

FORMATION OF BLACK WIDOWS AND REDBACKS—TWO DISTINCT POPULATIONS OF ECLIPSING BINARY MILLISECOND PULSARS

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ABSTRACT

Eclipsing binary millisecond pulsars (MSPs; the so-called black widows and redbacks) can provide important information about accretion history, pulsar irradiation of their companion stars, and the evolutionary link between accreting X-ray pulsars and isolated MSPs. However, the formation of such systems is not well understood, nor the difference in progenitor evolution between the two populations of black widows and redbacks. Whereas both populations have orbital periods between 0.1 and 1.0 days, their companion masses differ by an order of magnitude. In this paper, we investigate the formation of these systems via the evolution of converging low-mass X-ray binaries by employing the MESA stellar evolution code. Our results confirm that one can explain the formation of most of these eclipsing binary MSPs using this scenario. More notably, we find that the determining factor for producing either black widows or redbacks is the efficiency of the irradiation process, such that the redbacks absorb a larger fraction of the emitted spin-down energy of the radio pulsar (resulting in more efficient mass loss via evaporation) compared to that of the black widow systems. We argue that geometric effects (beaming) are responsible for the strong bimodality of these two populations. Finally, we conclude that redback systems do not evolve into black widow systems with time.

Key words: binaries: eclipsing – pulsars: general – stars: evolution – stars: mass-loss – X-rays: binaries

1. INTRODUCTION

It is widely accepted that millisecond pulsars (MSPs) are produced via the recycling scenario (Alpar et al. 1982; Bhattacharya & van den Heuvel 1991). In this scenario, the MSPs are formed from the evolution of low-mass X-ray binaries (LMXBs) and intermediate-mass X-ray binaries in which a neutron star (NS) accretes material and angular momentum from its companion star and thereby is spun up to become an MSP. During this process, the magnetic field of the NS decreases to $B \simeq 10^7$ – 10^9 G. The exact mechanism for this accretion-induced magnetic field decay is still unknown (e.g., Srinivasan et al. 1990; Konar & Bhattacharya 1997; Zhang 1998; Cumming et al. 2001). In most of the cases, a binary system with an MSP and a helium white dwarf is left behind when the LMXB mass transfer ends. It was therefore a bit of a surprise when the first black widow system was discovered, revealing that the MSPs in these black widow systems have very low-mass (0.02 – $0.05 M_\odot$) companions (Fruchter et al. 1988; Stappers et al. 1996). Since the pulsars in these systems suffer from eclipses of their radio signals, it was immediately clear that the companions are semi- or non-degenerate stars which suffer from irradiation-driven mass loss (Kluźniak et al. 1988; Ruderman et al. 1989a, 1989b).

King et al. (2003, 2005) proposed that these eclipsing MSP systems are produced in globular clusters and subsequently ejected into the Galactic field. In their scenario, the formation of eclipsing binary pulsars should go through two phases. In the first phase, a binary system consisting of an MSP and a helium white dwarf is formed via the evolution of an LMXB in a globular cluster. In the second phase, the helium white dwarf is replaced by a main sequence star via an exchange encounter event, leading to ablation and matter expelled from the system caused by strong irradiation of the new companion

by the energetic MSP. Regarding the low number of eclipsing binary MSPs known in the Galactic field at that time, they suggested that eclipsing binary pulsars are mainly generated in the globular clusters and subsequently ejected into the Galactic field or the systems entered the field population in case the cluster itself was disrupted.

However, in the last few years a rapidly increasing number of MSPs have been found in the Galactic field. Most of these discoveries are binary eclipsing MSPs in tight orbits ($P_{\text{orb}} \lesssim 24$ hr), the so-called spiders (Roberts 2013; Pallanca et al. 2012; Romani et al. 2012; Kaplan et al. 2013; Breton et al. 2013). A large fraction of these new MSPs are associated with *Fermi* γ -ray sources (e.g., Abdo et al. 2009; Pletsch et al. 2012). As Roberts (2013) suggested, the population of eclipsing binary MSPs can be divided into two different classes: black widows and redbacks. The black widows have very low-mass companions ($M_2 \ll 0.1 M_\odot$), while the redbacks have companion masses of a few tenths of a solar mass ($M_2 \simeq 0.1$ – $0.4 M_\odot$). In view of the many recent discoveries, it seems that the model suggested by King et al. may have difficulties in explaining the large number of such binary systems in the Galactic field.

