The population of black widow pulsars

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ABSTRACT
We consider the population of black widow pulsars (BWPs). The large majority of these are members of globular clusters. For minimum companion masses \( < 0.1 \, M_\odot \), adiabatic evolution and consequent mass loss under gravitational radiation appear to provide a coherent explanation of all observable properties. We suggest that the group of BWPs with minimum companion masses \( \gtrsim 0.1 \, M_\odot \) are systems relaxing to equilibrium after a relatively recent capture event. We point out that all binary millisecond pulsars (MSPs) with orbital periods \( P \lesssim 10 \, \text{hr} \) are BWPs (our line of sight allows us to see the eclipses in 10 out of 16 cases). This implies that recycled MSPs emit either in a wide fan beam or a pencil beam close to the spin plane. Simple evolutionary ideas favour a fan beam.

Key words: binaries: close

1 INTRODUCTION
It is widely believed that most millisecond pulsars (MSPs) are spun up by accretion from a close binary companion. This recycling (Radhakrishnan & Srinivasan, 1981) can only take place when the neutron star magnetic field has decayed to a value \( \sim 10^8 \, \text{G} \). If accretion subsequently stops for some reason, the neutron star appears as a millisecond pulsar with a very low spin-down rate, as its low magnetic field makes dipole radiation very weak.

In line with these ideas a large proportion of millisecond pulsars are members of binary systems. Often these pulsars undergo very wide eclipses, with an obscuring object much larger than the companion star’s Roche lobe. This must be an intense wind from the companion star, driven in some way by the pulsar emission (Fruchter et al., 1988). Whenever such eclipses are seen the binary eccentricity and the pulsar mass function are extremely small, implying companion masses \( M_2 \lesssim M_\odot \). There is another group of binary millisecond pulsars with systematically lower mass functions, and it is natural to assume that these are also evaporating systems with orbital inclinations which prevent us seeing the eclipses (Freire et al., 2001).

In a recent paper (King et al. 2003; hereafter KDB) we pointed out that the incidence of black widow pulsars (BWP) is far higher in globular clusters than in the field. We identified a favoured formation mechanism for BWPs in globulars in which turnoff–mass stars exchange into wide binaries containing recycled millisecond pulsars (MSPs) and eject their helium white dwarf companions. Once angular momentum loss or nuclear expansion bring the companion into contact with its Roche lobe the pulsar is able to expel the matter issuing through the inner Lagrange point \( L_1 \). Thus mass is lost on the binary evolution timescale. BWPs are observable only when this evolution and thus the mass loss are slow.

Here we consider the consequences of this picture for the subsequent evolution of BWPs. Our main aim is to understand the distribution of BWPs in the plane of minimum companion mass \( M_{\text{min}} \) and orbital period \( P \) (Fig. 1).

2 POPULATION OF LOW–MASS BWPS
BWPs appear to fall into two distinct groups which we shall call high–mass and low–mass, depending on whether \( M_{\text{min}} \gtrsim 0.1 \, M_\odot \). The high–mass group have noticeably more irregular eclipses than the low–mass group (e.g. Scott Ransom, talk at the Aspen Meeting on Binary Millisecond Pulsars in January 2004).

In the standard way we may associate with these two groups other binary MSPs which do not eclipse but whose values of \( M_{\text{min}} \) are even smaller than those of the eclipsing systems. The interpretation is that these are BWPs seen at low orbital inclination. With this association the distribution of Fig. 1 puts the dividing line between high– and low–mass BWPs at \( M_{\text{min}} \sim 0.05 \, M_\odot \).

We consider the low–mass group first. The small secondary mass (close to \( M_{\text{min}} \) for eclipsing systems) implies a thermal time much longer than the binary evolution timescale for mass loss causing BWP behaviour. The star therefore reacts adiabatically. As it is either fully convective or degenerate we can model approximately it as an \( n = 3/2 \) polytrope, with radius

\[
R_2 \simeq 10^9 (1 + X)^{5/3} m_2^{-1/3} \, \text{cm}
\]

(cf e.g. King 1988; for more accurate representations see Nelson & Rappaport, 2003). Here \( m_2 = M_2 / M_\odot \), \( X \) is the fractional hydrogen content, and \( k \gtrsim 1 \) measures the deviation from the fully–degenerate radius given by \( k = 1 \). We assume that low–mass BWPs

