Black Widow Pulsars: the Price of Promiscuity

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2 July 2003

ABSTRACT
The incidence of evaporating ‘black widow’ pulsars (BWPs) among all millisecond pulsars (MSPs) is far higher in globular clusters than in the field. This implies a special formation mechanism for them in clusters. Cluster MSPs in wide binaries with WD companions exchange them for turnoff–mass stars. These new companions eventually overflow their Roche lobes because of encounters and tides. The millisecond pulsars ejection the overflowing gas from the binary, giving mass loss on the binary evolution timescale. The systems are only observable as BWPs at epochs where this evolution is slow, making the mass loss transparent and the lifetime long. This explains why observed BWPs have low–mass companions. We suggest that at least some field BWPs were ejected from globular clusters or entered the field population when the cluster itself was disrupted.

Key words: accretion, accretion discs – pulsars: general – X-rays: binaries

1 INTRODUCTION
It is widely believed that most millisecond pulsars (MSPs) have been spun up by accretion from a close binary companion. This recycling (Radhakrishnan & Srinivasan, 1981) occurs when the neutron star magnetic field has decayed to a relatively low value \( \sim 10^8 \) G. If accretion ceases, the neutron star appears as a millisecond pulsar with a very low spindown rate, as dipole radiation is very weak.

Not surprisingly, a large fraction of millisecond pulsars are observed to be members of binary systems. In several cases the pulsars undergo very wide eclipses, implying obscuration by an object considerably larger than the companion star’s Roche lobe. The obvious explanation (Fruchter, Stinebring & Taylor 1988) is that the obscuring object is an intense wind from the companion star, driven in some way by energy injected by the pulsar. In every case where eclipses are seen, both the binary eccentricity and the pulsar mass function are extremely small, giving companion masses \( M_{2,\text{min}} \leq 0.1 M_\odot \) in most cases (see Figs 1, 2). Fig. 1 reveals another group of binary millisecond pulsars whose mass functions are systematically lower, 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).

There have been numerous attempts to provide a coherent scheme for the formation and evolution of these ‘black widow’ pulsars (henceforth BWPs). However these generally do not take account of the fact, manifest from Figs 1 and 2, that the incidence of BWPs is considerably higher among globular cluster MSPs than among field MSPs. (Rasio, Pfahl & Rappaport, 2000 consider the formation of short–period binary pulsars in globulars, and note that most of them are BWPs, but do not consider BW formation explicitly.) Considering binary MSPs with \( M_{2,\text{min}} < 0.05 M_\odot \), we find 11 BWPs among the 36 binary MSPs in globulars, but only 2 BWPs out of 45 field binary MSPs. An MSP is almost 7 times more likely to have a very low companion mass if it is in a globular cluster rather than in the field. Figures 1 and 2 show the observed population of binary MSPs in globulars and the field respectively. The globular population has been taken from the online catalogue of Paulo Freire (http://www.naic.edu/~pfreire/GCpsr.html) and the field from the review by Lorimer (2001). The figures also include the theoretical period–mass relation for endpoints of late low–mass and early massive case B evolution. The late low–mass case B endpoints lie on the solid curves, and are taken from Rappaport et al. (1995)

\[
P_{\text{orb}} = 1.3 \times 10^5 M_{\text{wd}}^{0.25} \big/ \left( 1 + 4 M_{\text{wd}}^{0.25} \right)^{1.5} \text{ d} ,
\]

where \( P_{\text{orb}} \) and \( M_{\text{wd}} \) are the period and white dwarf mass (in solar units) respectively, and the upper and lower curves represent the spread in the core mass–radius relation for both population I and population II abundances respectively. Endpoints of early massive case B evolution lie on the dashed curve, taken from Taam, King & Ritter (2000)

\[
\log P_{\text{orb}} \sim 2.56 - 3.1 M_{\text{wd}} \text{ d} .
\]

These figures clearly show that there is some mechanism favouring the production of BWPs in globular clusters. We

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Figure 1. The observed period versus minimum secondary mass distribution for binary MSPs in globular clusters. Diamonds represent systems with eccentricities greater than 0.1. A filled symbol indicates that the system has been observed to eclipse at some radio frequency. The solid curves represent the theoretical distribution of endpoints of late low-mass case B evolution for a range of abundances. The upper and lower of the solid curves refer to population I and population II stars respectively. The dashed curve represents this distribution for early massive case B evolution. See the Introduction for further details.

