On the progenitors of millisecond pulsars by the recycling evolutionary channel

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ABSTRACT

The recycling model suggested that low-mass X-ray binaries (LMXBs) could evolve into binary millisecond pulsars (BMSPs). In this work, we attempt to investigate the progenitor properties of BMSPs formed by the recycling evolutionary channel, and if sub-millisecond pulsars can be produced by this channel. Using Eggleton's stellar evolution code, considering that the dead pulsars can be spun up to a short spin period by the accreting material and angular momentum from the donor star, we have calculated the evolution of close binaries consisting of a neutron star and a low-mass main-sequence donor star, and the spin evolution of NSs. In calculation, some physical process such as the thermal and viscous instability of a accretion disk, propeller effect, and magnetic braking are included. Our calculated results indicate that, all LMXBs with a low-mass donor star of 1.0 - 2.0 $M_\odot$ and a short orbital period ($\lesssim 3 - 4d$) can form millisecond pulsars with a spin period less than 10 ms. However, it is difficult to produce sub-millisecond pulsars by this evolutionary channel. In addition, our evolutionary scenario cannot account for the existence of BMSPs with a long orbital period ($P_{\text{orb}} \gtrsim 70 - 80d$).

Key words: binaries: close – pulsars: general – stars: neutron – stars: evolution – stars: magnetic field – stars: low-mass

1 INTRODUCTION

Millisecond pulsars (MSPs) and normal pulsars have distinct observed properties, and they inhabit two different regions in magnetic field - spin period ($B - P$) diagram (Manchester et al. 2003). Normal pulsars have a spin period of $P \sim 1$ s and a magnetic field of $B \sim 10^{12}$ G. However, MSPs show some distinct observed properties such as short spin period ($P \lesssim 20$ ms), low spin-down rate ($\dot{P} \sim 10^{-19} - 10^{-21}$ s s$^{-1}$), old characteristic age ($\tau = P/(2\dot{P}) \sim 10^9 - 10^{10}$ yr), and weak surface magnetic fields ($B \sim 10^8 - 10^9$ G) (Manchester 2004; Lorimer 2008). About 75% MSPs are in binary system (called binary millisecond pulsars, BMSPs), whereas that is only $\lesssim 1\%$ for normal pulsars.

At present, there exist two scenarios to account for the formation of MSPs. The first one is the recycling model, in which MSPs are proposed to be the evolutionary product of neutron star (NS) low-mass X-ray binaries (LMXBs) or intermediate-mass X-ray binaries (IMXBs) (Alpar et al. 1982). The pulsar crossed the so-called deathline accretes the mass and angular momentum from the donor star that overflows its Roche lobe, and can be subsequently spun up to a millisecond spin-period (Bhattacharya & van den Heuvel 1991; Tauris & van den Heuvel 2006). During accretion, the magnetic field of the NS decrease to be $B \sim 10^8 - 10^9$ G due to accretion-induced field decay (Konar & Bhattacharya 1997). When the mass transfer ceases, a BMSP consisting of a recycling NS and a low-mass ($\lesssim 0.4M_\odot$) helium white dwarf is produced. The discovery of the accreting millisecond X-ray pulsar Sax J 1808.4-3658 presented strong support to this scenario (Wijnands & van der Klis 1998). Recent optical observations also confirm that there exists a transition link between X-ray pulsar and millisecond radio pulsar (e.g. Archibald et al. 2009).

In another evolutionary channel, MSPs may be formed by accretion-induced collapse (AIC) of ONeMg white dwarfs (Michel 1987). When the mass of an ONeMg white dwarf reaches the Chandrasekhar mass limit by accreting from its donor star, the electron-capture process leads to a gravitational collapse rather than a Type Ia explosion, and results in the formation of an NS (Nomoto & Kondo 1991)\footnote{When the ONeMg core of an asymptotic giant branch star (Siess 2007; Poelarends et al. 2008) or a He star (Nomoto 1987)\footnote{Siess 2007; Poelarends et al. 2008; Nomoto 1987}}. If MSPs

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formed by the collapse of low field \((10^3 - 10^4 \text{ G})\) white dwarf population \cite{Jordan2007}, their magnetic field should be in the range \(10^8 - 10^{15} \text{ G}\), and without invoking significant field decay. Recently, the calculated birthrates by population synthesis approach indicate that the AIC channel may play an important role in forming MSPs \cite{Hurley2010}. An alternative formation of MSPs, this evolutionary channel has been widely explored by some authors \cite{Wickramasinghe2009, Eggleton1971, Pols1995, Pols1998}. In particular, \cite{Du2009} argued that AIC process of massive white dwarfs can produce sub-millisecond pulsars (quark stars) with a spin-period less than 1 ms (or less than 0.5 ms).

