FORMACION OF MILLISECOND PULSARS WITH LOW-MASS HELIUM WHITE DWARF COMPANIONS IN VERY COMPACT BINARY

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ABSTRACT

Binary millisecond pulsars (MSPs) are old neutron stars (NSs) with short spin period ($P_s \lesssim 30$ ms) and weak magnetic fields ($B \sim 10^{-6}$–$10^{10}$ G; Lorimer 2008). Soon after the discovery of the first MSP B1937+21 (Backer et al. 1982), a scenario was proposed to link the evolution of low-mass X-ray binaries (LMXBs) with binary millisecond pulsars (BMSPs; Alpar et al. 1982; Radhakrishnan & Srinivasan 1982). An NS in LMXBs may accrete mass and angular momentum from its companion star for a sufficiently long time (usually a few gigayears), and subsequently be spun up to millisecond spin periods.3 After the mass transfer terminates, the radio radiation from the NS starts to reverse its spin-down (Refsdal & Weigert 1971; Webbink et al. 1983), thus resulting in a relation between the WD mass $M_{WD}$ and the final orbital period $P_f$ at the end of mass transfer (Joss et al. 1987; Rappaport et al. 1995; Tauris & Savonije 1999; De Vito & Benvenuto 2010).

Although this recycling scenario is now widely accepted for MSPs, some aspects such as the details of the accretion process are still not clear (Tauris & van den Heuvel 2006). For example, according to statistical analysis of the pulsar masses, the mean mass of MSPs is about 0.2 $M_{\odot}$ higher than that of non-recycled pulsars (PSRs; Zhang et al. 2011), which implies that the mass transfer is nonconservative in general, i.e., only a small fraction of the transferred matter is accreted and the rest escapes from the systems.

Previous works mainly focused on the $P_f - M_{WD}$ relation for wide systems with $P_i > 1$ day and paid less attention to compact MSP/He WD systems. In recent years, several compact MSP/He WD systems were discovered, including PSRs J0348+0432 (Antoniadis et al. 2013), J0751+1807 (Marsh et al. 2008), J1012+5307 (van Kerkwijk et al. 2005), J1738+0333 (Antoniadis et al. 2012), and J1910−5959A (Corongiu et al. 2012). These pulsars all have short ($<1$ day) orbital periods and low-mass ($<0.2 M_{\odot}$) WDs. In particular, the extremely short orbital period (2.46 hr) of PSR J0348+0432 is difficult to explain using the traditional evolutionary theory (Antoniadis et al. 2013).

The aim of this work is to investigate the formation of compact ($\lesssim 1$ day) MSP/He WD systems, and obtain a complete $P_i - M_{WD}$ relation down to the short-period end. A similar work was recently done by Smedley et al. (2014), and the authors were concentrating on BMSPs in the Galactic field. Here we extend

1. INTRODUCTION

Millisecond pulsars (MSPs) are old neutron stars (NSs) with short spin period ($P_s \lesssim 30$ ms) and weak surface magnetic fields ($B \sim 10^{-6}$–$10^{10}$ G; Lorimer 2008). Soon after the discovery of the first MSP B1937+21 (Backer et al. 1982), a scenario was proposed to link the evolution of low-mass X-ray binaries (LMXBs) with binary millisecond pulsars (BMSPs; Alpar et al. 1982; Radhakrishnan & Srinivasan 1982). An NS in LMXBs may accrete mass and angular momentum from its companion star for a sufficiently long time (usually a few gigayears), and subsequently be spun up to millisecond spin periods.3 After the mass transfer terminates, the radio radiation from the NS starts to reverse its spin-down (Refsdal & Weigert 1971; Webbink et al. 1983), thus resulting in a relation between the WD mass $M_{WD}$ and the final orbital period $P_f$ at the end of mass transfer (Joss et al. 1987; Rappaport et al. 1995; Tauris & Savonije 1999; De Vito & Benvenuto 2010).

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3 A large fraction of LMXBs may have evolved from binaries with an intermediate-mass secondary (e.g., Podsiadlowski et al. 2002). However, most of the spin-up processes should occur during the LMXB phase.
the relation to lower metallicities and apply it to the formation of PSRs J0348+0432 and J1738+0333. The rest of this paper is organized as follows. We first describe the binary evolution code used in this work in Section 2. We present the calculated results for a series of binary models in Section 3, and compare them with the observations of two BMSPs in Section 4. We summarize the results in Section 5.