It has been shown by Davies & Hansen (1998) that exchange encounters in globular clusters will tend to leave the most massive stars within binaries, independent of the initial binary composition. When neutron stars exchange into these binaries, the less massive of the two main-sequence stars will virtually always be ejected. The remaining main-sequence star will typically have a mass of $\sim 1.5 - 3\ M_\odot$. The binary will evolve into contact once the donor star evolves up the giant branch.

The subsequent evolution of such a system will depend on the mass of the donor star and the separation of the two stars when the donor fills its Roche lobe. For example, it has been suggested that the system may enter a common envelope phase (e.g. Rasio et al. 2000). Alternatively, the system may produce an intermediate-mass X-ray binary (IMXB). In such a system the neutron star may accrete sufficient material (and with it, angular momentum) for it to acquire a rapid rotation (i.e. milliseconds periods). Because the donors are all more massive than the present turn-off mass in globular clusters, all IMXBs will have undergone their mass transfer in the past. If these systems evolve into MSPs, then we obtain, quite naturally, what is observed today, namely a large MSP population and a relatively small X-ray binary population.

Observations and modelling of the X-ray binary Cygnus X-2, provide important clues in helping determine the subsequent evolution of intermediate-mass systems. This binary is unusual in that its donor has the appearance (by its position in an HR diagram) of a slightly-evolved 3–5 $M_\odot$ star, yet its measured mass is much lower ($\sim 0.5\ M_\odot$). The evolutionary history of Cyg X-2 has been considered (King & Ritter 1999, Podsiadlowski & Rappaport 2000, and Kolb et al. 2000). The unusual evolutionary state of the secondary today appears to indicate that the system has passed through a period of high-mass transfer from an initially relatively-massive star ($\sim 3.6\ M_\odot$) which had just evolved off the main sequence. The neutron star has somehow managed to eject most of the $\sim 2\ M_\odot$ of gas transferred at Super-Eddington rates from the donor during this phase. This evolutionary history may also apply to the IMXBs formed dynamically in globular clusters. Vindication of this model also comes from studying the dynamical evolution of the binary within the Galactic potential (Kolb et al. 2000). A suitable progenitor binary originating in the Galactic Disc has sufficient time, and could have received a sufficient kick when the primary exploded to produce a neutron star, to reach the current position of Cyg X-2.

2 WIDOWHOOD

Making millisecond pulsars requires two ingredients. First, the neutron star must be spun up to millisecond periods, and second, it must turn on as a radio pulsar. Adding a third ingredient – a companion which can be ablated – makes it a black widow.

Recycling by accretion torques supplies the first ingredient. The second is equivalent to demanding that this accretion should then stop, to the point that the pulsar magnetosphere attains a state of near-vacuum. No neutron star is observed both to accrete and pulse in the radio: X-ray emission from radio pulsars is generally attributed to mechanisms other than accretion (for the Be-pulsar binary PSR 1259-...
Deep searches for pulsed radio emission from quiescent soft X-ray transients containing neutron stars yield null results (Burgay et al., 2003), despite the fact that the accretion rate, as measured by the X-ray luminosity, drops as low as \( \sim 5 \times 10^{-15} \, M_\odot \, \text{yr}^{-1} \). Evidently a spun-up neutron star can appear as an MSP only if accretion effectively stops, and thus only if the companion star detaches from its Roche lobe by many scaleheights.