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have a range $1 < k \lesssim 3$ for reasons we will discuss in the next section. Assuming a Roche-lobe filling donor gives the mass-period relation

$$m_2 = 1.5 \times 10^{-2} (1 + X)^{3/2} T_6^{3/2} P_h^{-1}$$

(2)

where $P_h$ is the orbital period measured in hours. We assume further that loss of orbital angular momentum via gravitational radiation (GR) drives orbital evolution, so that

$$M_2 \frac{3(1+q)}{2 - 3\beta + q} \frac{\dot{J}_{\text{GR}}}{J}$$

(3)

where $q = M_2 / M_1$, $M_1 \approx 1.4 M_\odot$ is the pulsar mass, and $\beta$ is the specific angular momentum of the lost mass relative to that of the secondary (van Teeseling & King 1998). Thus

$$\beta = \left( \frac{b}{a} \right)^2 (1 + q)^2$$

(4)

where $a$ is the binary separation and $b$ is the distance from the centre of mass at which the matter is ejected from the binary. This is between the circularization radius of the infalling matter and the $L_1$ point. As all BWPs have $M_2 \ll M_1$, $\beta < 2/3$ except for very small $q$ (see below) the first term on the right hand side of (3) is 3/2 and we can rewrite (3) as

$$M_2 = 1.9 \times 10^{-10} P_h^{-8/3} m^{2/3} m_{0.1}^{12} \text{M}_\odot \text{yr}^{-1}$$

(5)

where $m = (M_1 + M_2) / M_\odot$ and $m_{0.1} = m_2 / 0.1$. According to KDB the system is only visible as a BWP if this rate is less than the critical value

$$M_{\text{crit}} = 1.5 \times 10^{-12} P_h T_6^{3/4} \text{M}_\odot \text{yr}^{-1}$$

(6)

for free–free absorption at typical (400 – 1700 MHz) observing frequencies, where $T_h \sim 1$ is the temperature of the lost mass near $L_1$ in units of $10^6$ K. The resulting constraint

$$P_h \gtrsim 3.7 T_6^{-9/4} m^{-2/11} m_{0.1}^{6/11}$$

(7)

is plotted on Fig. 2 as ‘Visibility line’.

In a similar way we can plot various other constraints on this figure. For very small mass ratios $q = M_2 / M_1$ the $\beta$ term in the denominator of (3) becomes significant. This signals dynamical instability, as the Roche lobe moves inwards wrt the stellar surface (cf Stevens, Rees & Podsiadlowski, 1992). At such masses the companion must be broken up and sheared into a large disc surrounding the pulsar. This is presumably the origin of the planets observed around PSR B1257+12 (Wolszczan & Frail 1992; Konacki & Wolszczan 2003). Direct numerical calculation of $b$ from Roche geometry shows that dynamical instability occurs when $M_2 / M_1 < 0.02$ if matter is ejected from the $L_1$ point. However, matter can be ejected from anywhere between the $L_1$ point and the circularization radius (which even for small mass ratios is not comparable with the distance to the $L_1$ point). If matter reaches in 5 per cent of the distance from the centre of mass to the $L_1$ point this gives $M_2 / M_1 = 0.011$ i.e. $m_2 = 0.016$. This line is labelled ‘Dynamical Instability’ on Fig. 2. We also plot the line (‘Hubble line’) on which the binary evolution has a characteristic timescale longer than a Hubble time. Finally we plot the binary evolution of a system whose secondary is fully degenerate (‘Degenerate’) and one whose radius is 3 times as large for the same mass ($k = 3$) as given by equation (4). Arrows on the degenerate sequences indicate the direction of evolution.

If this is a viable picture of the evolution of low–mass BWPs, we expect them to have combinations of $P, M_2$ lying inside the various constraints shown in Fig. 2. Given that eclipsing systems (solid circles) have $M_2 \approx M_{\text{min}}$ while non–eclipsing systems have $M_2 > M_{\text{min}}$, we see that the data plotted on Fig. 2 are indeed reasonably consistent with adiabatic evolution under mass loss driven by gravitational radiation.

Figure 1. A plot of log period in hours versus log minimum companion mass for all the binary MSPs in globulars. Filled circles denote eclipsing systems and open circles non–eclipsing systems.