The purpose of this paper is to systemically explore the initial parameter space of LMXBs that could evolve into BMSPs via the recycling evolutionary channel. In addition, we also attempt to examine if this channel can form the so-called sub-millisecond pulsar. The structure of this paper is as follows. We describe the input physics that is necessary in the evolution calculation of LMXBs in section 2. The calculated results are presented in section 3. Finally, we give a brief discussion and summary in section 4.

2 INPUT PHYSICS

Using a stellar evolution code developed by Eggleton \cite{Eggleton1971, Eggleton1972, Eggleton1973}, which has been updated with the latest input physics over the past three decades \cite{Han1994, Pols1995, Pols1998}, we calculate the evolution of binaries consisting of a NS (of mass \(M_{\text{NS}}\)) and a main-sequence donor star (of mass \(M_d\))\footnote{\textsuperscript{2}Certainly, NSs may also recycled by accreting the material from the He star companion. However, some studies show that the evolution products of NS + He star systems should be intermediate-mass binary pulsars or high-mass binary pulsars (see Franciscelli2002, Chen2011).}, and test if they can evolve into MSPs. The stellar OPAL opacities was taken from Rogers & Iglesias \cite{Rogers1992} and Alexander & Ferguson \cite{Alexander1994} for a low temperature. In our calculation, the ratio of the outburst timescale to the recurrence time [the accretion rate of the NS \(M_{\text{ac}} = -\dot{M}_d/d\)]. Otherwise for a high mass transfer rate \(-\dot{M}_d > \dot{M}_{\text{cr}}\), we assume \(M_{\text{ac}} = -\dot{M}_d\). Certainly, the mass growth rate of the NS should suffer the limitation of the Eddington accretion rate \(\dot{M}_{\text{Edd}} \approx 1.5 \times 10^{-8} M_\odot \text{ yr}^{-1}\). The excess material is assumed to be expelled from the vicinity of the NS by radiation pressure, and carries away the specific orbital angular momentum of the NS.

2.1 Accretion disk instability

With nuclear evolution, the donor star overflows its Roche lobe, and transfer hydrogen-rich material onto the NS. Due to the high angular momentum, the accreting material forms a disk surrounding the NS. If the effective temperature in the accretion disk is below \(\sim 6500 \text{ K}\) (the hydrogen ionization temperature), the disk accretion should be thermally and viscous unstable \cite{vanParadijs1996, King1997, Lasota2001}. Meanwhile, the accreting NS will be a transient X-ray source, which appears as short-lived outbursts phase and long-term quiescence phase. Recently, \cite{Chen2011} found that accretion disk instability model successfully reproduces the orbital period and the mass of the WD of PSR J1713+0747.

When the mass transfer rate \(-\dot{M}_d\) is lower than the critical mass-transfer rate \cite{Paradijs1994, Dubus1994}:

\[
\dot{M}_{\text{cr}} \approx 3.2 \times 10^{-9} \left( \frac{M_{\text{NS}}}{1.4 M_\odot} \right)^{0.5} \left( \frac{M_d}{1.0 M_\odot} \right)^{-0.2} \left( \frac{P_{\text{orb}}}{1.0 \text{ d}} \right)^{1.4} M_\odot \text{ yr}^{-1},
\]

where \(P_{\text{orb}}\) is the orbital period of the binary, the NS accretes only during outbursts. Defining a duty cycle \(d\) to be the ratio of the outburst timescale to the recurrence time, the accretion rate of the NS \(M_{\text{ac}} = -\dot{M}_d/d\).

For the angular momentum loss rate via magnetic braking, \cite{Rappaport1983} developed an empirical formula, i. e.

\[
\dot{J}_{\text{mb}} \approx -3.8 \times 10^{-30} M_2 R_2^4 \left( \frac{R_d}{R_\odot} \right)^7 \gamma^3 \text{ dyn cm},
\]

where \(R_2\) is the radius, \(\omega\) the angular velocity of the donor star, and \(\gamma\) is a dimensionless parameter in the range of zero to four. This standard magnetic braking model is widely applied in studying the evolution of cataclysmic variables. However, studies on rapidly rotating low-mass stars with a spin period below 2.5 - 5 days in young open clusters show that the standard model overestimates the angular momentum loss rate \cite{Queloz1998, Andronov2003}.