The most obvious way of detaching is when the companion has a core–envelope structure, and the latter is all lost. Thus in binaries where a neutron star accretes from a low–mass giant (late low–mass Case B evolution) we are eventually left with the low–mass helium white–dwarf core of the giant in a wide detached binary whose separation was set by the Roche lobe size of the giant just before it lost its envelope. Many MSPs of this kind are seen, both in globulars and the field (Figs. 1, 2). A second channel producing much tighter and more massive MSP–WD binaries is early mass case B evolution (King & Ritter, 1999; Taam et al., 2000), where the evolved star was initially more massive than the neutron star. Some of the field distribution is consistent with this channel (Fig. 2). Van den Heuvel & van Paradijs (1988) proposed a third potential channel, to explain an apparent lack of LMXBs below orbital periods of 3 hr. They suggested that main–sequence companions might detach at this period, as in cataclysmic binaries (see e.g. King, 1988 for a review of the latter). However the most recent catalogue of Ritter & Kolb (2003) shows that neutron–star LMXBs have an apparently uniform distribution at short periods, with no sign of a gap or lack of systems (cf King, 2003): of the 35 NLMXBs with known periods between 80 minutes and 10 hr, 8 lie between 80 minutes and 3 hr. It appears that the majority of LMXBs do not detach at 3 hr, probably because their secondary stars are somewhat nuclear–evolved (Schenker et al., in prep). Hence the low–mass and intermediate–mass giant channels identified above probably account for the production of most MSPs (Taam et al., 2000).

But this conclusion makes it difficult to supply the third BWP ingredient listed above. If all binary MSPs emerge in binaries with detached white dwarf companions, it is hard to see how efficient ablation can occur and turn the system into a BWP. Observed MSP – WD binaries show no signs of incipient ablation. This is hardly surprising given both the small target that the white dwarf presents to the ablating radiation, and its high surface gravity, which must reduce potential mass loss. At this point we recall the observation above that the incidence of BWPs is far higher in globular clusters than in the field.

3 Companion Exchange

The obvious difference between field and cluster binaries is the possibility of encounters and exchange interactions in clusters. A cluster MSP in a binary with a white dwarf can exchange this unpromising partner for one which is a potential BWP victim. The wide low–mass MSP–WD remnants of low–mass Case B discussed above are obvious candidates for this type of exchange. Their encounter cross–sections are large, they are only loosely bound, and most cluster stars are more massive than their white dwarfs and will thus exchange into them in an encounter.

In globular clusters, the timescale for a given binary to undergo an encounter with a single star may be approximated as

\[
\tau_{\text{encounter}} \simeq 7 \times 10^{10} \, \text{yr} \left( \frac{10^5 \, \text{pc}^{-3}}{n} \right) \left( \frac{V_\infty}{10 \, \text{km/s}} \right) \times \left( \frac{R_\odot}{R_{\text{min}}} \right) \left( \frac{M_\odot}{M} \right),
\]

where \( n \) is the number density of single stars and \( M \) is the combined mass of the binary and a typical single star. An exchange encounter occurs when a third star, which is more massive than the white dwarf, passes within a distance comparable to the binary separation, i.e. \( R_{\text{min}} \simeq a \). For \( a \sim 10 \, R_\odot \), and \( n \sim 10^5 \) stars pc\(^{-3} \), \( \tau_{\text{encounter}} \sim 2 \times 10^9 \) yr. Hence the remnants of LMXBs are vulnerable to exchange within the centres of virtually all globular clusters. The few, relatively long-period, systems shown in Fig. 1 are indeed located either in the haloes of typical globular clusters or in the cores of very low–density systems.

The product of an exchange encounter is an eccentric binary containing the MSP and, typically, a main–sequence star close to the cluster turn–off mass. The eccentricity is drawn from the distribution \( f \) where \( df/de = 2e \). For wide binaries (periods around 100 days; i.e. \( a \sim 100 \, R_\odot \)), subsequent encounters with single stars perturb the binary, making it more bound, and leaving it with a new eccentricity drawn from this distribution. Tidal circularization is important for binaries with eccentricities close to unity, as the two stars are much closer at periastron. If a binary circularizes, the final separation, \( a_f = (1 - e^2) a_{\text{ecc}} \), where \( e_{\text{ecc}} \) is the semi–major axis of the eccentric binary, having eccentricity \( e \). The timescale to achieve such circularization is a very sensitive function of separation (e.g. Tassoul 1995). Observations reveal an absence of eccentric binaries below periods of 10 days or so for stellar clusters which are 1 Gyr old (Mathieu et al. 1992). Given a sufficient number of fly–by scatterings, we would therefore expect all wide binaries to be left with very high eccentricities at some point, and for these systems to then circularize with separations in the range \( 10 - 20 \, R_\odot \).