Detailed stellar evolution modeling has previously demonstrated that black widows form as the outcome of converging LMXB evolution (e.g., Ergma & Fedorova 1992; Podsiadlowski et al. 2002; Benvenuto et al. 2012). In this paper, we perform binary evolution calculations to study the formation of both redbacks and black widows, and also investigate whether or not redback systems can evolve into black widow systems. We apply a simple geometric argument (beaming) for the evaporation efficiency of companion stars and demonstrate that it can explain the strongly bimodal distribution of the observed systems quite well.

The outline of the paper is as follows. In Section 2, we introduce the details of our formation scenario. In Section 3, we compute the evolution of binary systems in the framework of this scenario. A discussion and a brief summary are given in Section 4.

2. FORMATION SCENARIO AND BINARY EVOLUTION CODE

Several ingredients must be considered for the formation of an eclipsing MSP system: the NS must be able to spin up to a millisecond period and the pulsar must turn on as a radio MSP, the companion star should be ablated in order to produce orbital eclipses, and the orbital period and the companion star mass must match the observed values. We find that these ingredients can be satisfied by the evolution of cataclysmic variable (CV) like LMXBs. Similar to the evolution of CVs, the companion star becomes fully convective when its mass decreases to $0.2\text{--}0.3 M_\odot$ (e.g., Rappaport et al. 1983; Pylyser & Savonije 1989; Podsiadlowski et al. 2002). As a result, we assume that the magnetic braking stops operating and hence the mass transfer is temporarily halted (Rappaport et al. 1983; King 1988). At this time, the NS has accreted about $0.35 M_\odot$ (assuming that the mass accumulation efficiency is 0.5 and the typical initial donor mass is $1 M_\odot$), which is more than enough to spin up the NS to become an MSP (Tauris et al. 2012). When the NS turns on as a radio MSP (once the expanding magnetospheric boundary crosses the light-cylinder radius during termination of the mass transfer), it begins to evaporate its companion star (van den Heuvel & van Paradijs 1988; Ruderman et al. 1989a) by its pulsar wind of TeV (e^- , e^+) particles either directly or indirectly via secondary synchrotron MeV γ -rays produced near the companion star. Even if the companion star refills its Roche lobe, as a result of adiabatic expansion due to mass loss by evaporation, the radio ejection mechanism (Kluźniak et al. 1988; Burderi et al. 2001) will prevent accretion onto the MSP and expel the mass transferred from the companion star. This mass loss, if strong enough, may account for the orbital eclipse of the radio signal by free-free absorption.

In order to test this formation scenario, we have carried out detailed binary evolution calculations with a newly developed Henyey evolutionary code, Modules for Experiments in Stellar Astrophysics (MESA; see Paxton et al. 2011, 2013 for details). In the binary evolution calculations, we included orbital angular momentum loss due to mass loss, gravitational wave radiation, and magnetic braking. Previous studies indicated that a circumbinary (CB) disk can effectively extract angular momentum (Spruit & Taam 2001) and greatly affect the evolution of the binary system (Chen & Li 2006). Hence, we added this possibility and also included the effect of irradiation-induced mass loss from the companion star (as explained below).

More specifically, we assumed that the accretion efficiency of the NS is 0.5 and the mass lost from the system takes the specific angular momentum of the NS before the radio emission turns on (Podsiadlowski et al. 2002). After the radio emission turns on, no mass will be accreted by the NS because of the dominating pulsar radiation pressure, causing the transferred material to be expelled from the neighborhood of the inner Lagrangian point (e.g., Burderi et al. 2001). Regarding the angular momentum loss due to gravitational wave radiation, we adopt the formula given by Landau & Lifshitz (1971):

$$\frac{dJ_{\text{GR}}}{dt} = -\frac{32}{5} \frac{G^{7/2}}{c^5} \frac{M_{\text{NS}}^2 M_2^2 (M_{\text{NS}} + M_2)^{1/2}}{a^{7/2}}, \quad (1)$$

where M_{NS} and M_2 denote the NS and the companion star mass, a is the semi-major axis of the (circular) orbit, c is the speed of light in vacuum, and G is the gravitational constant.

To compute the angular momentum loss due to magnetic braking, we adopt the prescription of Rappaport et al. (1983, Equation (36) with $\gamma = 4$):

$$\frac{dJ_{\text{MB}}}{dt} = -3.8 \times 10^{-30} M_2 R_2^4 \omega^3 \text{ dyn cm}, \quad (2)$$

where R_2 is the radius of the donor star and ω is equal to the orbital angular velocity of the binary system.

