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Evolution of Black Widow Pulsars

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Abstract. We consider the evolution 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 $P \lesssim 10\,\mathrm{hr}$ 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.

1. Introduction

In a recent paper (King et al. 2003; hereafter KDB) we pointed out that the incidence of black widow pulsars (BWPs) 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 $M_{\rm min}$ and orbital period P (Fig. 1).

2. Evolution of Low–Mass BWPs

BWPs appear to fall into two distinct groups which we shall call high–mass and low–mass, depending on whether $M_{\rm min} \gtrsim$ or $< 0.1\,M_\odot$. The high–mass group have noticeably more irregular eclipses than the low–mass group (e.g., Ransom et al., in this volume). In the standard way we may associate with the two groups binary MSPs which do not eclipse but whose values of $M_{\rm min}$ are even smaller; the interpretation is that these are BWPs seen at low orbital inclination. With this association the distribution of Figure 1 puts the dividing line between high– and low–mass BWPs at $M_{\rm min} \simeq 0.05\,M_\odot$.

We consider the evolution of the low–mass group first. The small secondary mass (close to $M_{\rm min}$ 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 it as an

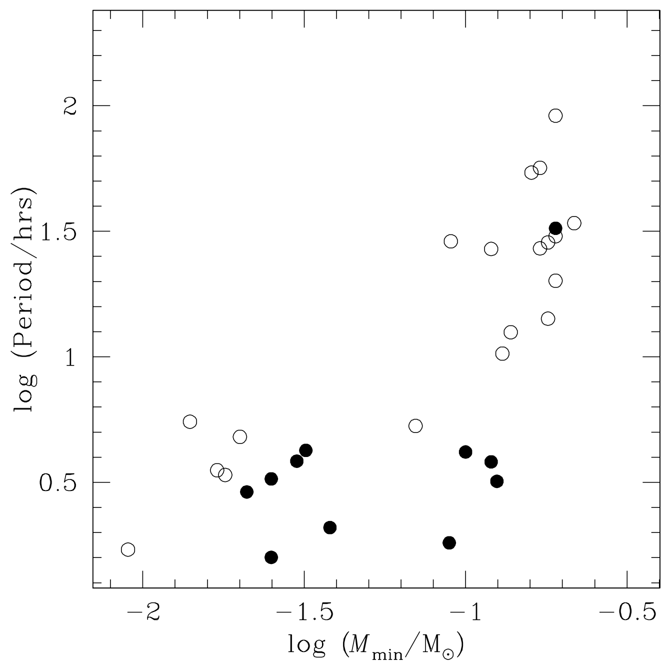

Figure 1. A plot of log period in hours versus log minimum companion mass for all the binary MSPs in globulars.

$n = 3/2$ polytrope, with radius

$$R_2 \simeq 10^9(1+X)^{5/3} m_2^{-1/3} k \text{ cm} \tag{1}$$

(see, e.g., King 1988). Here $m_2 = M_2/M_\odot$, X is the fractional hydrogen content, and $k \geq 1$ measures the deviation from the fully–degenerate radius given by $k = 1$. We assume that low–mass BWPs have a range $1 < k \lesssim$ few for reasons we will discuss in the next section. Assuming a Roche-lobe filling donor gives the mass-period relation

$$m_2 = 1.5 \times 10^{-2}(1+X)^{5/2} k^{3/2} P_{\rm h}^{-1} \tag{2}$$

where $P_{\rm h}$ 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

$$\frac{\dot M_2}{M_2} = \frac{3(1+q)}{2 - 3\beta + q}\frac{\dot J_{\rm GR}}{J} \tag{3}$$

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

$$\beta = \left(\frac{b}{a}\right)^2 (1+q)^2 \tag{4}$$

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 will be between the circularisation radius of the infalling matter and the L_1 point. As all BWPs have $M_2 \ll M_1$, $\beta \ll 2/3$ except

