2: Positions in Galactic coordinates of pulsars discovered so far in the Parkes southern pulsar survey. The dashed line is declination 0^0, the northern limit of the survey. Millisecond pulsars are marked with an asterisk, others with a filled circle.

In May 1991, observations for a major survey of the southern sky for millisecond and low-luminosity pulsars began at the Parkes 64-m telescope. This survey is a collaboration between groups at the Australia Telescope National Facility, the University of Manchester, Jodrell Bank, and the Istituto di Radioastronomia del CNR, Bologna. The observing frequency is 436 MHz, and there are a total of 44,000 beam positions in the survey. Each point is observed for 2.5 minutes giving a limiting sensitivity of about 3 mJy. Currently, the survey is about 80% complete and a total of 12 millisecond pulsars and 82 ‘ordinary’ pulsars have been discovered. Table 2 lists the millisecond pulsars, showing that eight of the 12 are members of low-mass binary systems. Perhaps the most notable is PSR J0437–4715, which is by far the strongest and closest millisecond pulsar known. It has a white dwarf companion which has been optically identified and also an associated Hα bowshock nebula (Bell et al. 1993). One of the slower pulsars, PSR J0108–1431, is probably the closest known neutron star (Tauris et al. 1994).

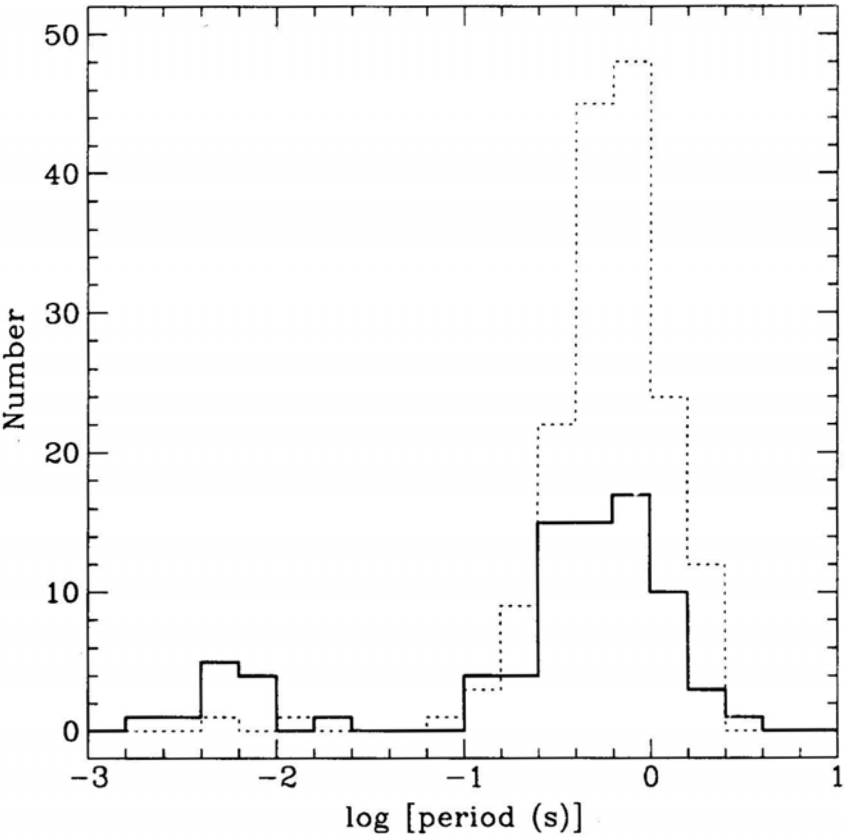

Figure 3: Period distribution for pulsars detected in the Parkes southern survey; thick line – new discoveries, dashed line – previously known pulsars.

The distribution on the sky of the pulsars discovered so far in the Parkes southern survey is shown in Figure 2. Ordinary pulsars are concentrated near the Galactic equator, but the distribution of the millisecond pulsars is essentially isotropic. Most are relatively close to the Sun, within 1 kpc. For both populations the Galactic *z*-distribution has a scale height of about 600 pc, although, especially for the millisecond pulsars, this is likely to be reduced by flux density selection.

Figure 3 shows the distribution in period of both the newly discovered pulsars and the previously known pulsars detected in the survey. This distribution is clearly bimodal. It is worth noting that the ratio of millisecond to ordinary pulsars is much greater for the new pulsars than for the old.