During the evolution, we assume that a small part of mass lost from the companion is injected into a CB disk. The rate of CB disk mass injection is $\dot{M}_{\text{CB}} = -\delta \dot{M}_2$. Assuming that the disk follows Keplerian rotation, the angular velocity of the disk is less than that of the binary system. Hence the CB disk will exert tidal torques on the binary and extract angular momentum from the system. To calculate the angular momentum loss due to a CB disk, we adopt the prescription proposed by Spruit & Taam (2001; see also Equation (28) in Shao & Li 2012):

$$\dot{J}_{\text{CB}} = -\gamma \left(\frac{2\pi a^2}{P} \right) \dot{M}_{\text{CB}} \left(\frac{t}{t_{\text{vi}}} \right)^{1/3}, \quad (3)$$

where t is the time since mass transfer begins, $\gamma^2 = r_i/a$, $t_{\text{vi}} = (2\gamma^3 P / 3\pi\alpha\beta^2)$, and where r_i is the inner radius of the disk, α is the viscosity parameter, $\beta = (H_i/r_i)$, and H_i is the scale height of the disk (Shakura & Sunyaev 1973). In the following calculation, we set $\gamma^2 = 1.7$ (Muno & Mauerhan 2006), $\alpha = 0.01$, $\beta = 0.03$ (Belle et al. 2004), and $\delta = 0.005$.

For the evaporation wind driven by the pulsar irradiation, a simple prescription was proposed by Stevens et al. (1992):

$$\dot{M}_{2,\text{evap}} = -\frac{f}{2v_{2,\text{esc}}^2} L_p \left(\frac{R_2}{a} \right)^2, \quad (4)$$

where the pulsar's spin-down luminosity is given by $L_p = 4\pi^2 I \dot{P} / P^3$ (I is the pulsar moment of inertia, P is the spin period of the NS, and \dot{P} is its spin-down rate), $v_{2,\text{esc}}$ is the escape velocity of a thermal wind from the surface of the companion star, and f , whose value is not well determined, is an efficiency factor. However, the implicit assumption of an isotropic energy flux leaving the pulsar is not valid if the outflow of the relativistic pulsar (e^- , e^+) wind follows the geometry of the magnetosphere (and if this wind constitutes a significant part of the spin-down torque acting on the pulsar compared to the magnetodipole radiation, which is approximately emitted without much directivity). Thus we propose that there is a beaming effect that depends on the orientation of the pulsar B-field axis with respect to the direction of the companion star. This leads to a variety of evaporation efficiencies in systems which may otherwise have similar characteristics with respect to M_2 , P_{orb} , P , and \dot{P} . To simplify the description, we can still adopt Equation (4) under the assumption that f is now a (free) parameter that takes *different* values for different binaries and that depends on the geometry of the system, i.e., a “beaming efficiency parameter,” which may in principle reach a value above unity in the working frame of Equation (4).

As we shall demonstrate, the value of f is rather important for the outcome of our calculations. For a recent discussion of the fraction of the incident spin-down luminosity being used for reprocessing to increase the dayside temperature of companion stars in eclipsing MSPs, see Breton et al. (2013).

