FORMATION OF BINARY MILLISECOND PULSARS BY ACCRETION-INDUCED COLLAPSE OF WHITE DWARFS UNDER WIND-DRIVEN EVOLUTION

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ABSTRACT

Accretion-induced collapse (AIC) of massive white dwarfs (WDs) has been proposed to be an important channel to form binary millisecond pulsars (MSPs). Recent investigations on thermal timescale mass transfer in WD binaries demonstrate that the resultant MSPs are likely to have relatively wide orbit periods ($\gtrsim 10$ days). Here we calculate the evolution of WD binaries taking into account the excited wind from the companion star induced by X-ray irradiation of the accreting WD, which may drive rapid mass transfer even when the companion star is less massive than the WD. This scenario can naturally explain the formation of the strong-field neutron star in the low-mass X-ray binary 4U 1822−37. After AIC the mass transfer resumes when the companion star refills its Roche lobe, and the neutron star is recycled owing to mass accretion. A large fraction of the binaries will evolve to become binary MSPs with an He WD companion, with the orbital periods distributed between $\gtrsim 0.1$ days and $\lesssim 30$ days, while some of them may follow the cataclysmic variable-like evolution toward very short orbits. If we instead assume that the newborn neutron star appears as an MSP and that part of its rotational energy is used to ablate its companion star, the binaries may also evolve to be the redback-like systems.

Key words: binaries: close – stars: evolution – stars: neutron – white dwarfs – X-rays: binaries

1. INTRODUCTION

Theoretically, a neutron star (NS) can be formed in three different ways: core–collapse supernova (CCSN) of a massive star, electron capture supernova of an intermediate-mass star, and accretion-induced collapse (AIC) of a massive white dwarf (WD; van den Heuvel 2009 and references therein). AIC may occur either through rapid mass transfer onto an ONeMg WD in a binary from a nondegenerate companion star or through merger of two WDs in a compact binary, and the evolutionary processes are similar to those in the single- and double-degenerate scenarios for Type Ia SNe, respectively. In the former case the ONeMg WD may retain the transferred H- and/or He-rich material by stable nuclear burning and grow to the Chandrasekhar mass (Ivanova & Taam 2004). Electrons are then captured by Mg and Ne, heating the surroundings. However, the energy released by the O+Ne deflagration is too small to cause an explosion of the tightly bound core (Miyaji et al. 1980). Further electron capture eventually leads to gravitational core collapse to form an NS without an SN (Canal et al. 1980; Nomoto & Kondo 1991).

AIC has been proposed as an alternative channel to form millisecond pulsars (MSPs) besides the standard recycling scenario with core–collapse SNe (Channumag & Brecher 1987; Michel 1987; Kulkarni & Narayan 1988; Bailyn & Grindlay 1990). MSPs are old radio pulsars with spin periods less than 20 ms. Most of them are found in binary systems, and their magnetic fields ($\approx 10^8−10^9$ G) are significantly lower than those ($\approx 10^{11−10^{13}}$ G) of ordinary pulsars (Lorimer 2008). In the standard recycling model, MSPs are thought to be the descendants of low-mass X-ray binaries (LMXBs), in which NSs have accreted sufficient mass and angular momentum from the companion star via Roche lobe overflow (RLOF) and have been spun up to millisecond periods (Bhattacharya & van den Heuvel 1991; Tauris & van den Heuvel 2006, for reviews). A long-standing problem for the recycling scenario is the discrepancy between the birth rates of Galactic LMXBs and MSPs, as first noticed by Kulkarni & Narayan (1988). This problem has been tackled by many authors both observationally and theoretically (e.g., Coté & Pyleser 1989; Narayan & Ostriker 1990; Camilo et al. 1994; Iben et al. 1995; Lorimer 1995; Cordes & Chernoff 1997; Lyne et al. 1998; White & Ghosh 1998; Pfahl et al. 2003; Story et al. 2007; Ferrario & Wickramasinghe 2007; Dai & Li 2010; Hurley et al. 2010). Most recent works on the Galactic MSP population show that the birth rate problem is still present (Grégoire & Knödlseder 2013; Levin et al. 2013).