In calculation, we adopt an induced magnetic braking description given by \cite{King2004}, in which the angular momentum loss rate is

\[
\dot{J}_{\text{mb}} = \begin{cases} 
-K \omega^3 \left( \frac{R_a}{R_\odot} \frac{M_\odot}{M_a} \right)^{1/2}, & \omega \leq \omega_{\text{crit}} \\
-K \omega_{\text{crit}}^3 \left( \frac{R_a}{R_\odot} \frac{M_\odot}{M_a} \right)^{1/2}, & \omega > \omega_{\text{crit}}
\end{cases}
\]

where \(K = 2.7 \times 10^{17} \text{ cm}^2\) \cite{Andronov2003}. \(\omega_{\text{crit}}\) is the critical angular velocity at which the angular momentum loss rate reaches a saturated state, \(\omega = 2\pi/P_{\text{orb}}\) and \(R_a\) are the angular velocity and the radius of the donor star, respectively. \cite{Kim1996} proposed that \(\omega_{\text{crit}}\) is

\[
\dot{J}_{\text{mb}} = \begin{cases} 
-K \omega^3 \left( \frac{R_a}{R_\odot} \frac{M_\odot}{M_a} \right)^{1/2}, & \omega \leq \omega_{\text{crit}} \\
-K \omega_{\text{crit}}^3 \left( \frac{R_a}{R_\odot} \frac{M_\odot}{M_a} \right)^{1/2}, & \omega > \omega_{\text{crit}}
\end{cases}
\]
inversely proportional to the convective turbulent timescale of the star when its age is 200 Myr, i.e.

$$\omega_{\text{crit}} = \frac{\tau_0}{\tau},$$

where $\omega_{\text{crit}, \odot} = 2.9 \times 10^{-5}$ Hz, $\tau_\odot$, and $\tau$ are the convective turbulent timescales of the Sun and the donor star, respectively.

### 2.3 Spin evolution of the NS

In stellar evolution code, we also consider the spin evolution of pulsars as follows. With the spin-up of the NS, the accreting material would interact with the magnetosphere of the NS. We simply define the magnetosphere radius as the position that the ram pressure of the infalling material is balanced by the magnetic pressure of the NS $P_{\text{m}}$. Under assumption of spherical accretion (Ghosh & Lamb 1979a,b), the magnetosphere radius is

$$r_m = 1.6 \times 10^8 \left( \frac{B_i}{10^{12} \, \text{G}} \right)^{4/7} \left( \frac{|M_i|}{10^{38} \, \text{g s}^{-1}} \right)^{-2/7} \, \text{cm},$$

where $B_i$ is the surface magnetic field of the NS. Some observations and analysis argued that the mass accretion of the NS can lead to its magnetic field decay (see Shibazaki et al. 1989). Here we adopt an empirical model given by Shibazaki et al. (1989), i.e.,

$$B_s = \frac{B_i}{1 + \Delta M_{\text{acc}} / m_B},$$

where $B_i$ is the initial magnetic field of the NS, $\Delta M_{\text{acc}}$ is the accreted mass of the NS, and $m_B$ is $\sim 10^{-4} M_\odot$.

When the NS rotation is too fast, the gravitational force of the accreting material at $r_m$ is less than its centrifugal force. The centrifugal barrier would eject the accreting material and exert a propeller spin-down torque on the NS (Illarionov & Sunyaev 1975). Namely, if the magnetosphere radius is greater than the co-rotation radius

$$r_c = 1.5 \times 10^8 \left( \frac{M_\odot}{M_{\text{NS}}} \right)^{1/3} P_s^{2/3} \, \text{cm},$$

where $P_s$ is the spin-period of the NS in units of second, the propeller effect occurs. The spin angular momentum loss rate via the propeller effect can be written as

$$\dot{J}_p = 2M_\odot r_m^2 |\Omega_s - \Omega|,$$

where $\Omega_s (r_m)$ is the Keplerian angular velocity at $r_m$. When $r_m < r_c$, the accreting material is bound in the magnetic field lines to co-rotate with the NS, and is accreted onto its surface. Assuming rigid body rotation and the momentum of inertia $I = 10^{35} \, \text{g cm}^2$, the spin-up torque of the accreting material exerting on the NS is given by

$$J_{\text{ac}} = \dot{M}_{\text{ac}} \sqrt{GM_{\text{NS}} R},$$

where $G$ is the gravitational constant, $R$ is the radius of the NS.