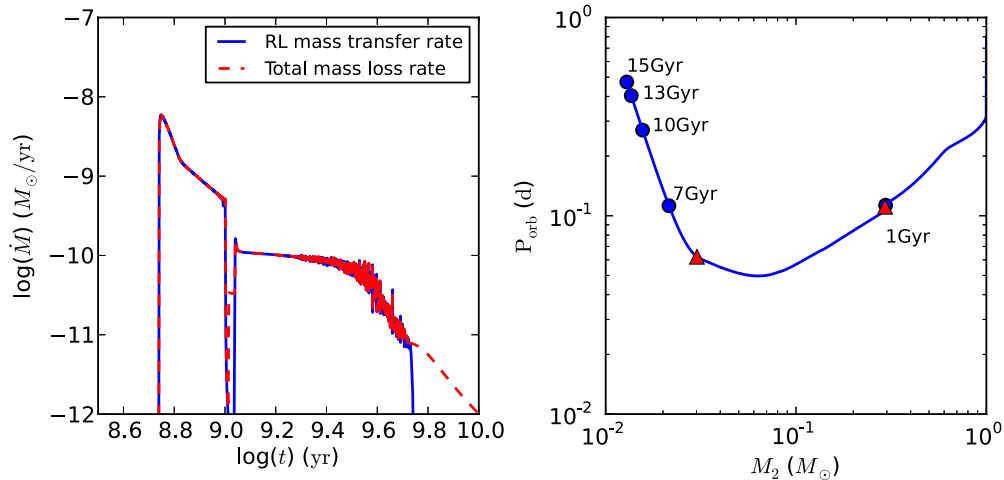


Figure 1. Evolution of a binary system with $M_{\text{NS}} = 1.4 M_{\odot}$, $M_2 = 1.0 M_{\odot}$, an initial orbital period $P_{\text{orb}} = 0.8$ days, and $f = 0.02$. Left: evolution of the mass-transfer rate (blue line) and the total mass-loss rate (red, dashed line). Right: evolution of the donor mass and the orbital period. The age of the system is indicated at certain epochs. Detachments from the Roche lobe are marked by a triangle (see the text).

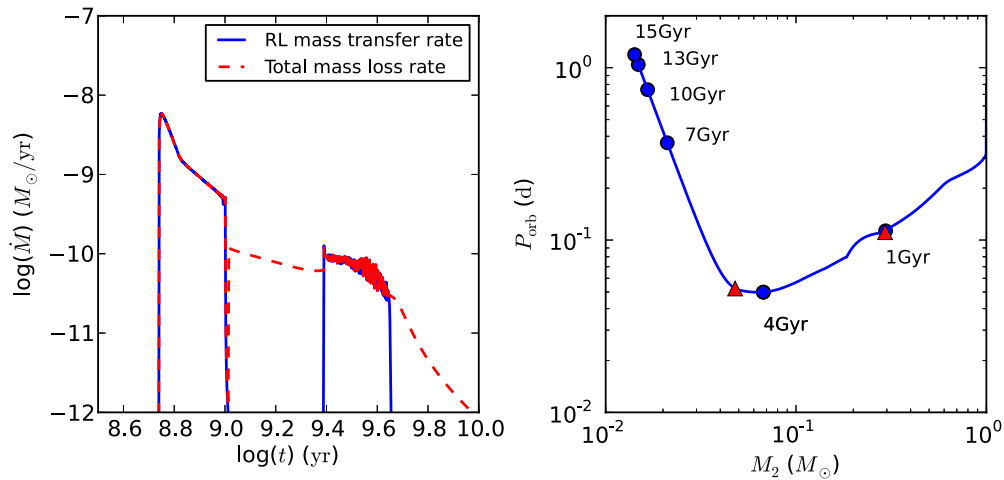


Figure 2. Similar to Figure 1 but for $f = 0.07$.

To calculate L_p , we assumed for all evolutionary tracks an initial spin period $P_0 = 3$ ms and an initial period derivative $\dot{P}_0 = 1.0 \times 10^{-20} \text{ s s}^{-1}$ (corresponding roughly to a surface magnetic field strength of $\sim 10^8$ G) at the epoch of radio MSP turn-on. L_p was then calculated as a function of time by assuming evolution with a constant braking index $n = 3$, and using $I = 10^{45} \text{ g cm}^2$.

3. RESULTS OF THE BINARY EVOLUTION CALCULATIONS

Figures 1–3 show the evolution of a binary system consisting of a $1.4 M_{\odot}$ NS and a $1.0 M_{\odot}$ donor star with an initial orbital period of 0.8 days, and for $f = 0.02$, $f = 0.07$, and $f = 0.10$, respectively. We end the calculations when the age exceeds 15 Gyr. The donor star begins mass transfer while it is still on the main sequence ($P_{\text{orb}} \simeq 0.3$ days). Because of angular momentum loss mainly due to magnetic braking (initially gravitational wave radiation is less important), the orbital period continues to decrease as the donor mass decreases. When the donor mass decreases to about $0.3 M_{\odot}$ and the orbital period has decreased to about 2.5 hr, we find that the donor star becomes fully convective, leading to Roche lobe decoupling and a switch-on of the radio pulsar and subsequent evaporation of the companion star (see Section 2).