2. BINARY EVOLUTION CODE

We adopt an updated stellar evolution code EV originally developed by Eggleton (1971, 1972) (also see Han & Podsiadlowski 2004; Pols et al. 1995) to calculate the evolution of binary systems composed of an NS (of mass $M_1$) and a zero-age main sequence (ZAMS) secondary (of mass $M_2$). For the secondary/donor star, we consider three kinds of chemical compositions (Pop I with $X = 0.70, Z = 0.02$; Pop II with $X = 0.75, Z = 0.001$; and $X = 0.7597, Z = 0.0001$). We take the ratio of the mixing length to the pressure scale height to be 2.0 and the convective overshooting parameter to be 0.12. The effective RL radius of the secondary star is given by the empirical formula proposed by Eggleton (1983):

$$ R_{L,2} = \frac{0.49q^{-2/3}}{0.6q^{-2/3} + \ln(1 + q^{-1/3})} \sigma, \quad (1) $$

where $q = M_2/M_1$ is the mass ratio and $\sigma$ is the orbital separation. During the RLO phase, we adopt the mass transfer rate as $\dot{M}_2 = -10^3[\log(R_2/R_{L,2})^3]^{-1/3} M_\odot \text{yr}^{-1}$, where $R_2$ is the radius of the secondary.

The rate of the orbital AML is composed of three parts:

$$ \dot{J} = \dot{J}_{GR} + \dot{J}_{ML} + \dot{J}_{MB}. \quad (2) $$

The first term on the right-hand side of the above equation is the AML due to gravitational radiation (GR; Landau & Lifshitz 1975), given by

$$ \dot{J}_{GR} = -\frac{32}{5} G \frac{M_1^2 M_2^2 (M_1 + M_2^{1/2})}{a^{7/2}} \epsilon^5, \quad (3) $$

where $G$ is the gravitational constant and $c$ is the speed of light. The second term is due to mass loss. We assume that a fraction $\alpha$ of the transferred mass is accreted by the NS, and the rest is ejected out of the system from the vicinity of the NS as isotropic winds, taking away the specific angular momentum of the NS. Then we have

$$ \dot{J}_{ML} = -(1 - \alpha) \frac{M_2}{M_1 + M_2} \frac{2}{a^2} \epsilon^2 \omega, \quad (4) $$

where $\omega$ is the angular velocity of the binary. The third AML mechanism is magnetic braking (MB). Here, we adopt the MB formula postulated by Verbunt & Zwaan (1981) and Rappaport et al. (1983):

$$ \dot{J}_{MB} = -3.8 \times 10^{-30} M_2 R_2^4 \epsilon^3 \text{dyn cm.} \quad (5) $$

When the convective envelope of the secondary becomes too thin, the MB effect is much reduced. Following Podsiadlowski et al. (2002), we add an ad hoc factor

$$ \exp(-0.02/q_{\text{conv}} + 1) \quad \text{if } q_{\text{conv}} < 0.02 $$

to Equation (5), where $q_{\text{conv}}$ is the mass fraction of the surface convective envelope.

3. RESULTS

In our control model, we consider a binary composed of an NS of initial mass $M_1 = 1.4 M_\odot$, and a ZAMS secondary of initial mass $M_2 = 1.4 M_\odot$ with Pop I chemical compositions. Figure 1 shows the calculated $P_1$–$M_{WD}$ relation (left panel) and the $P_1$–$P_1$ relation (right panel), for three different mass transfer efficiencies, $\alpha = 0, 0.5$, and 1.0. We calculate the binary evolution down to the lower WD mass limit by gradually reducing the initial orbital period until the donor star can no longer form a WD. According to our calculations, the $P_1$–$M_{WD}$ relation extends to $M_{WD} \sim (0.14–0.15) M_\odot$ for $Z = 0.02$, $\sim 0.16 M_\odot$ for $Z = 0.001$, and $\sim 0.17 M_\odot$ for $Z = 0.0001$. Additionally, there is always a break between the final compact and wide systems, which is due to the temporary overall contraction of the donor star when the H-burning shell crosses the hydrogen discontinuity.
Figure 2. Solid lines in the left panel show the evolutionary sequences in the control model with different initial orbital periods, and the thick parts of the lines indicate the RLO phase. The dashed line represents the evolutionary track of a 1.4 $M_\odot$ single star. The diamonds denote the RL detachment of the donor, which gives the $P_f-M_{\text{WD}}$ relation. The lines in the right panel show the corresponding radius evolution of the donor, and the RLO phase is also denoted by thick lines. The circles indicate the temporary contraction of the donor due to the dredge-up process. (A color version of this figure is available in the online journal.)