After considering the selection effects inherent in these surveys, Lorimer et al. (1994) estimate that there are at least 40,000 millisecond pulsars with radio luminosity greater than 2.5 mJy kpc^2 in the Galaxy. The known sample is therefore a very small part of the total.

Table 2. Millisecond Pulsars discovered in the parkes southern survey

PSR J	Pulse Period (ms)	Binary Period (d)	Min. Comp. Mass ($M_\odot$)	Ref.
0034−0534	1.88	1.58	0.14	1
0437−4715	5.75	5.74	0.14	2
0613−0200	3.06	1.20	0.13	3
0712−68	5.49	–	–	4
1025−07	5.16	–	–	4
1045−4509	7.47	4.1	0.16	1
1455−3330	7.97	78.1	0.26	3
1643−1224	4.62	149.3	0.12	3
1730−2304	8.12	–	–	3
1804−27	9.34	11.1	0.20	4
2124−33	4.93	–	–	4
2145−0750	16.05	6.83	0.43	1

Refs. 1. Bailes et al. (1994). 2. Johnston et al. (1993). 3. Lorimer et al. (1994) 4. Unpublished

Table 3. Globular cluster pulsars

Cluster	–	PSR B	Nr of Pulsars	Nr of MSPs	Nr of Binaries
M 28	–	1821−24	1	1	–
M 4	–	1620−26	1	1	1
M 15	–	2127+11	8	4	1
M 13	–	1639+36	2	2	1
M 53	–	1310+18	1	–	1
M 5	–	1516+02	2	2	1
47 Tuc	–	0021−72	11	11	4+
NGC 6440	–	1745−20	1	–	–
Terzan 5	–	1744−24	1	1	1
NGC 6624	–	1820−30	2	1	–
NGC 6539	–	1802−07	1	1	1
NGC 6760	–	1908+00	1	1	1
NGC 6342	–	1718−19	1	–	1

As mentioned in the Introduction, just over half of the known millisecond pulsars are found within globular clusters. Well over half of these are found in just two clusters, M 15 and 47 Tucanae. References to these discoveries are given in the Taylor et al. (1993) pulsar catalogue. Table 3 lists the known globular cluster pulsars, showing the number of millisecond and binary pulsars in each cluster. This table illustrates the fact that, although M 15 and 47 Tucanae are similar in harbouring a large number of detectable pulsars, the characteristics of these pulsars are quite different.