The advantage of the AIC scenario is that it might maintain a sufficiently high formation rate to account for MSPs (e.g., Hurley et al. 2010). However, MSPs formed via AIC are actually difficult to distinguish from those evolved from LMXBs, since the subsequent mass transfer after the AIC event proceeds in a similar way to that in the recycling scenario (Sutantyo & Li 2000; Tauris et al. 2013). The AIC scenario is especially favored for the pulsars in globular clusters that have characteristic ages significantly less than the ages of the clusters, suggesting that they were formed very recently with a very small kick imparted on the newly born NS (Lyne et al. 1996; Boyle et al. 2011). AIC is also invoked to explain the strong-field pulsars with an He WD companion (e.g., Taam & van den Heuvel 1986) or strong-field accreting NSs in LMXBs (e.g., van Paradijs et al. 1997; Xu & Li 2009), which seem to have experienced extensive mass accretion and should have very weak fields according to the recycling scenario.

In a recent work, Tauris et al. (2013) investigated the binary evolution leading to AIC to examine whether NSs formed in this way can subsequently be recycled to form MSPs. It was found that this scenario is possible for systems with companion stars that are either main-sequence (MS) stars, giants stars, or He stars. The first type of companion stars lead to fully recycled MSPs with He WD companions, whereas the other two types of donors lead to more mildly recycled pulsars with mainly CO.
WD companions. For MSP/He WD binaries the orbital periods are predicted to lie between about 10 days and about 60 days, consistent with Hurley et al. (2010). Since observations of MSPs reveal an orbital period range between a few hours and up to 1000 days, one needs to know whether MSPs with shorter orbital periods can also be formed via AIC.

In this paper we explore a supplementary AIC channel to the MSP formation, taking into account the influence of irradiation-excited wind in accreting WD binaries (van Teeseling & King 1998; King & van Teeseling 1998). Our study is similar to Tauris et al. (2013), but the evolutionary processes are considerably different. In particular, our calculations can reproduce MSP/He WD binaries with relatively short orbital periods (less than a few days) and the LMXBs containing a strong-field NS like 4U 1822−37. We also show that the evolutions can lead to the formation of redbacks.

This paper is arranged as follows. We describe the model assumptions in Section 2. Our calculated results of pre- and post-AIC evolution are shown Section 3, which are also compared with observations of binary MSPs. We discuss the possible implications of our results and conclude in Section 4.

2. THE WIND-DRIVEN MODEL

The growth of the WD mass in a binary requires that the accreted material can be stably burned on the surface of the WD, and this usually occurs when the companion star, if it is an MS star, is more massive than the WD, so that mass transfer can proceed on a thermal timescale (van den Heuvel et al. 1992). In this case the accreting WD often appears as a supersoft X-ray source (SSS; Kahabka & van den Heuvel 1997). However, the observational properties of some SSSs, including RX J0439.8−6809, 1E 0035.4−7230, RX J0537.7−7034, and CAL 87 (Schmidtko et al. 1996; Steiner et al. 2006; Oliveira & Steiner 2012), as well as the recurrent Nova T Pyxidis (Knigge et al. 2000), seem not to fit into the classical picture. Most of them have orbital periods of a few hours, smaller than expected for thermal timescale mass transfer (King et al. 2001), and the companion stars are therefore less massive than the WDs, but they can still maintain a high mass transfer rate.

Another challenge comes from the dipping LMXB 4U 1822−37 (Mason et al. 1982; Cowley et al. 2003). The companion star in 4U 1822−37 is of low mass (~0.44−0.56 M⊙; Muñoz-Darias et al. 2005). X-ray and optical light curves indicate an orbital period ~5.7 hr (Mason et al. 1982; Burderi et al. 2010). Recent Suzaku observation detected a cyclotron resonance scattering feature at an energy of 3.3(±2) keV, implying that the NS in this source has a strong magnetic field of 2.8 × 1012 G (Sasano et al. 2014). Since the NS must have accreted at least a few tenths M⊙ of matter from its companion, which would significantly reduce the field as in typical LMXBs, an AIC model seems to be the most likely explanation for its current strong field. In this model the renewed mass transfer should not have lasted a long time, so that the companion star and the orbit have not changed considerably since the AIC, but the short orbital period and small companion mass are both inconsistent with the traditional SSS expectation.