Binaries which were initially much tighter (with periods around 10 days), are likely to suffer the initial exchange encounter and perhaps only one or two scatterings. In any case, these binaries are already tight enough to circularize.

The outcome for virtually all binaries which have undergone exchanges is thus a close binary (separation \( a \sim 10 - 20 \, R_\odot \)) containing an MSP in a circular orbit with a captured cluster star. Subsequent angular momentum loss via a magnetized wind is likely, driving the system into contact (Verbunt & Zwaan 1981). The initial mass \( M_2 \) of the captured cluster star must be close to the turnoff value, as the capture probability rises steeply with mass. This value is \( \sim 0.7 \, M_\odot \) for globular clusters in the present epoch, but was of course higher in the past.

4 Binary Bereavement

In every case where an MSP is observed or inferred to ablate its companion, the mass \( M_2 \) of the latter is much smaller.
than the initial mass $M_2$, inferred above. BWPs are apparently observable only when ablation has reduced $M_2$ below $\sim 0.1 M_\odot$.

To investigate this we consider the evolution of the Roche lobe radius $R_L \simeq 0.462(M_2/M)^{1/3}a$ of the companion, where $a$ is the binary separation. We assume that the matter lost from this star and thus from the binary carries specific angular momentum $\beta$ times that of the companion $(M_1/J/M_2 M)$. Here $M_1(\simeq 1.4M_\odot)$ is the pulsar mass and $M = M_1 + M_2$. Evidently the value of $\beta$ depends on how the mass is lost. It is straightforward to show (van Teeseling & King, 1998) that

$$\frac{R_L}{R_L^\text{eq}} = \frac{2}{t_J} + \frac{M_w}{M M_2} \left[ \frac{2}{3} \beta - \frac{5}{3} \right] \frac{M_1 - M_2}{M_2} ,$$

where $t_J$ is the timescale for orbital angular momentum loss by other means, e.g. gravitational radiation or magnetic braking. We compare this change of $R_L$ with the change of the secondary's radius $R_2$. We write $R_2/R_2^\text{eq} = 1/t_{\text{exp}}$ if the star expands independently of mass loss, e.g. via thermal expansion across the Hertzsprung gap or nuclear expansion, and

$$\frac{R_2}{R_2^\text{eq}} = \frac{M_2}{M_2^\text{eq}}$$

if the radius change results from mass loss. Here $\zeta$ is the effective mass-radius index, i.e. the mass-radius index actually followed by the companion along its evolutionary track. In general it depends both on the nature of the secondary and the rate at which it is losing mass, and must in general be calculated self-consistently through the evolution. However we can infer its likely value quite easily in many cases (see below).

The evolution of the BWP binary depends on whether the mass loss timescale $t_w = -M_2/M_\text{exp}$ is shorter or longer than $t_J$ or $t_{\text{exp}}$. Observations of the known BWPs imply that $t_w$ for them is quite long ($> 10^8$ yr; Fruchter & Goss, 1992; Stappers et al., 2003), making their survival and observability understandable. (Although orbital decay timescales of order $3 \times 10^7$ yr are measured [Ryba & Taylor, 1991] these must represent short–term period derivatives of alternating sign rather than the long–term evolutionary trend, a situation familiar for accreting systems such as CVs and LMXBs.) Thus taking $t_w > \min(t_J, t_{\text{exp}})$ we see that the companion star comes into contact with its Roche lobe on an angular momentum loss timescale $t_J$ or a nuclear or thermal timescale $t_{\text{exp}}$.

At this point, mass overflows the inner Lagrange point $L_1$. If this mass were to accrete on to the neutron star, this would extinguish the millisecond pulsar and turn the BWP into an LMXB. It is instead more likely that the pulsar pressure is able to blow away the matter flowing through $L_1$. We compare the pressure of the pulsar wind at radius $R$

$$P_{\text{PSR}} = \frac{\dot{E}_{\text{rot}}}{4\pi R^2 c} ,$$

(where $\dot{E}_{\text{rot}}$ is the pulsar's rotational energy) with the ram pressure of the matter trying to accrete at a rate $\dot{M}$

$$P_{\text{ram}} = \rho v^2 < \frac{\dot{M}}{4\pi R^2 \Omega} \left( \frac{2GM_1}{R} \right)^{1/2}$$