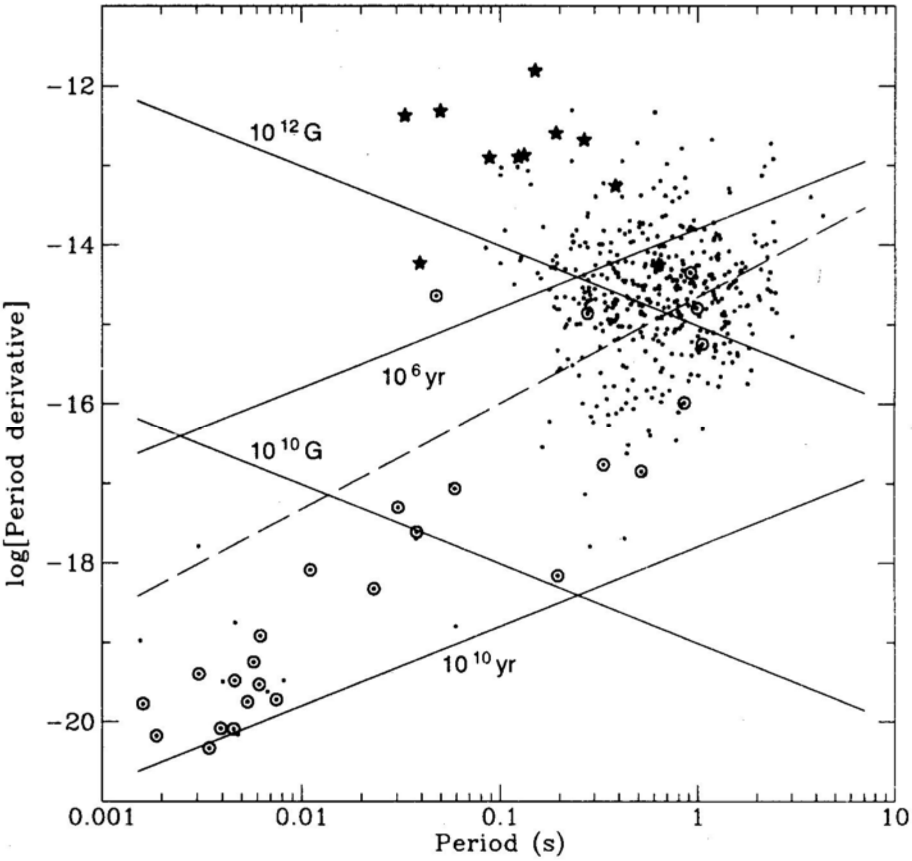

Figure 4: Plot of pulsar period derivative versus pulse period. Pulsars associated with supernova remnants are marked with a ★ and those which are members of a binary system are marked with an ⊙. Lines of constant surface magnetic field and constant characteristic age are marked. The dashed line is the so-called 'spin-up' line, which is the limiting period for pulsars being spun up by accretion from a binary companion.

3. Properties

Millisecond pulsars are not only characterized by their short period. As shown in Figure 4, the rate at which this period is changing, the period derivative ($\dot{P}$), is typically five orders of magnitude smaller than that for ordinary pulsars. Since a pulsar's 'characteristic age', $\tau_c = P/(2\dot{P})$, is an upper limit to the true age, this implies that millisecond pulsars may be very old. Optical observations of white dwarf companions (Kulkarni 1986; Bell et al. 1993) confirm that at least some millisecond pulsars have ages in excess of 1 Gyr. The small period derivative also implies that the magnetic field at the surface of the neutron star, which is proportional to$(P\dot{P})^{1/2}$, is very small, typically 10^8 G compared to 10^{12} G for an ordinary pulsar.

The pulsars associated with supernova remnants are grouped in the top-left corner of the diagram and are therefore young. If they evolve with constant magnetic field (as is believed to be the case) they will move down to join the pulsar 'pool' centred at about $P = 0.6$ s and $\dot{P} = 10^{-15}$. The millisecond pulsars clearly do not form by simple ageing of young pulsars. Intervention by some agency is required to give them their short period (and probably also their weak magnetic field; Shibazaki et al. 1989). The fact that most of these pulsars are binary and also that almost all of them lie below and not too far from the spin-up line strongly suggests that they are spun up by accretion from a binary companion. It is notable that most of the millisecond pulsars with periods shorter than 10 ms lie closer to the 10^{10} yr line (also known as the Hubble line) than to the spin-up line. This suggests that they were born with spin periods not too different from those they presently have. This conclusion is reinforced by the fact that a significant fraction of the observed period derivative may be kinematic in origin (Camilo et al. 1994), making the pulsar characteristic ages even greater. The intermediate period pulsars (period between 10 and 100 ms) lie closer to the spin-up line. This group includes the neutron star – neutron star binaries such as PSR B1913+16, which have a lifetime limited by gravitational decay of their orbits.

Three binary pulsars lie above the spin-up line. Two of them (PSR B1259–63, $P = 47$ ms, $\dot{P} = 2.3 \times 15^{15}$, and PSR J0045–7319, $P = 926$ ms, $\dot{P} = 4.5 \times 10^{15}$) are in eccentric orbits with massive main-sequence companions (Johnston et al. 1994; Kaspi et al. 1994) and are almost certainly in a pre-spin-up phase. The other, PSR B1820–11 ($P = 279$ ms, $\dot{P} = 1.4 \times 10^{15}$) also has an eccentric orbit, but has a companion of lower mass (Lyne & McKenna 1989). The nature of the companion and the evolutionary history of the system are unclear.