Our calculations show that, in converging systems with very late Case A mass transfer, the donor may have time to develop a He core during the mass transfer, and the $P_f-M_{\text{WD}}$ relation would be followed. When it leaves the main sequence and reaches the base of the red giant branch, the donor star consists of a shell-burning layer located between the degenerate He core and the convective envelope. After the convective envelope reaches its deepest extent, the H-burning shell has burned its way out to the discontinuity of higher H abundance left by the first dredge-up, leading to a slightly lower burning rate and a slight decrease in its radius. Figure 2 shows four evolutionary tracks of the donor star on the H-R diagram with the initial orbital periods $P_i$ lying between 1.057 days and 1.4 days (left panel) and its radius evolution (right panel) based on the control model, where the temporary contraction is emphasized by a circle. In cases of relatively long initial orbital period, the donor star possesses a large convective envelope so that it still has enough material in the envelope for burning after the dredge-up. It can pass through the temporary contraction and expand again to refill its RL, leaving a relatively massive WD. For a relatively short initial orbital period, the donor star possesses a small convective envelope so that it cannot refill its RL after the temporary contraction, or it has already exhausted all the nuclear fuel and entered the final contraction phase before the temporary contraction. Hence the break in the $P_f-M_{\text{WD}}$ relation actually reflects whether the donor star can refill its RL after the first dredge-up.

3.1. Dependence on the Input Parameters

1. The efficiency of mass transfer. There is mounting evidence of nonconservative mass transfer in LMXBs even at sub-

4 Here very late Case A mass transfer means that at the beginning of RLO, the secondary has evolved near the end of main sequence but has not developed a He core within it. The initial conditions of the binary (e.g., the evolutionary status of the donor at the onset of RLO) and the timescale of the RLO phase depend on the efficiency of MB adopted.

Eddington mass transfer rates (e.g., Jacoby et al. 2005; Marsh et al. 2008; Antoniadis et al. 2012). Our calculated results with different values of $\alpha = 0$, 0.5, and 1 in Figure 1 shows that the $P_f-M_{\text{WD}}$ relation and the related discontinuity are insensitive to $\alpha$. The former has already been noted by many authors.

2. The initial NS mass. Investigations of the formation of PSR J1614$-$2230 (Demorest et al. 2010) suggest that it may have been born massive (Tauris et al. 2011; Lin et al. 2011). In Figure 3, we compare the $P_f-M_{\text{WD}}$ relations with two different initial NS masses of 1.4 and 2.0 $M_\odot$. Though the increase in the NS mass may influence the initial parameter space to form BMSPs (Shao & Li 2012), it barely affects
the final $P_1 - M_{\text{WD}}$ relation (De Vito & Benvenuto 2010), so we cannot obtain the initial NS mass simply from the current WD mass.

3. The initial donor mass. In Figure 4, we show the $P_1 - M_{\text{WD}}$ relations with initial donor masses of 1.0 $M_\odot$, 1.4 $M_\odot$, and 2.0 $M_\odot$. The left and right panels correspond to $Z = 0.02$ and $Z = 0.001$, respectively. In the case of the 2.0 $M_\odot$ donor star, systems with massive ($\gtrsim 0.28 M_\odot$) WDs deviate from the expected relation for less massive donors. The reason is that, due to the large mass ratio, when the RLO initiates, the thermal timescale mass transfer is extremely super-Eddingtonian and highly nonconservative, thus the evolution typically terminates long before this relation is reached (Podsiadlowski et al. 2002; Lin et al. 2011).

4. The metallicities. We compare the $P_1 - M_{\text{WD}}$ relations for different donor masses and chemical compositions ($Z = 0.02$, 0.001, and 0.0001) in Figure 5. The reduction of metallicities leads to smaller stellar radius, shorter nuclear evolutionary timescale, and hence shorter bifurcation period. Stars with the same mass but lower metallicities form WDs in a narrower orbit.

![Figure 4](image_url)

**Figure 4.** Comparison of the $P_1 - M_{\text{WD}}$ relations with initial donor masses of 1.0 $M_\odot$, 1.4 $M_\odot$, and 2.0 $M_\odot$. The metallicities are taken to be $Z = 0.02$ and 0.001 in the left and right panels, respectively. The meanings of the lines are same as in Figure 1. (A color version of this figure is available in the online journal.)