Here $\rho, v$ are the density and infall velocity of matter at radius $R$, and $\Omega$ is the solid angle subtended by this matter at the pulsar. Thus

$$P_{\text{PSR}} < \frac{\dot{E}_{\text{rot}}}{cM} \left( \frac{R}{2GM_1} \right)^{1/2} ,$$

where the units of $\dot{E}_{\text{rot}}/M$ are $10^{35}$ erg s$^{-1}$, $10^{-10} M_\odot$ yr$^{-1}$ respectively. Millisecond pulsars have $\dot{E}_{\text{rot,35}} > 1$, and we shall find $\dot{M}_{-10} \sim 1$ below. Thus as the matter issuing through $L_1$ spreads out and tries to form a disc, $\Omega$ increases to the value $\lesssim 0.1$ where the pulsar pressure is able to blow it away. (In the interval between submission and revision of this paper, the paper of Sabbi et al., 2003 appeared, showing that just this appears to occur in the globular cluster BWP J1740-5340.)

This ejection increases $|\dot{M}_w|$, and thus affects the evolution of the binary. If the mass-radius index $\zeta$ exceeds the critical value

$$\zeta_{\text{crit}} = \left( \frac{2}{3} \beta - \frac{5}{3} \right) \frac{M_1}{M} - \frac{M_2}{3} ,$$

the mass loss stabilizes when $\dot{R}_2 = \dot{R}_L$, so that

$$- \dot{M}_w = \frac{2M_2}{(\zeta - \zeta_{\text{crit}}) t_J}$$

if evolution is driven by orbital angular momentum loss and

$$- \dot{M}_w = \frac{M_2}{(\zeta - \zeta_{\text{crit}}) t_{\text{exp}}}$$

if the evolution is instead driven by radius expansion independent of mass loss (cf eqn. 22 of van Teeseling & King, 1998). Note that, unlike the case of mass transfer, a large companion mass tends to stabilize mass loss, because it reduces the associated specific angular momentum. Mass loss is stable even for a low–mass fully convective or fully degenerate companion ($\zeta = -1/3$) provided $\zeta_{\text{crit}} < -1/3$, i.e.

$$\beta < \frac{2M - M_2}{3M - M_2}$$

which approaches $\beta < 2/3$ for small $M_2/M$. This process remains stable even for small companion masses provided that $\beta \lesssim 2/3$. This value evidently requires that mass is lost from some position inside the pulsar’s Roche lobe. We shall investigate this process in more detail in a future paper. We conclude quite generally that an evaporating pulsar binary loses mass on a stellar expansion or angular momentum loss timescale.

This conclusion poses stringent constraints on the observability of such systems. The mass loss itself may obscure the pulsar and render it impossible to detect, for example by increasing the dispersion measure to the point that the pulses are smeared out. We note that in several BWPs the pulsar is often obscured in this way for whole orbital cycles (e.g. Lyne et al., 1990). This strongly suggests that an evaporating pulsar binary is only detectable as a BWP at rather small mass loss rates. We can quantify this effect

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by regarding the outflow as a roughly spherical wind blown away from a region of the size of the binary orbit. From the work of Burderi & King (1994) the free–free optical depth through this outflow at typical (400 - 1700 MHz) observing frequencies is $\gtrsim 1$ for mass loss rates

$$\dot{M}_w > \dot{M}_{\text{crit}} \simeq 10^{-11} T_b^{3/4} P_0 M_\odot \text{ yr}^{-1}$$

(scaling their eqn 9 to general orbital periods $P_0 = (P/6 \text{ hr})$, with the temperature in units of $10^6$ K, the expected value for an ablated wind: Fruchter & Goss, 1992). Note that Rasio, Shapiro & Teukolsky (1989) have to take a much cooler low–density wind in order to reproduce the dispersion measure seen in PSR 1957+20. In the absence of this constraint we can adopt a more reasonable wind temperature: cf Wijers & Paczynski (1993).