From this point onward, the evolution of the binary system deviates with different values of f . This is a result of the competition between the widening of the orbit due to expelled, evaporated material and the shrinking of the orbit due to gravitational wave radiation. In Figure 1, the donor star will refill its Roche lobe and resume mass transfer again after 57 Myr. However, as mentioned previously, the radio ejection mechanism will prevent the NS from accreting at this stage. In Figure 2, the donor star is decoupled from its Roche lobe for a long time as a consequence of using a higher f -value. The more efficient evaporation of the companion star causes the system to shrink less quickly and the system remains detached for 1.4 Gyr. Finally, in Figure 3, the donor star remains detached from its Roche lobe at all times after the pulsar emission turns on. For different LMXBs with different initial parameters (M_2 , M_{NS} , and P_{orb}), we find that the shapes of the evolution tracks are rather similar.

In order to compare with observations, we calculated the evolution of several binary systems with different values of f . Figure 4 shows the evolution of constant initial donor star mass ($1.0 M_{\odot}$) and orbital period (0.80 days) but with different values of f between 0.0 and 0.20. Also plotted are four examples of binary systems with 1.0 and $1.2 M_{\odot}$ donor stars and initial orbital periods of 0.8 and 1.4 days. (In addition, we calculated tracks for a $1.6 M_{\odot}$ donor star with practically the same outcome

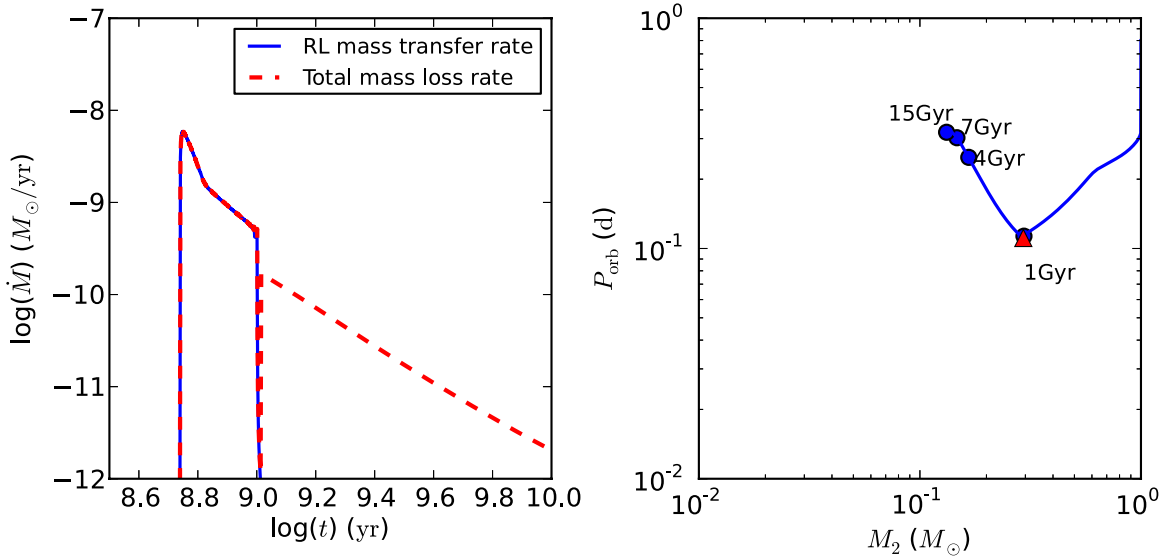
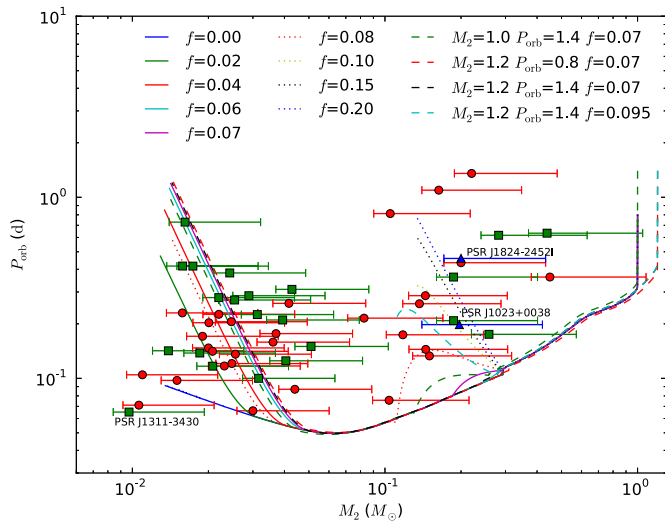
Figure 3. Similar to Figure 1 but for $f = 0.10$.