Figure 5 shows binary period versus pulsar period for all known binary pulsars with established orbital parameters; this figure is analogous to that plotted by Corbet (1984) for X-ray binary pulsars. Several different groupings of pulsars are apparent in this diagram. Those with elliptical orbits tend to have longer pulse periods but cover a wide range of orbital period. The existence of an elliptical orbit implies substantial mass loss and/or a kick to the neutron star at birth and also the absence of an orbit circularization phase in subsequent evolution. Systems with neutron-star companions are quite tightly bunched at low orbital periods – they have evolved from high-mass binary systems and their evolution is reasonably well understood (Bhattacharya & van den Heuvel 1991). The two systems with

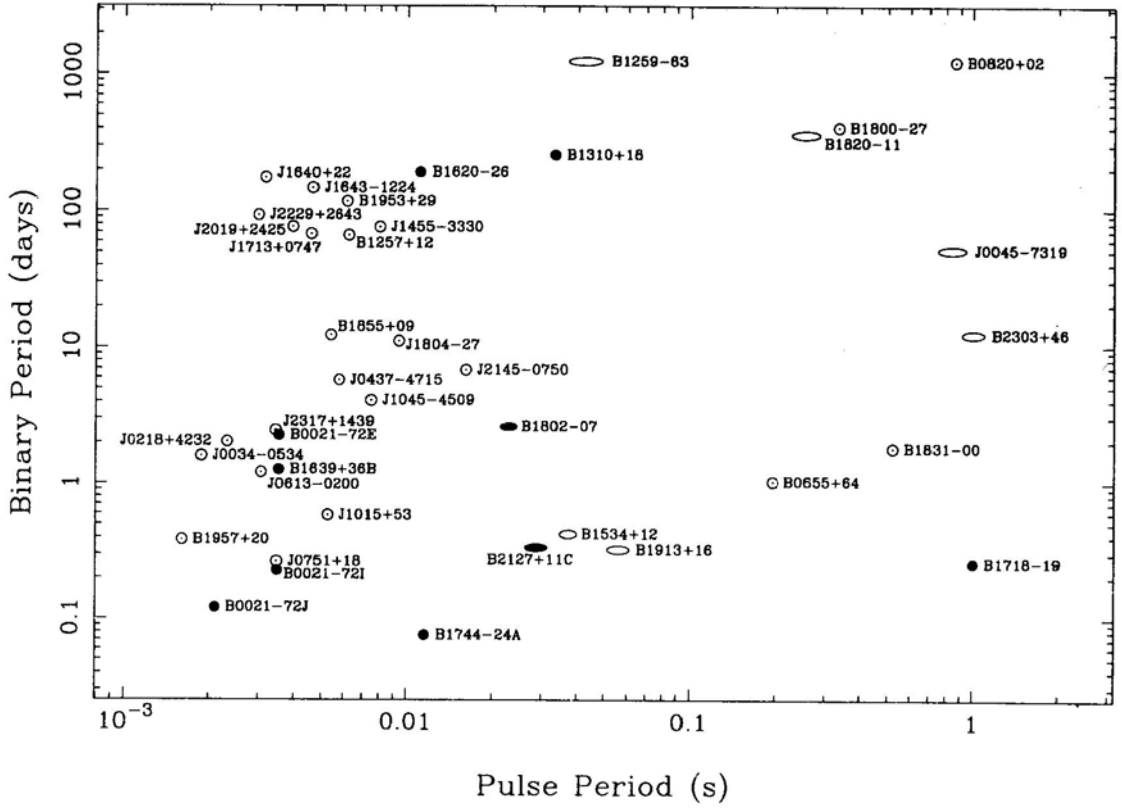

Figure 5: Plot of binary period versus pulsar period for all known binary sytems. Systems with near-circular orbits ($e < 0.05$) are plotted with a circle and those with more elliptical orbits are represented by an ellipse of the appropriate eccentricity. For systems associated with a globular cluster, the symbol is filled.