Figure 2. A plot of log period in hours versus log minimum companion mass for all the BWPs in globulars along with the evolutionary constraints as described in the text for the low-mass systems. Also labelled is the longest period BWP PSR J1740–5340 which has a sub-giant companion.
3 HIGH-MASS BWPS

We now consider the remaining systems on Fig. 1, i.e. those with $M_{\text{min}} \gtrsim 0.05 M_\odot$. Nelson (talk at the Aspen Meeting on Binary Millisecond Pulsars in January 2004) has studied the evolution of the long-period system J1740–5340, which has a subgiant companion (D’Amico et al. 2001; Ferraro et al. 2001) and shown that it is consistent with a location near a bifurcation point, at which nuclear evolution and angular momentum loss are comparable. The remaining 4 systems have $P \lesssim 5$ hr and $M_{\text{min}} \lesssim 0.13 M_\odot$. Except for implausibly small orbital inclinations these companions have main–sequence radii far too small to fill their Roche lobes. There are various ways around this difficulty, including competition between nuclear and orbital evolution, or attributing the eclipses to strong stellar winds of detached companions. However the most likely explanation appears to us to follow from the turbulent history these binaries must have had.

The process of gaining a new companion must involve considerable disturbance to that star, probably leading to extensive mass loss. This is clearly indicated for tidal capture (Podsiadlowski 1996), but is probably true in any picture. For an exchange encounter to give a short period system a large post–exchange eccentricity is required (see section 4). When this eccentric system circularizes the tidal effects on the secondary can in some cases be similar to tidal capture if the periastrom distance is comparable to the stellar radii. The globular–cluster X–ray binary AC211 (van Zyl et al. 2004; Charles, Clarkson & van Zyl 2002, and references therein) may be an example where the companion star is oversized because of the capture process, the only difference being that the neutron star in this system accretes the overflowing matter rather than expelling it, presumably because no previous partner recycled it. For an exchange encounter the lowest mass star is ejected and so the captured star, in a high–mass BWP formed through this route, must have lost a significant portion of its initial mass. This mass loss, however, occurs during the tidal circularization (not afterwards) and so the companion could still be thermally bloated.

After the tidal disturbance and consequent mass loss, the companion attempts to reach its new main–sequence radius on a thermal timescale. This process competes with orbital shrinkage via GR and reduces the mass loss (already weak – cf equation 5) for the relatively long orbital periods of most of this group). It is therefore plausible that BWPs ultimately emerge from the tidally induced mass loss with the parameters of the high–mass BWPs. The thermal timescale of some of these BWPs may be less than the GR timescale and so eventually these would shrink from contact with their Roche lobes. However, they would still be observed as high–mass BWPs for the length of their thermal timescale.

If the companion has a sufficiently strong stellar wind, this can produce orbital eclipses through free–free absorption. This appears to happen in PSR 1718–19 (Wijers & Paczyński 1993; Burderi & King 1994). Here $P \approx 6$ hr, and modelling of the absorption light curve (Burderi & King 1994) shows that $M_2 \sim 0.2 M_\odot$. We note that PSR 1718–19 is probably a cluster member (Wijers & Paczyński 1993) and that the stellar wind must be the eclipsing agent as the pulsar is not an MSP, and thus incapable of driving mass loss.

Although the companion must relax towards the main sequence, its radius ultimately shrinks only slowly, whereas orbital shrinkage via GR accelerates. Depending on the initial separation, the binary reaches contact with the companion somewhat oversized compared with its thermal–equilibrium radius. This is probably the origin of the range of radii ($k$–values) inferred for low–mass BWPs above.

Grindlay (talk at Aspen Meeting on Binary Millisecond Pulsars in January 2004) has found 108 X-ray sources in the globular cluster 47 Tuc. A number of these are claimed to be quiescent low–mass X-ray binaries (LMXBs) and have measured periods from X-ray dips/eclipses (eg W37 at 3 hrs), power law components (possibly from a wind) and variable absorption. These may be BWPs, rather than quiescent LMXBs, where the absorption is too large to observe the radio emission and the stellar wind is responsible for the X-ray emission.