A possible solution to the above puzzles is the self-excited wind model suggested by van Teeseling & King (1998) and King & van Teeseling (1998). They argue that perhaps in all WD binaries the soft X-ray radiation from an accreting WD may lead to a strong stellar wind from the heated side of the companion star. If the wind takes away the specific angular momentum of the companion from the binary, mass transfer will be driven at a rate comparable with the wind-loss rate. The relation between the mass transfer rate M wd and the wind-loss rate M w obeys

\[ \dot{M}_w \simeq (3.5 \times 10^{-7} \frac{M_\odot}{M_{\odot}} \text{yr}^{-1}) \left( \frac{M_2}{M_\odot} \right)^{5/6} \left( \frac{M}{M_\odot} \right)^{-1/3} (\eta_\text{He} \eta_\text{He})^{1/2} \phi \times \left( \frac{M_\text{WD}}{10^{-7} M_\odot \text{yr}^{-1}} \right)^{1/2} \]

for \( M_2 \lesssim M_{\text{WD}} \) and

\[ \dot{M}_w \simeq (3.5 \times 10^{-7} \frac{M_\odot}{M_{\odot}} \text{yr}^{-1}) \left( \frac{M_2}{M_\odot} \right)^{0.95} \left( \frac{M}{M_\odot} \right)^{-1/3} \]

\[ \times \left( \frac{M_\text{WD}}{M_\odot} \right)^{-0.12} (\eta_\text{He} \eta_\text{He})^{1/2} \phi \left( \frac{M_\text{WD}}{10^{-7} M_\odot \text{yr}^{-1}} \right)^{1/2} \]

for \( M_2 \gtrsim M_{\text{WD}} \). Here \( M_{\text{WD}}, M_2, \) and \( M = M_1 + M_2 \) are the WD mass, the companion mass, and the total mass, respectively; \( \eta_\text{He} \) measures the efficiency of the WD’s spectrum in producing ionizing photons normalized to the case of supersoft X-ray sources with a temperature of 10^5 K. \( \eta_\text{He} \) measures the luminosity per gram of matter accreted relative to the value for H shell burning, and \( \phi \) is an efficiency factor parameterizing the fraction of the companion’s irradiated face and the fraction of the wind mass escaping the system.

Considering the irradiation-excited winds from the companion star and their effect on the binary evolution, we investigate the mass transfer processes of a binary consisting of an ONeMg WD and an MS companion star with an updated version of Eggleton’s stellar evolution code (Eggleton 1971, 1973). In addition, angular momentum loss caused by gravitational wave radiation (Landau & Lifshitz 1975) and magnetic braking (Verbunt & Zwaan 1981; Rappaport et al. 1983) is also included in the calculation. We explore the parameter space of the initial binaries for AIC and, if NSs are formed in this way, the properties of the resultant binaries.

During accretion, the growth of the WD mass is associated with the accumulation efficiencies of H- and He-rich matter,

\[ \dot{M}_\text{WD} = \eta_\text{H}\eta_\text{He} \dot{M}_\text{tr}, \]

where \( \eta_\text{H} \) and \( \eta_\text{He} \) represent the fraction of the transferred H- and He-rich matter from the companion that eventually burns into He- and C-rich matter and stays on the WD, respectively. Here we fit the numerical results of Prialnik & Kovetz (1995) and Yaron et al. (2005) for the H mass accumulation efficiency \( \eta_\text{H} \) and adopt the prescriptions in Kato & Hachisu (2004) for the He mass accumulation efficiency \( \eta_\text{He} \). If the WD mass reaches the Chandrasekhar limit (\( M_{\text{Ch}} = 1.38 M_\odot \)), we assume that the WD collapses to be an NS with a gravitational mass of 1.25 M⊙ (termed as the Chandrasekhar model). During this process, a mass of 0.13 M⊙ is assumed to convert into the binding energy. The sudden mass loss makes the orbit wider and causes the temporary detachment of the Roche lobe (RL). The relation between the orbital separations (\( a_0 \) and \( a \)) just before and after the collapse is (Verbunt et al. 1990)