Figure 4. Evolution of various binary systems calculated with different values of f . The observed data shows the black widows ($M_2 \ll 0.1 M_\odot$) and the redbacks ($M_2 \simeq 0.1\text{--}0.4 M_\odot$). For the error bars, the left and right ends correspond to an orbital inclination angle of 90° and $25^\circ 8'$ (the 90% probability limit), respectively, for $M_{\text{NS}} = 1.4 M_\odot$. The data for the Galactic field (green squares) and globular cluster sources (red circles) were taken from the ATNF Pulsar Catalogue <http://www.atnf.csiro.au/research/pulsar/psrcat> (Manchester et al. 2005), P. Freire's Web site <http://www.naic.edu/~pfreire/GCpsr.html>, Roberts (2013), and references therein. PSR J1023+0038 and J1824-24521 are marked with blue triangles.

and thus it is not plotted here.) From this figure, it is clear that we can explain the formation of most of the eclipsing binary pulsars. In addition, we find that redbacks are more easily produced with larger values of f , while black widows require smaller values of f . This means that a larger fraction of the pulsar luminosity is absorbed by the companion star in redback systems compared with the companions in black widow systems. There is apparently a bifurcation in the evolutionary tracks at about $f \simeq 0.08$ ($f \simeq 0.10$ for $1.6 M_\odot$ donor stars), such that systems with larger f -values produce redbacks and systems with smaller f -values lead to black widows. Furthermore, we note that the evolutionary tracks leading to the redbacks (the dotted lines in Figure 4), in general, do not evolve into black widow systems. Only in a few cases with f -values fine-tuned near the bifurcation

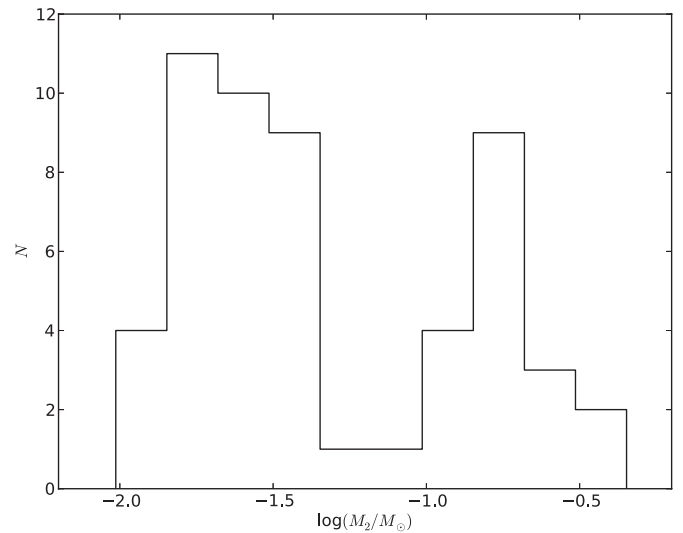


Figure 5. Histogram of the mass distribution of eclipsing MSPs. The bimodal splitting into the populations of black widows (left) and redbacks (right) is clearly seen. According to Freire (2005), all black-widow-like systems may be evaporating systems, but in some cases low orbital inclinations prevent detection of eclipses.

value ($f \simeq 0.08$) will redback systems with $P_{\text{orb}} < 4$ hr evolve into black widow systems.

4. DISCUSSION AND CONCLUSION

4.1. Formation of Redbacks versus Black Widows

In Figure 5 we plot a histogram of the distribution of companion masses in eclipsing MSP systems. It is clearly seen that the distribution is bimodal, with black widow companions being lighter than redback companions (see also Freire 2005 and Roberts 2013 for globular cluster and Galactic field sources, respectively). We have demonstrated that this strongly bimodal distribution is caused by a bifurcation in the evolution of binaries depending on the efficiency of the companion evaporation following pulsar switch-on when the donor star detaches from its Roche lobe. We propose that the reason for the different values of f may simply be related to the distribution of angles between the orbital angular momentum axis and the pulsar magnetic axis, which determines the geometry (beaming) of the outflow of

charged particles from the pulsar magnetosphere. Unfortunately, for MSPs it is very difficult to determine the magnetic inclination angle from polarization measurements and test this hypothesis. Observations of γ -ray detected MSPs show large variations in the conversion of pulsar spin-down luminosity into γ -rays (e.g., Ransom et al. 2011), which could also affect the evaporation efficiency.