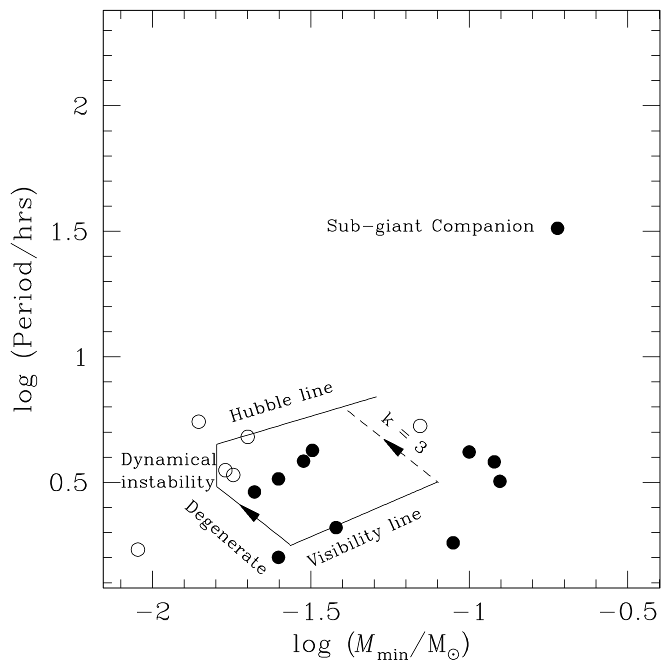

Figure 2. A plot of log period in hours versus log minimum companion mass for all the BWPs in globulars along with the evolutionary constraints as described in the text.

for very small q (see below) the first term on the right hand side of (3) is 3/2 and we can rewrite (3) as

$$\dot{M}_2 = -1.9 \times 10^{-10}\, P_{\rm h}^{-8/3}\, m^{2/3}\, m_{0.1}^2 \;\, M_\odot {\rm yr}^{-1} \tag{5}$$

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

$$\dot{M}_{\rm crit} = 1.5 \times 10^{-12}\, P_{\rm h}\, T_6^{3/4} \;\, M_\odot {\rm yr}^{-1} \tag{6}$$

for free–free absorption at typical (400 – 1700 MHz) observing frequencies, where $T_6 \sim 1$ is the temperature of the lost mass near L_1 in units of 10^6 K. The resulting constraint

$$P_{\rm h} \gtrsim 3.7\, T_6^{-9/44}\, m^{2/11}\, m_{0.1}^{6/11} \tag{7}$$

is plotted on Figure 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 β term in the denominator of (3) becomes significant. This signals dynamical instability, as the Roche lobe moves inwards with respect to 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 two MSPs (Wolszczan & Frail 1992; Konacki & Wolszczan 2003; Sigurdsson et al. 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 $L1$ point. However, matter can be ejected from anywhere between the $L1$ point and the circularisation radius (which even for small small mass ratios is not comparable with the distance to the $L1$ point).

If matter reaches in 5 per cent of the distance from the centre of mass to the $L1$ point this gives $M_2/M_1 = 0.011$, i.e., $m_2 = 0.016$. This line is labelled 'Dynamical Instability' on Figure 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 ($k = 3$). Arrows on the degenerate sequences indicate the direction of evolution.

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

3. High–Mass BWP Evolution

We now consider the remaining systems on Figure 2, i.e., those with $M_{\rm min} \gtrsim 0.05\,M_\odot$. Nelson (this volume) 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 $P \lesssim 5\,{\rm hr}$ and $M_{\rm min} \lesssim 0.13\,M_\odot$. Except for implausibly small orbital inclinations these companions would 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 the 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 capturing a new companion must involve considerable disturbance to that star, probably leading to extensive mass loss. This is clearly indicated for tidal capture, but is probably true in any picture. The globular–cluster X–ray binary AC211 (van Zyl et al. 2004; Charles et al. 2002 and references therein) may be another 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.

After the capture event 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 eq (5) for the relatively long orbital periods of most of this group). It is therefore plausible that BWPs ultimately emerge with the parameters of the high–mass BWPs.

Ultimately GR cannot prevent the companion shrinking within its Roche lobe and detaching. We should therefore expect to see some detached systems at these periods. If the companion has a sufficiently strong stellar wind, this can still produce orbital eclipses through free–free absorption. This appears to happen in PSR 1718–19 (Wijers & Paczyński 1993; Burderi & King 1994). Here $P \simeq 6\,{\rm hr}$, 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 detach from the Roche lobe, its radius ultimately shrinks only slowly, whereas orbital shrinkage via GR accelerates. Depending on the initial separation, the binary resumes 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 (this volume) 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 and have measured periods from X-ray dips/eclipses (e.g., W37 at 3 hrs), power law components (possibly from a wind) and variable absorption. These may be BWPs where the absorption is too large to observe the radio emission.

4. Fan or Pencil Beam?

Figure 1 reveals the striking fact that *all binary MSPs with orbital periods* $P \lesssim 10\,\mathrm{hr}$ *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. Acknowledgments

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