\[ \frac{a}{a_0} = \frac{M_\text{WD} + M_2}{M_\text{NS} + M_2}. \]
WD can exist and that it undergoes a collapse when \( \dot{M} \) mass to rest mass of the accreted matter. In this paper we take calculated results are described as follows.

The observed superluminous SNe Ia hint that there may be super-Chandrasekhar-mass WD progenitors (Howell et al. 2006; Hicken et al. 2007; Scalzo et al. 2010). Yoon & Langer (2004, 2005) found that rapid rotation allows a massive WD to continue accreting when the accretion rate is \( > 3 \times 10^{-7} M_{\odot} \, \text{yr}^{-1} \), and there would not be the central C ignition even if its mass exceeds \( M_{\text{Ch}} \). We accordingly assume that a super-Chandrasekhar-mass WD can exist and that it undergoes a collapse when \( M_{\text{tr}} < 3 \times 10^{-7} M_{\odot} \, \text{yr}^{-1} \), so that there is no differential rotation to support the WD (termed as the super-Chandrasekhar model).

After AIC, the companion star will refill its RL as a result of angular momentum loss or nuclear/thermal evolution. Mass transfer is then resumed, and the post-AIC binary evolves as an LMXB. The interplay between angular momentum loss and nuclear expansion of the donor leads to the so-called bifurcation periods (\( P_{\text{bif}} \)). LMXBs with orbital periods shorter or longer than \( 25–3 \times 10^{0} \) days. The parameter space is smaller than in the former two cases because generally more massive donors are required to sustain sufficient matter to form a super-Chandrasekhar WD. In the figure the red lines divide the final results. The initial orbital periods range from about 0.2 to 4 days. Compared with the results without the wind considered (Li & van den Heuvel 1997; Tauris et al. 2013), in which the lower limit of the donor mass \( \sim 2 M_{\odot} \), the donor mass extends to smaller mass (\( \lesssim 1 M_{\odot} \)), and the orbital period distribution becomes narrower. The reason is that here the mass transfer is mainly driven by the excited wind when \( M_{\text{tr}} < 2 M_{\odot} \), rather than the thermal evolution of the companion star. Meanwhile, the wind can somewhat stabilize the mass transfer when \( M_{\text{tr}} > 2 M_{\odot} \). Outside the confined regions either the mass transfer becomes dynamically unstable or the WD can never reach the Chandrasekhar limit because of relatively low mass transfer rate. In the right panel, the WD is assumed to rotate rapidly and continue accreting matter when its mass exceeds the Chandrasekhar limit. When the mass transfer rate becomes \( 3 \times 10^{-7} M_{\odot} \, \text{yr}^{-1} \), it slows down and begins to collapse. In this case, systems that can successfully evolve to AIC have companions of initial masses \( \sim 1–3.5 M_{\odot} \) and initial orbital periods \( \sim 0.25–3.5 \) days. The parameter space is smaller than in the former two cases because generally more massive donors are required to sustain sufficient matter to form a super-Chandrasekhar WD. In the figure the red lines divide the final evolutionary products of the binaries. Systems above the red line will evolve to become NS/WD binaries. The companion stars in the regions below the red line are of low mass and in short orbits after AIC, and they stay in the MS phase within the Hubble time.

In Figure 2 we show the distribution of the companion mass \( M_{c} \) versus the orbital period \( P_{\text{orb}} \) at the moment of AIC. The left, middle, and right panels correspond to those in Figure 1. The most striking feature is that the orbital periods occupy a small range of \( \sim 0.3–1.7 \) days, and the companion mass goes down to \( \sim 0.2–0.3 M_{\odot} \) for the Chandrasekhar model. The low mass of the companion star and the short orbital period mainly originate from the mass and angular momentum loss related to the irradiation-excited wind. The WD accretes more mass from the donor in the super-Chandrasekhar model. Therefore, the range of the companion mass (\( \sim 0.4–1.1 M_{\odot} \)) when AIC occurs.