In addition, if $r_m$ is greater than the light cylinder radius

$$r_c = \frac{c}{\Omega} = \frac{cP_s}{2\pi},$$

the NS appears as a radio pulsar. As a result of magnetic dipole radiation, the spin angular momentum loss rate is

$$\dot{J}_m = -\frac{2B_s^2 R^2 Q^2}{3c^3}.$$
properties of BMSPs formed by the recycling evolutionary channel, therefore we have calculated the evolution of large numbers of LMXBs with different initial orbital periods and donor star masses. In Figure 2 we present the progenitor distribution of BMSPs in $M_{d,i} - P_{\text{orb},i}$ diagram. The regions enclosed by the solid, dashed, and dotted curves represent the distribution areas of LMXBs that can result in a BMSP with a spin period of 10 ms, 20 ms, and 30 ms, respectively. Our results show that all NSs in LMXBs have a chance to be spun up to millisecond period, and the final fate strongly depend on the separation of the binary. When the initial mass of the donor star is located in the range of $1.3 - 1.6 M_{\odot}$, the initial orbital period have a wider distribution from 1.0 day to 20 days. When the initial mass of the companion is between $1.0 M_{\odot}$ and $1.4 M_{\odot}$, the system cannot produce a BMSP unless the initial orbital period is less than 2.0 days.

Beyond these areas, BMSPs cannot be formed due to either a low spin-up efficiency or unstable mass transfer. For donor stars with a mass of $1.4 - 1.6 M_{\odot}$, a lower mass accumulation and spin-up efficiency of the NS result in an upper limit on the initial orbital period. However, for massive donor stars with a mass of $1.7 - 2.0 M_{\odot}$, the upper limit on the orbital period originates from the dynamical instability of mass transfer (Willems & Kolb 2002). In particular, in our calculated results, the relation obtained by Tauris & Savonije (1999), and Rappaport et al. (1995), respectively.

Figure 1. Evolutionary track of an LMXB with $M_{d,1} = 1.5 M_{\odot}$, and $P_{\text{orb},1} = 1.5$ day, which can evolve into a BMSP. The solid and dotted curves represent the evolution the NS mass and the magnetic field in the left panel, the donor star mass and the orbital period in the middle panel, and the mass transfer rate and the spin period of the NS in the right panel, respectively.

Figure 2. Distribution of the initial orbital periods $P_{\text{orb},i}$ and the initial donor star masses $M_{d,i}$ of LMXBs that can evolve into BMSPs via the recycling evolutionary channel.

Figure 3. Predicted relation between the orbital period $P_{\text{orb}}$ and the white dwarf mass $M_{\text{WD}}$ for low-mass binary pulsars. The filled circles, the solid curve and the dotted curve denote our calculated results, the relation obtained by Tauris & Savonije (1999), and Rappaport et al. (1995), respectively.
white dwarf, which is called low-mass binary pulsar (LMBP) (Stairs 2004; Tauris & van den Heuvel 2006). Stellar evolution theory predicts a tight relation between the core mass of giants and their radius (Joss et al. 1987). During the evolution of LMXBs, the giant should overflow its Roche lobe, and its radius relates to the orbital separation. When the giant envelope is exhausted, its core evolve into a white dwarf. Therefore, the final orbital period of LMBPs should be correlated with the mass of the white dwarf companion (Tauris & Savonije 1993). Previous works presented a simple relation between the orbital period \( P_{\text{orb}} \) and the white dwarf mass \( M_{\text{WD}} \) for low-mass binary pulsars (see also Rappaport et al. (1993) and Tauris & Savonije (1999)).

In Figure 3, we show our obtained low-mass binary pulsars by filled circles in \( P_{\text{orb}} \) vs. \( M_{\text{WD}} \) diagram. It is clear that our calculated results are consistent with the relation obtained by Tauris & Savonije (1999). To compare with observations, we summarize the observed parameters for 17 low-mass binary pulsars in Table 1. In Figure 4, we compare the calculated results with the observed data in the \( P_{\text{orb}} \) vs. \( P_s \) plane. It seems that our evolutionary model can account for the formation of part BMSPs. However, it is difficult for our evolutionary scenario to produce BMSPs with a short spin-period (3–8 ms) and a long orbital period (\( \gtrsim 70 \) – 80 day).