4 FAN OR PENCIL BEAM?

Fig. 1 reveals the striking fact that all binary MSPs with orbital periods $P \lesssim 10$ hr are BWPs: 10 out of 16 actually eclipse. There are two obvious possible explanations for this:

(a) Fan beam. The pulsar beam of a recycled MSP is so wide that it always includes the orbital plane, whatever the relative orientation of spin and orbit. For a wide fan beam such systems are detectable at any spin inclination. Then all binary MSPs become BWPs as soon as their companions fill their Roche lobes.

(b) Pencil beam. The beam of a recycled MSP is narrowly confined. Clearly the only plausible geometry for making BWPs has the beam axis orthogonal to the spin, with the latter roughly aligned with the binary orbit.

It is quite difficult to break the degeneracy between these two possibilities. However the pencil beam requires alignment, and thus that the pulsar has accreted $\gtrsim 0.1 M_\odot$ from its current companion. This requires it to have been an LMXB and then somehow broken contact, and seems harder to reconcile with the picture of high–mass BWP evolution we have sketched above. We thus tentatively conclude that a fan beam offers a simple explanation for the universality of eclipsing behaviour in MSPs with short orbital periods.

5 DISCUSSION

It is generally agreed that dynamical encounters must be invoked to explain the overproduction of BWPs in globular clusters (KDB; Rasio et al. 2000). Rappaport, Putney & Verbunt (1989) considered the problem of exchanging out the white dwarf companion of the neutron star in a binary MSP. Their Fig. 1 shows that the timescale (in 47 Tuc) for ejecting the white dwarf from systems with periods of 10, 100 and 1000 days is $\sim$10, 3, and 1 Gyr, respectively. Thus an exchange encounter is likely only for orbital periods $\gtrsim 30$ days. The post–exchange period is generally not substantially shorter, and most of these systems would not become BWPs. However the post–exchange eccentricity is unevenly distributed in $e^2$ (Heggie 1975). For large $e^2$ tides circularize the orbit at much tighter separations than the initial post-exchange value. The post-exchange period after tidal circularization can thus be much shorter (hours) in a few cases, producing a BWP.

The need for the exchange into the binary MSP is set by the assumption that radio pulsars do not turn on as long as there is a binary companion in near contact; thus the need for removing it altogether after the initial recycling. Burgay et al. (2003), however, claim that the lack of detection of radio pulsations from quiescent LMXBs could result from pulsar radiation driving a large outflow from the system which then attenuates the radio emission. A problem with this scenario is that the pulsar must remove the accretion
disc before it can blow away matter flowing through the inner Lagrangian point. Burderi et al. (2001) show that this can only occur in some wide systems, and only then when the magnetic pressure due to the neutron star overcomes the disc’s internal pressure. Consequently it is unlikely that the companion in a BWP is the one that spun the pulsar up, unless the latter has somehow contracted well inside its Roche lobe. If this occurs through evolutionary loss of the envelope one then has the problem of bringing the system to short periods in a reasonable time.

Converting wide orbits to narrow ones was the main motivation for Rasio et al. (2000) in considering an alternative scenario. This invokes binary formation through exchange interactions, producing neutron star systems with companions which are more massive. This must occur in a relatively short interval of 1 – 2 Gyr before all the potential extended companions with masses larger than that of the neutron star have finished their evolution. Given such a system, a common envelope phase results once the companion evolves and overfills its Roche lobe. The envelope of the red giant is ejected and the core spirals in, leaving a He-rich white dwarf in a relatively close orbit with the neutron star. If contact is established, the pulsar could presumably begin to evaporate the companion. However because the donor star has no hydrogen, the orbital periods of systems made this way are much shorter than those of observed BWPs (see equation 1 and Fig 2).

The evolutionary outcome for BWPs depends on whether they have evolved to a period where they have become dynamically unstable. A number of BWPs exist which have reached or are evolving towards the ‘Hubble line’ and so are not yet old enough to have been dynamically disrupted. The systems which have undergone dynamical instability are observed as isolated MSPs. In the globular 47 Tuc 7 out of 21 of MSPs are isolated (see [http://www.naic.edu/~pfreire/GCpsr.html for an up to date list of pulsars in globular clusters]) while 5 out of 21 are low-mass BWPs. Objects may undergo evolution through the low-mass evolutionary route and disruption of the companion. However, the number of resulting isolated MSPs should not be significantly greater than the number of BWPs unless there is a process which strongly favours short periods (less bloated secondaries). The similar number of low-mass BWPs and isolated pulsars in 47 Tuc supports this conclusion.

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