(2010) and Tauris et al. (2013) have shown that including a kick velocity with a dispersion of 50 km s\(^{-1}\) does not seriously affect the final results.

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is smaller, but the orbital period range (~0.3–2.9 days) is a bit larger.

Figures 3 and 4 display four examples of the evolution of the mass transfer rate, the orbital period, the companion mass, and the WD/NS mass for binaries with different initial parameters in the pre- and post-AIC phases, respectively. Here we adopt the Chandrasekhar model with Z = 0.02.

In the top panel of Figure 3 we take $M_{2,1} = 1.7 \, M_\odot$ and $P_{\text{orb},i} = 1.25$ days. In such a binary the traditional thermal timescale mass transfer is not rapid enough for stable H burning. However, its rate is enhanced by the irradiation-excited wind up to a few $10^{-7} \, M_\odot$ yr$^{-1}$; thus, the WD can grow in mass to $M_{\text{Ch}}$. The orbital period decreases along with the mass transfer. In the second panel we take $M_{2,1} = 2.54 \, M_\odot$ and $P_{\text{orb},i} = 1.95$ days. Since the donor mass is considerably larger than the WD mass, although the irradiation-excited wind also works, the mass transfer actually proceeds on a thermal timescale, similar to that in typical SSSs. In the third panel we take $M_{2,1} = 1.8 \, M_\odot$ and $P_{\text{orb},i} = 1.0$ day. The binary evolution seems to be similar to that in the top panel before AIC, but it differs after AIC as shown in Figure 4. In the bottom panel we take $M_{2,1} = 1.5 \, M_\odot$ and $P_{\text{orb},i} = 0.75$ days, which are below the red line in Figure 1. This binary will evolve toward a very compact system after AIC.

Figure 4 shows the post-AIC mass transfer processes in the four binaries discussed above. The binaries evolve in a similar way as low- and intermediate-mass X-ray binaries (L/IMXBs). In the first one (in the top panel), the mass transfer initiates when the orbital period is ~0.34 days and the companion mass is ~0.48 $M_\odot$. These values are roughly in accord with the donor mass and the orbital period of the LMXB 4U 1822–37. Hence, if the newborn NS possesses a strong magnetic field (~10$^{12}$ G), the evolutionary sequence in the top panels of Figures 3 and 4 provides a possible formation path of 4U 1822–37. The orbital period increases with mass transfer to ~3.07 days when the donor loses its envelope and leaves an He WD. About 0.197 $M_\odot$ is accreted by the NS, which should be recycled to be an MSP. In the second case, the mass transfer begins at a longer orbital period (~1.2 days). The orbital period increases to ~30 days when the donor evolves to become a WD. The NS accretes a large amount of mass ($\Delta M \sim 0.54 \, M_\odot$), and a significant decay of its magnetic field is also expected. In the third panel the mass transfer initiates when the orbital period is ~0.30 days.

That is very close to $P_{\text{orb}}$, so the final orbital period does not change much. The companion star finally becomes a ~0.16 $M_\odot$ He WD, and the NS is recycled by accreting about 0.18 $M_\odot$. The last binary evolves all the way to be a very compact X-ray binary. The NS continues accreting mass when the donor star stays on the MS, and the orbital period decreases down to ~0.066 days when the donor mass is lower than 0.1 $M_\odot$. The fate of the binary may be a black widow system.

In Table 1 we list the calculated parameters of selected binary evolutionary sequences. In most cases the NSs can accrete >0.05 $M_\odot$ during the post-AIC mass transfer phase, which seems to be sufficient to reduce the NS fields to $\lesssim 10^9$ G and accelerate the NS spin periods to $\lesssim 20$ ms. However, this is strongly dependent on the (unknown) mass transfer efficiency, and there is mounting evidence that NSs may accrete a small fraction of the transferred mass in the evolution of LMXBs (e.g., Jacoby et al. 2005; Antoniadis et al. 2012).