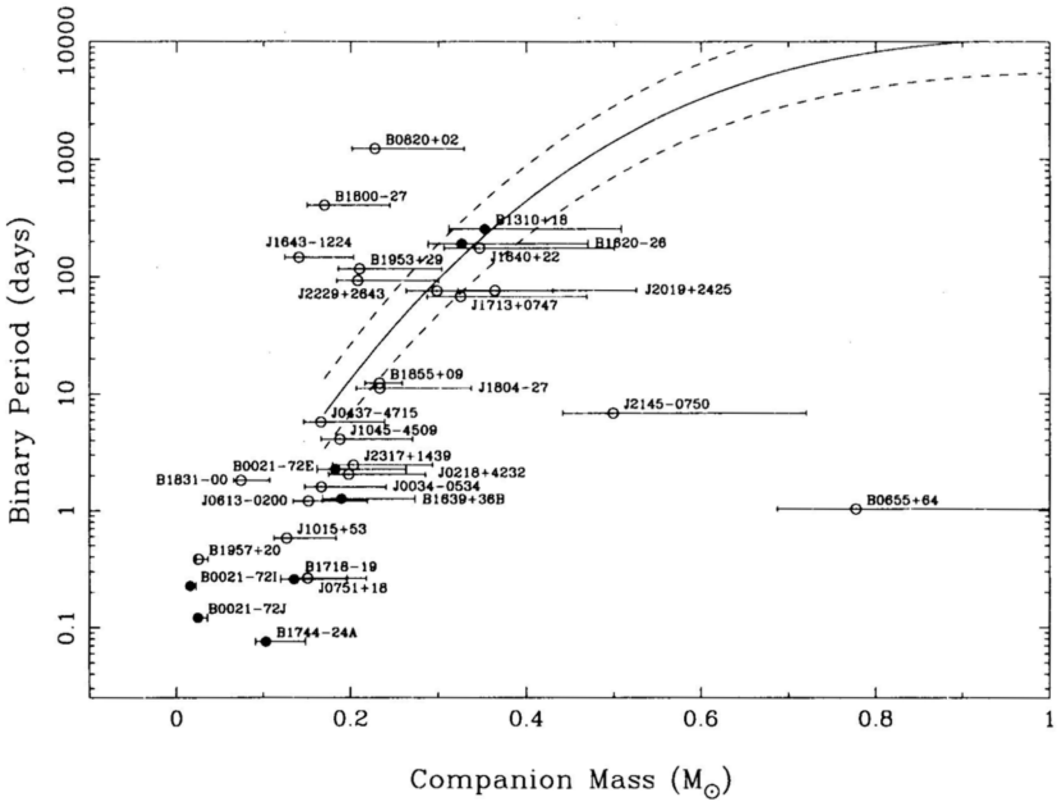

Figure 6: Orbital period versus companion mass for binary pulsars with near-circular orbits ($e < 0.05$). Systems associated with globular clusters are marked with a filled circle. For all except PSR B1855+09 (Ryba & Taylor 1991), the mass limits are plotted for $1 - \cos i = 0.2$ and 0.8, that is, the points where the probability of an inclination less than i is 20% and 80% respectively.

Main-sequence companions have long orbital periods and high eccentricity. PSR B1259–63 is eclipsed at periastron and so similar systems with shorter and more circular orbits would be hard to detect, but this is not true for PSR J0045–7319.

Systems with circular orbits generally have low-mass companions and are believed to have been circularized during a spin-up or accretion phase. If this accretion is due to Roche-lobe overflow from a companion, one expects a correlation between orbital and pulsar period as the accretion phase is shorter for wide systems. Such a correlation is seen, at least for orbital periods of less than 30 days or so, supporting the idea that these pulsars are old neutron stars which have been 'recycled' by the accretion process. It is not clear if this correlation extends to the very long period systems such as PSR B0820+02. There is now also a substantial group at orbital periods of about 100 days, above the so-called 'period gap' (Camilo 1994) and these also may evolve differently. Collapse of a high-mass white dwarf as a result of accretion (e.g. Helfand et al. 1983) provides an alternative formation mechanism for these systems.

Another plot relevant to the discussion of evolution of millisecond pulsars is shown in Figure 6. As first pointed out by Joss et al. (1987), if these systems evolve by Roche-lobe overflow, then a relation is expected between the final orbital period and companion mass. Since the size .of the companion's Roche lobe is dependent on its mass, the orbital period must decrease as the companion mass decreases to maintain the system in Roche lobe overflow. With a few exceptions, the observed companion masses are broadly in agreement with the theoretical relation. Joss et al. modelled stars to 0.17 $M_\odot$ only, but in fact the relation appears to extrapolate quite well to lower masses. PSRs J2145–0750 and B0655+64 clearly do not lie on the expected curve, suggesting that these two systems evolved in a different way. For example, van den Heuvel & Taam (1984) suggest that the neutron star in such systems spirals into the envelope of a giant star, ejecting the envelope and terminating the accretion phase. Several of the low-mass, long-period systems such as PSR B1800–27 appear to be significantly off the theoretical line. These systems may be formed in some other way (e.g. accretion-induced collapse) or may spiral out farther than predicted by the standard models.

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