![Figure 5](image_url)

**Figure 5.** $P_1 - M_{\text{WD}}$ relations from all the calculated results with different metallicities. Also plotted are BMSPs with both component masses measured. (A color version of this figure is available in the online journal.)

3.2. Comparison with Previous Works

The $P_1 - M_{\text{WD}}$ relation has been investigated extensively. An empirical fitting formula was first proposed by Rappaport et al. (1995) for a giant star with a core mass between 0.15 $M_\odot$ and 1.15 $M_\odot$ with single star evolution calculations. Tauris & Savonije (1999) investigated the evolution of LMXBs with $P_1 > 2$ days based on binary evolution calculations, and presented modified fitting formulae in the range of $0.18 M_\odot \lesssim M_{\text{WD}} \lesssim 0.45 M_\odot$, for both Pop I and II stars. Ergma et al. (1998) showed that for converging binaries, if the initial orbital periods lie between the bifurcation period and the so-called boundary orbital period, the binaries will evolve to short-period BMSPs with a He WD, the mass of which can be as low as 0.15–0.16 $M_\odot$ (for $Z = 0.03$) and 0.17 $M_\odot$ (for $Z = 0.003$), while below the boundary orbital period the binaries will evolve through a period minimum with an RLO donor and end their evolution as ultrashort-period LMXBs. De Vito & Benvenuto (2010) and Lin et al. (2011) also systematically calculated the evolution of LMXBs and obtained the $P_1 - M_{\text{WD}}$ relation for Pop I stars. More recently, Smedley et al. (2014) showed that the $P_1 - M_{\text{WD}}$ relation can be reproduced, extending to orbital periods of less than 1 day for a 1 $M_\odot$ giant donor. They also noticed some discontinuities in the relation around a WD mass of 0.225 $M_\odot$. In this work we found the lower limit of the WD mass, following the $P_1 - M_{\text{WD}}$ relation, to be $\sim (0.14–0.15) M_\odot$ (for $Z = 0.02$), $\sim (0.16 M_\odot$ (for $Z = 0.001$), and $\sim (0.17 M_\odot$ (for $Z = 0.0001$), consistent with previous results. Our calculations not only confirm the existence of the discontinuities, but also show that their positions vary with the donor’s mass and metallicities. Generally, for wide systems our results are in accordance with Tauris & Savonije (1999), while for the compact systems are closer to De Vito & Benvenuto (2010). The whole range of the relation agrees well with the fit given by Lin et al. (2011).

4. COMPARISON WITH OBSERVATIONS

In Figure 5 we plot seven BMSPs in which both component masses have been measured. The mass error bars correspond to 1σ uncertainties (data are taken from Smedley et al. 2014 and references therein). There is broad agreement for both compact and wide systems if a range of chemical abundances are taken into account. In the following we discuss two specific
cases of BMSPs with low-mass WDs, PSRs J1738+0333 and J0348+0432.

4.1. PSR J1738+0333

PSR J1738+0333 is a 5.85 ms pulsar accompanied by a He WD in an 8.5 hr orbit. It was first discovered with the Parkes 64 m telescope in a 20 cm survey in 2001 (Jacoby 2005). The WD companion is bright enough for optical spectroscopy and photometric study, which revealed its mass $0.18_{-0.06}^{+0.07} M_{\odot}$ (Antoniadis et al. 2012). Combined with the mass ratio $q = 8.1$ inferred from the radial velocities and the precise pulsar timing ephemeris, the NS mass was inferred to be $1.47_{-0.06} M_{\odot}$. These estimates imply a highly nonconservative mass transfer during the LMXB evolution.

For the evolutionary history of this system, Antoniadis et al. (2012) pointed out that the system is most likely to be the fossil of Case A RLO, but the WD mass and the orbital eccentricity are both consistent with Case B RLO, although there is a gray zone for properties from both cases.