Figure 5 shows the distribution of the produced NS/WD binaries in the orbital period ($P_{\text{orb},f}$) versus the WD mass ($M_2$) diagram. The solid, dotted, and dashed lines represent the results of the Chandrasekhar model with $Z = 0.02$ and 0.001 and the super-Chandrasekhar model with $Z = 0.02$, respectively. The observed binary pulsars with a WD companion are also plotted with dots, with different colors denoting the range of the pulsar magnetic fields (data are taken from the ATNF pulsar catalog$^4$): red, blue, and green colors are for $B < 10^{10}$ G, $10^{10} \, G < B < 10^{12}$ G, and $B > 10^{12}$ G, respectively. They roughly correspond to recycled, mildly recycled, and nonrecycled pulsars, respectively. It is seen that the predicted orbital periods of NS/WD binaries are distributed between $\gtrsim 0.1$ and $\lesssim 30$ days, and the WD masses are between ~0.15 and ~0.45 $M_\odot$, compatible with a large fraction of the known MSP/He WD binaries.$^5$ However, it is still unable to account for some peculiar systems like PSR 1831–00, which has a strong ($7.5 \times 10^{10}$ G) magnetic field, a short (1.81 days) orbit, and a very low mass (0.075 $M_\odot$) WD companion (Sutantyo & Li 2000).
4. DISCUSSION AND CONCLUSIONS

With population synthesis calculations, Hurley et al. (2010) suggested that, while both the CCSN and AIC channels lead to populations of X-ray binaries and binary MSPs at the end of the accretion phase, the birth rates of binary MSPs via AIC are comparable to or even exceed those for CCSNe, and it appears to be the major channel for the pulsars in long-period (> a few days) systems with He WD companions under certain model assumptions. These conclusions are further confirmed by Tauris et al. (2013) with detailed evolutionary calculations. They showed that MSPs formed via AIC and that have He WD companions generally have $P_{\text{orb}}$ between 10 and 60 days. However, as pointed out by Hurley et al. (2010), both the AIC and CCSN channels have a problem producing the observed orbital period range of the binary MSP/WD binaries.

The predicted orbital period and WD mass distributions of the binary pulsar systems depicted in Figure 5 are in broad agreement with those in previous investigations on L/IMXBs (Rappaport et al. 1995; Tauris & Savonije 1999; Podsiadlowski et al. 2002; Lin et al. 2011; Smedley et al. 2014; Jia & Li 2014; Istrate et al. 2014). For binaries with low-mass He WDs, lower metallicities tend to result in shorter orbital periods, as in Jia & Li (2014). However, since MSPs with He WD companions in very compact binaries can also be accounted for by LMXB evolution if the progenitor binary experienced very late Case A mass transfer (Smedley et al. 2014; Jia & Li 2014; Istrate et al. 2014), it is difficult to distinguish the formation channels for MSPs only from their currently measured parameters. Besides (partially) alleviating the birth rate discrepancy between MSPs and LMXBs, the AIC channel under wind-driven evolution may be preferred for the formation of the strong-field NSs in “old” binaries with short orbital periods. The NS in 4U 1822−37, as...
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Figure 4. Post-AIC evolution of the four binaries depicted in Figure 3. From left to right are shown the mass transfer rate, the orbital period, the companion mass, and the NS mass vs. age.

mentioned before, is one example. The binary radio pulsar PSR B1718−19 in the globular cluster NGC 6342 (Lyne et al. 1993) could be another example. It is a young, long-spin-period (\(\sim 1\) s) pulsar, with a characteristic age of 10 Myr and a magnetic field of \(1.5 \times 10^{12}\) G. The origin of such apparent young objects in very old systems has not been understood. If PSR B1718−19 was formed through AIC recently (e.g., Lyne et al. 1996), its 6.2 hr orbital period can be accounted for by the irradiation-excited wind during the previous mass transfer phase.