This explains why BWPs are seen to have very small companion masses: these evidently correspond to cases of rather low mass loss. Since the mass loss timescale is also the evolution timescale, such systems also have a long lifetime, increasing their discovery probability. Evolution and mass loss are clearly slow once $M_2 \lesssim 0.1 M_\odot$ for systems driven by angular momentum loss through gravitational radiation. This account for all but one of the known BWPs. The other BWP (J1740–53) has $P \simeq 1.35$ d, $M_{2,\text{min}} \simeq 0.2 M_\odot$ and is a subgiant (Ferraro et al., 2001). The nuclear timescale of such a low mass subgiant is quite long, allowing mass loss rates satisfying (14) here also; Watson et al (1985) find a mass transfer rate $\sim 7.5 \times 10^{-10} M_\odot \text{ yr}^{-1}$ in the CV GK Per, which has almost the same period and secondary mass, compared with $M_{\text{crit}} \simeq 6 \times 10^{-11} T_b^{3/4} M_\odot \text{ yr}^{-1}$ for these parameters. In all cases, detailed observational comparison evidently needs full binary evolution calculations allowing for the change of $\zeta$ with evolutionary state, as well as the full range of possible initial companions. We shall present these in a later paper.

5 BWPS IN THE FIELD

We have argued that in globular clusters, captures provide a mechanism for making BWPs, whose formation is otherwise problematical. However there are two BWPs in the field, namely 1957+20 and 2051–0827. Occam’s razor suggests that we should not look for a second formation mechanism, but a variation on the first. Two ideas suggest themselves. Some BWPs made in globulars may be ejected by some dynamical event (or the cluster itself was disrupted), or (rarely) captures may occur in the field. The latter is very unlikely given the relatively low space density of stars in the field.

PSR 1957+20 has a tangential velocity of 190 kms$^{-1}$ (Arzoumanian et al., 1994) which corresponds to a space velocity $> 220$ km s$^{-1}$. However its motion is restricted to the plane of the Galaxy (its current galactic latitude is a mere $-5.2$ degrees). J2051–0827 is further out of the galactic plane ($b \sim -30.4$ degrees) but with a much smaller tangential velocity of 14 kms$^{-1}$ (Toscano et al 1999). It is unlikely, though not impossible, that both objects formed from encounters in the field. It is much more probable that these two systems have either been ejected from a cluster or that the clusters themselves have been broken up. Metal–rich clusters having kinematic properties similar to the thick disk are most likely to be relevant here.

6 CONCLUSIONS

The formation of black widow pulsars has until now resisted simple explanation. The problem is that formation requires two stages. A binary companion is needed to spin up (recycle) the neutron star to millisecond periods. But attempts to use the same companion as the target which the pulsar ablates run into difficulty. A semidetached binary always transfers some mass unless the donor shrinks drastically. Thus neutron stars in short–period LMXBs are always accreting, and therefore have difficulty in turning on as millisecond pulsars and thus reaching the black widow stage.

Our answer to this difficulty uses the observed fact that the incidence of BWPs in globulars is far higher than in the field. Millisecond pulsars in ‘dead’ wide binaries with WD companions can exchange them for turnoff–mass stars. Encounters and tides bring these new companions into tight orbits, where they eventually fill their Roche lobes. The MSPs can eject from the binary gas overflowing the inner Lagrange point, resulting in mass loss on the binary evolution timescale. The systems are observable as BWPs only if this timescale is long, making the mass loss transparent and the binary lifetime long. This explains the preference of observed BWPs for low–mass companions. We suggest that at least some field BWPs were ejected from globular clusters, or were members of clusters that were broken up.

A consequence of the picture suggested here is that a globular cluster neutron star is likely to form a BWP rather than an LMXB if it changes partners. Hence most LMXBs in globular clusters are still with their original companions, and thus old. We shall investigate this idea in a future paper.

7 ACKNOWLEDGMENTS

ARK and MBD are grateful to the organisers of the meeting on Globular Clusters at the Kavli Institute for Theoretical Physics, Santa Barbara, which provided the stimulus for this work. Theoretical astrophysics research at Leicester is supported by a PPARC rolling grant. ARK gratefully acknowledges a Royal Society Wolfson Research Merit Award. MEB acknowledges the support of a UKAFF fellowship. We thank the referee, Fred Rasio, for a very helpful report.

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