As shown in Figures 5 and 6 (left panel), PSR J1738+0333 fits well with the $P_{\text{f}}-M_{\text{WD}}$ relation, located between the cases of $Z = 0.001$ and $Z = 0.0001$. According to our calculations of binary evolution with $M_1 = 1.4 M_{\odot}$ and $Z = 0.001$, the boundary between Case A and B RLO is $M_{\text{WD}} \sim (0.2-0.3) M_{\odot}$ on the $P_{\text{f}}-M_{\text{WD}}$ relation, for the initial donor masses $M_2 \sim (1.0-2.0) M_{\odot}$. Then the $\sim 0.18 M_{\odot}$ He WD companion suggests that PSR J1738+0333 is more likely to have been recycled through Case A RLO. In the right panel of Figure 6, we show three examples of binary evolutionary sequences with the final WD mass lying between $0.176 M_{\odot}$ and $0.187 M_{\odot}$, with $Z = 0.001$. After the RLO, the orbit decays due to GR, the rate of which depends on the WD mass. This may put useful constraints on the cooling age of the WD.

4.2. PSR J0348+0432

PSR J0348+0432 is a 39 ms pulsar in a 2.46 hr orbit accompanied by a $0.17 M_{\odot}$ He WD, discovered with the Green Bank Telescope (Boyles et al. 2013; Lynch et al. 2013). Similar to PSR J1738+0333, the component masses of the binary were determined using spectroscopic and photometric methods (Antoniadis et al. 2013). The extremely narrow orbit and the low mass of the He WD suggest that it experienced an efficient loss of orbital angular momentum and an envelope-stripping phase. These can be achieved either through the common-envelope (CE) channel or the converging LMXB channel. As pointed out by Antoniadis et al. (2013), the formation via a CE and spiral-in phase is less possible, since the mass transfer in the progenitor binary would be dynamically stable without forming a CE. In the more promising converging LMXB channel, according to the estimated $\sim 2$ Gyr cooling age of the WD, the donor star should detach from its RL at an orbital period of $\sim$ five hr, which was derived from the GR-induced orbital decay during this time. The main issue is that converging LMXBs often keep evolving with continuous mass transfer and evolve to more compact systems. In order to get the decoupling from the RL at the correct values of the orbital period and the companion mass, a finely tuned termination of the mass transfer process at $\sim$ five hr is required.

As seen in Figure 5, the $P_{\text{f}}-M_{\text{WD}}$ relation at the lower WD mass end is mainly affected by the metallicity of the donor. For a given WD mass, the final orbital period decreases with metallicity. We have calculated the evolution of LMXBs with different metallicities to form a BMSP with a $\sim 0.17 M_{\odot}$ WD companion, and found that the orbital period at the decoupling is about 5 hr for $Z = 0.0001$, 7 hr for $Z = 0.001$, and 14 hr for $Z = 0.02$. The latter two values can be ruled out since they indicate too long a time for orbital decay after RLO that the lifetime of the pulsar becomes longer than a Hubble time. In the right panel of Figure 6, we show the possible formation tracks of PSR J0348+0432 to demonstrate that it is possible to form PSR J0348+0432-like systems within a Hubble time if the donor’s metallicity was extremely low ($Z = 0.0001$). Furthermore, we mention that the WD cooling time increases with decreasing metallicity (Serenelli et al. 2001, 2002), so the orbital period at the decoupling could be longer than 5 hr. This may also help solve the formation puzzle of PSR J0348+0432.

5. CONCLUSIONS

The main results in this work are summarized as follows.

1. The $P_{\text{f}}-M_{\text{WD}}$ relation for BMSPs with He WD companions can extend to $\sim (0.14-0.15) M_{\odot}$ for $Z = 0.02$, $\sim 0.16 M_{\odot}$ for $Z = 0.001$, and $\sim 0.17 M_{\odot}$ for $Z = 0.0001$. 

Figure 6. Left panel is part of Figure 5 for comparison between the theoretical $P_{\text{f}}-M_{\text{WD}}$ relations and the observations of PSRs J1738+0333 and J0348+0432. The right panel shows the possible evolutionary tracks for these two pulsars in the control model, with various initial orbital periods and final WD masses. The thick solid lines represent the RLO phase, and the subsequent orbital decay is dominated by GR. The two horizontal dotted lines represent the current orbital periods of PSRs J1738+0333 and J0348+0432, respectively.

(A color version of this figure is available in the online journal.)
2. The $P_f-M_{WD}$ relation is not smooth in reality, but with a discontinuity at around 0.2 $M_\odot$, which separates converging and diverging binaries.

3. BMSPs with low-mass He WD companions in compact binaries can be accounted for if the progenitor binaries experienced very late Case A mass transfer. The WD companion of PSR J1738+0333 is likely to evolve from a Pop II star. For PSR J0348+0432, to explain its extremely small orbit, even lower metallicity ($Z = 0.0001$) is needed.

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