The magnetic field of a newborn NS after AIC depends on the property and the accretion history of the WD, as well as the complicated field decay/generation mechanisms (Ferrario & Wickramasinghe 2007 and references therein), so that it is difficult to precisely predict the field distribution. If the WD originally has a very weak field, the NS may be born with rapid rotation (milliseconds in periods) and a low field (\(\sim 10^8\) G), if we assume that the magnetic flux is conserved. During the AIC, some baryonic mass is abruptly lost to its binding energy, so that the orbit expands and the companion star is detached from its RL. The mass transfer terminates and the NS appears as an MSP, which may be able to ablate/evaporate the companion with its high-energy radiation and particles, leading to the redback-like systems (see Roberts 2013, for a review on redbacks). This turning on of an MSP activity was previously assumed to occur during the LMXB evolution when the mass transfer rate is temporarily decreased (Chen et al. 2013; Benvenuto et al. 2014). The AIC scenario for the redback formation was recently proposed by Smedley et al. (2015). They showed that the subsequent evolution is determined by orbital angular momentum loss due to gravitational radiation and magnetic braking and ablation of the companion star at a rate of (Stevens et al. 1992)

\[
-M_2 = \frac{f L_{\text{psr}}}{2v_{\text{esc}}^2} \left( \frac{R_2}{a} \right)^2,
\]

where \(L_{\text{psr}}\) is the MSP’s spin-down luminosity (taken a typical value of \(1.5 \times 10^{34}\) erg s\(^{-1}\)), \(f\) is an efficiency parameter denoting the fraction of the MSP’s luminosity that is used to ablate the companion, \(v_{\text{esc}}\) is the escape velocity of a thermal wind from the surface of the companion, \(R_2\) is the companion’s radius, and \(a\) is the binary separation. It was shown that if \(f > 0.12\), ablation is strong enough to overcome the pull of magnetic braking immediately after AIC and the systems evolve to longer orbital periods without the occurrence of a second RLOF. In Smedley et al. (2015), all the initial systems have a 1.2 \(M_\odot\) WD and a 1.0\(M_\odot\) donor with a 0.3 day orbital period. However, it is already known that the evolution of such a binary cannot lead to
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Figure 5. Distributions of the final orbital periods and companion masses of the binaries that end as PSR/WD binaries. The solid, dotted, and dashed lines are for cases of the Chandrasekhar model with $Z = 0.001$ and $Z = 0.02$ and the super-Chandrasekhar model with $Z = 0.02$, respectively. The circles represent the observed binary pulsar systems with known magnetic fields.