As seen in Figure 4, a few of the redback systems with relatively large companion masses and large orbital periods are not reached by our evolutionary tracks. We suggest that these systems somehow became (temporarily) detached when $M_2 \sim 0.5 M_\odot$, resulting in radio pulsar switch-on and ablation of the donor star at an early stage. It is unknown whether this is the result of a decrease in the effect of magnetic braking or a temporary radial contraction of the donor star, for example, due to a chemical abundance discontinuity in the hydrogen burning layer. Another possibility is accretion-powered radiation of the companion star. It has been argued that MeV γ -rays may be produced in the inner region of the accretion disk and that such high-energy photons deposit more energy in the outer layers of the irradiated stellar atmosphere than any other kind of illumination (Kluźniak et al. 1988; Ruderman et al. 1989b). According to Hameury (1996), however, the secular evolution of LMXBs is not much different from that of unilluminated systems (see also the brief discussion in Section 4.3).

4.2. Comparison with Observations

In some cases, the spectra of eclipsing MSPs display prominent H α emission lines (Kulkarni & Hester 1988; Kaplan et al. 2013). In addition, some optical studies show that Roche-lobe filling factors are $0.4 \sim 1.0$ and that the companions are being ablated (Stappers et al. 1999; van Kerkwijk et al. 2011; Breton et al. 2013). This evidence shows that the companions are probably non-degenerate stars instead of white dwarfs. In our models, the companions are indeed often hydrogen-rich non- or semi-degenerate stars, consistent with the observations. For the black widow systems, the donors may, in principle, be hydrogen deficient.

PSR J1023+0038 is a redback system, which is regarded as a “missing link” of the recycling formation scenario, discovered in a Green Bank Telescope drift scan pulsar survey by Archibald et al. (2009). This binary MSP was revealed to be spinning at a period of 1.69 ms while orbiting an $\sim 0.2 M_\odot$ companion star with an orbital period of 4.8 hr. In 2000–2001, the optical spectra showed double peaked emission lines indicating the presence of an accretion disk (Wang et al. 2009).⁶ This indicates that the companion was previously overflowing its Roche lobe and transferring mass, forming an accretion disk around the NS. However, there was no strong evidence of accretion-powered X-ray emission, possibly as a result of a propeller effect during this epoch (Tauris 2012). The eclipsing nature of PSR J1023+0038, its orbital period of 4.8 hr, and a $0.14\text{--}0.42 M_\odot$ companion star are all consistent with the evolutionary tracks presented here (cf. Figure 3 and the dotted lines in Figure 4). It is very likely that this source is currently undergoing cyclic episodes of accretion, possibly related to a combination of donor star irradiation (Bünning & Ritter 2004) and accretion disk instabilities (Dubus et al. 1999) combined with the radio ejection mechanism (L. Burderi 2013, private communication). The probability of

catching this system in the act of a one time transition from an LMXB to a radio MSP is simply too small.

Indeed, similar evidence is found in another redback system: PSR J1824–2452I in M28 (Bégin 2006). This source has recently been discovered to undergo cyclic transitions between accretion- and rotation-powered states (Papitto et al. 2013). The MSP has an orbital period of 11.0 hr and a median (minimum) companion mass of $M_2 \simeq 0.20 M_\odot$ ($0.17 M_\odot$) for an assumed NS mass of $1.35 M_\odot$. According to the $(M_{\text{WD}}, P_{\text{orb}})$ relation for helium white dwarfs formed in LMXBs (e.g., Tauris & Savonije 1999), this companion star may still have a few $0.01 M_\odot$ of hydrogen left which forms the bloated envelope around the degenerate helium core. Whether or not the system will continue evolving on a long timescale of several Gyr with a bloated donor (cf. Figure 3) or finally detach and leave behind a helium white dwarf is unclear. In the latter case, the secular evolution (Myr) may lead to a spin period increase of this MSP depending on the timescale at which the magnetosphere expands due to the decreasing mass-transfer rate (Tauris 2012). However, on much shorter timescales (years or decades) several small torque reversals arise from alternating phases of accretion and radio ejection, which will cause a rather erratic behavior of the spin period evolution.⁷

PSR J1816+4510 (K. Stovall et al., in preparation) is yet another interesting example illustrating the puzzling nature of a redback system. Kaplan et al. (2013) recently reported optical spectroscopy of this system and demonstrated that, on the one hand, the companion star possesses the characteristic features of a helium white dwarf spectrum while on the other hand, it is metal-rich and has a low surface gravity—typical of that of a much larger, bloated non- or semi-degenerate star (causing the ionized gas eclipses of the radio pulsar signal).