Table 1
Selected Examples of the Evolutionary Sequences that Form Binary Pulsars

| $P_{\text{orb},i}$ (days) | $M_{\text{z},i}$ ($M_\odot$) | $P_{\text{orb,asc}}$ (days) | $M_{\text{z,asc}}$ ($M_\odot$) | $P_{\text{orb,f}}$ (days) | $M_{\text{z,f}}$ ($M_\odot$) | $\Delta M$ ($M_\odot$) |
|---------------------------|-----------------------------|----------------------------|----------------------------|---------------------------|-----------------------------|------------------------|
| 1.2                       | 1.7                         | 0.32                       | 0.37                       | 1.56                      | 0.187                       | 0.06                   |
| 1.2                       | 1.9                         | 0.42                       | 0.86                       | 8.15                      | 0.225                       | 0.22                   |
| 1.2                       | 2.4                         | 0.84                       | 1.85                       | 28.3                      | 0.275                       | 0.55                   |
| 1.95                      | 2.5                         | 1.23                       | 1.847                      | 32.81                     | 0.312                       | 0.537                  |
| 1.95                      | 3.2                         | 0.75                       | 1.1                        | 6.91                      | 0.377                       | 0.253                  |
| 2.9                       | 3.2                         | 1.22                       | 0.99                       | 7.63                      | 0.411                       | 0.202                  |
| 2.9                       | 3.5                         | 1.4                        | 0.738                      | 4.58                      | 0.428                       | 0.108                  |
| 3.5                       | 3.5                         | 1.93                       | 0.679                      | 4.97                      | 0.44                        | 0.083                  |
| 1.0                       | 2.2                         | 0.56                       | 1.5                        | 17.96                     | 0.25                        | 0.43                   |
| 1.0                       | 2.7                         | 0.61                       | 2.02                       | 24.62                     | 0.26                        | 0.64                   |
| 2.0                       | 1.9                         | 0.81                       | 0.975                      | 17.42                     | 0.25                        | 0.253                  |
| 2.0                       | 2.2                         | 1.31                       | 1.615                      | 38.54                     | 0.286                       | 0.465                  |
| 2.0                       | 2.9                         | 0.84                       | 1.625                      | 15.83                     | 0.347                       | 0.447                  |
| 3.0                       | 2.2                         | 1.65                       | 1.508                      | 42.6                      | 0.295                       | 0.424                  |
| 3.0                       | 3.0                         | 1.2                        | 1.42                       | 15.32                     | 0.38                        | 0.363                  |
| 4.0                       | 3.1                         | 1.73                       | 1.065                      | 12.41                     | 0.408                       | 0.229                  |
| 1.0                       | 2.0                         | 0.36                       | 0.68                       | 5.84                      | 0.213                       | 0.16                   |
| 1.0                       | 2.6                         | 0.46                       | 1.049                      | 11.73                     | 0.234                       | 0.28                   |
| 2.0                       | 2.1                         | 1.01                       | 0.627                      | 9.5                       | 0.26                        | 0.13                   |
| 2.0                       | 2.7                         | 1.54                       | 0.54                       | 6.08                      | 0.317                       | 0.08                   |
| 2.0                       | 3.2                         | 1.62                       | 0.531                      | 3.1                       | 0.373                       | 0.06                   |
| 3.0                       | 2.9                         | 2.9                        | 0.502                      | 5.42                      | 0.376                       | 0.045                  |
| 3.0                       | 3.4                         | 1.91                       | 0.57                       | 3.61                      | 0.429                       | 0.05                   |
| 3.5                       | 3.5                         | 2.32                       | 0.57                       | 4.08                      | 0.44                        | 0.046                  |

Notes. The three parts correspond to the results of the Chandrasekhar model with $Z = 0.02$ and 0.001 and the super-Chandrasekhar model with $Z = 0.02$, respectively.

The formation of a Chandrasekhar-mass WD because the mass transfer driven by magnetic braking is too low to allow stable H and He burning (e.g., Li & van den Heuvel 1997; Ivanova & Taam 2004; Tauris et al. 2013). Aided with an irradiation-excited wind, it is able to evolve to AIC as shown in this work. We have calculated the binary evolution after AIC assuming that the NSs are born as MSPs. In Figure 6 we illustrate the evolutionary tracks for six example binary pulsars. Here the green, black,
and red lines are for the cases with $f = 0.1$, 0.45, and 0.8, respectively. The blue triangles show the positions of known redbacks. Figure 6 confirms that it is possible to account for redbacks at both small and large companion masses by changing the value of $f$ or $L_{\text{psr}}$ within a proper range.

Finally, it should be noted that the conditions for the wind-driven evolution are not well understood, so the birth rate of MSPs via wind-driven AIC currently cannot be confidently estimated. Although there is evidence that there is or has been rapid mass transfer in short-period WD binaries with a low-mass companion star, most of the known such WD binaries are ordinary cataclysmic variables, suggesting that the wind-driven case might not be popular, and its occurrence requires some special conditions (see King & van Teeseling 1998, for a discussion). Obviously, a thorough investigation on this subject will be of great value not only for AIC and SNe Ia but also for the overall evolution of cataclysmic variables.

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Figure 6. Post-AIC evolution of six binary pulsars. The NSs are assumed to be born as MSPs and able to ablate the secondaries. The green, black, and red lines describe the results with the efficiency factor $f = 0.1$, 0.45, and 0.8, respectively. The known redbacks are plotted as triangles. Their mass error bars correspond to the orbital inclinations between 25.8° and 90° (data are taken from Smedley et al. 2015 and references therein).