PSR J1719–1438 (Bailes et al. 2011) has an intriguing formation history. If the very low-mass companion (planet) has a composition of helium, then the system could have formed via the converging LMXB scenario as described here (as demonstrated in detail by Benvenuto et al. 2012). However, if the composition is made of carbon and oxygen then the formation of this system is most likely the result of an ultra-compact X-ray binary (UCXB; van Haaften et al. 2012), a scenario in which an intermediate-mass carbon–oxygen white dwarf transfers basically all its mass toward an NS on a Hubble timescale while the system widens. The eclipsing black widow PSR J1311–3430, recently discovered by Pletsch et al. (2012) and Romani et al. (2012), has $P_{\text{orb}} = 93$ minutes and a minimum mean density of 45 g cm^{-3} , which hints that this system may also have evolved from a UCXB. This may explain its location slightly below our evolutionary tracks in Figure 4. For a study on the formation of black-widow-like MSPs in globular clusters from UCXBs, see also Rasio et al. (2000).

In general, it is not straightforward to compare our estimated mass-loss rates from modeling (and the predicted rates of orbital widening) with those inferred from observations. In particular, in the classical black widow systems PSR 1957+20 and J2051–0827 there is observational evidence (Arzoumanian et al. 1994; Lazaridis et al. 2011) for spin–orbit couplings and tidal dissipation leading to changes in the gravitational

⁶ However, only absorption lines were observed in 2004, showing that the accretion disk had vanished.

⁷ The reason for the magnetospheric boundary being pushed back and forth with respect to the light cylinder may be related to thermal viscous instabilities in the accretion disk (Dubus et al. 1999), disk–magnetosphere instabilities (Spruit & Taam 1993; Nelson et al. 1997), instabilities related to the irradiation of the donor (Bünning & Ritter 2004), a warped disk or other changes in the disk geometry/flow (van Kerkwijk et al. 1998; Yi et al. 1997), or possibly clumps in the material transferred from the convective envelope of the companion.

quadrupole moment of the companion (Applegate & Shaham 1994). These effects result in severe orbital evolution, even with sign changes of the orbital period derivative, thereby making a comparison to our long-term evolution models difficult.

4.3. Formation of Isolated MSPs

At present, almost 300 MSPs (here defined with $P < 30$ ms) are detected in the Galactic field (154) and in globular clusters (130). These MSPs are thought to be formed by the recycling process. However, about one-third of all MSPs are isolated. It is still not well known how these solitary MSPs are formed. It was suggested by van den Heuvel & van Paradijs (1988) that isolated MSPs are formed from black widows that ablate away their companions by the energetic particles and the γ -rays emanating from radio MSPs. Furthermore, there is evidence for such a scenario by the discoveries of MSPs with planets (Wolszczan & Frail 1992), and even indications of an MSP with an asteroid belt (Shannon et al. 2013), possibly the debris of a former tidally disrupted planet-like companion.

From Figures 1 and 2, it seems that it is difficult to produce isolated MSPs within a Hubble time from our calculations of the converging LMXB scenario. However, we have not considered the structure change of the companion star due to the penetration of radiation into its envelope. As Podsiadlowski (1991) suggested, the radius of such a companion will greatly expand. Hence, the mass-loss rate due to an evaporation wind could increase significantly and the evaporation timescale of the companion should be shorter. Benvenuto et al. (2012) did include irradiation feedback of the donor star but find that this effect (while causing cyclic mass-transfer episodes) does not induce any remarkable changes in the evolution in the (M_2 , P_{orb}) plane. To judge from their Figure 1, the evolution is accelerated slightly with respect to time and it may still be possible for the pulsar to ablate away the companion and produce an isolated MSP.

To conclude, we have demonstrated that the two populations of eclipsing binary MSPs, the black widows and the redbacks, are not only distinct with respect to their observational properties, but also from an evolutionary point of view. The determining factor for producing black widows or redbacks is the efficiency of the companion evaporation. Our calculations suggest that the fraction of pulsar spin-down luminosity absorbed by the companion is larger for redbacks than for black widows (possibly as a result of a different beaming geometry and/or MSP γ -ray luminosity). Despite our rather simple modeling, we are able to reproduce the distribution of the observed systems quite well. Last but not least, we find that redback systems do not evolve into black widow systems with time.

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