In Figure 5, we show the distribution of the final accreted mass and the final spin-period of NSs. One can see that, if NSs accretes a mass of \( \gtrsim 0.1 \ M_\odot \), they can be spun up to \( \gtrsim 10 \) ms. In our calculated results, there exist 3 NSs that can accrete mass of \( \gtrsim 0.6 \ M_\odot \). Recent Shapiro delay measurements of PSR J1614-2230 suggested that it is a massive MSPs (\( \sim 2 \ M_\odot \)), and with a CO white dwarf of \( \sim 0.5 \ M_\odot \) (Demorest et al. 2010). We expect the discovery of LMBP with a massive NS like PSR J1614-2230 to test our evolutionary results.

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### Table 1. Observed parameters for 17 low-mass binary pulsars.

| Pulsars        | \( P_s \) (ms) | \( P_{\text{orb}} \) (days) | \( M_\ast \) (M\(_\odot\)) | References |
|----------------|----------------|-----------------------------|-----------------------------|------------|
| J1455–3330     | 7.987          | 76.17                       | 0.3                         | 1          |
| J1600–3053     | 3.598          | 14.35                       | 0.2                         | 2          |
| J1618–3921     | 11.987         | 22.80                       | 0.2                         | 3          |
| J1643–1224     | 4.622          | 147.02                      | 0.1                         | 1          |
| J1709+2313     | 4.631          | 22.70                       | 0.3                         | 4          |
| J1713+0747     | 4.570          | 67.83                       | 0.3                         | 5          |
| J1751–2857     | 3.915          | 110.75                      | 0.2                         | 6          |
| J1804–2717     | 9.343          | 11.13                       | 0.2                         | 7          |
| J1853+1303     | 4.092          | 115.65                      | 0.3                         | 6          |
| J1910+1256     | 5.362          | 12.33                       | 0.2                         | 8          |
| J1918–0642     | 7.646          | 10.91                       | 0.1                         | 3          |
| J1933–6211     | 3.543          | 12.82                       | 0.4                         | 2          |
| J1953+29       | 6.133          | 117.35                      | 0.2                         | 9          |
| J2019+2425     | 3.935          | 76.51                       | 0.3                         | 10         |
| J2033+1734     | 5.949          | 56.31                       | 0.2                         | 11         |
| J2229+2643     | 2.978          | 93.02                       | 0.1                         | 12         |

References: (1) Lorimer (1995); (2) Jacoby et al. (2007); (3) Edwards & Bailes (2001); (4) Lewandowski et al. (2004); (5) Foster et al. (1993); (6) Stairs (2005); (7) Lorimer et al. (1996); (8) Segelstein et al. (1996); (9) Boriakoff et al. (1993); (10) Nice & Taylor (1997); (11) Ray et al. (1996); (12) Woźniak et al. (2000).

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### Figure 5. Distribution of our simulated results in the spin-period \( P_s \) of BMSPs vs. the accreted mass of NSs \( M_\ast \).
the recycled channel (see Figure 2). Our results show that all LMXBs with a donor star of 1.0 - 2.0 $M_{\odot}$ have a chance to evolve into a BMSp with a spin-period of $P_s \lesssim 10$ ms.

2. The final fate of LMXBs strongly depend on the initial donor star mass and the separation of the binary. When the donor star mass is in the range 1.0 - 1.4 $M_{\odot}$, only LMXBs with a short orbital period ($P_{\text{orb}} \lesssim 2.0$ day) can evolve into low-mass binary pulsars. However, for a higher mass donor star, the upper limitation of the orbital period that can result in birth of binary millisecond pulsars is 2.0 - 3.6 days.

3. Our calculated results show that, if the NS accretes a mass of $\gtrsim 0.1 M_{\odot}$, it can be spun up to millisecond period. In addition, it is possible that few MSPs gain a mass of $\gtrsim 0.5 M_{\odot}$.

4. It is difficult for our evolutionary scenario to produce a sub-millisecond pulsar. This result is consistent with the conclusion obtained by Ferrario & Wickramasinghe (2007). However, AIC evolutionary channel may produce a sub-millisecond pulsar (or quark star) (Du et al. 2009).

Obviously, our evolutionary results depend on the parameterized input physics, especially the magnetic braking model, the duty cycle, and the magnetic field decay model, which have not been fully understood. Firstly, the loss of orbital angular momentum plays a vital role in the evolution of LMXBs, hence magnetic braking model can influence the final orbital period of BMSps. Secondly, the duty cycle can influence the outburst timescale and the mass growth of the NS. Therefore, a large duty cycle can result in the birth of MSPs with a short spin-period. In addition, the duty cycle may relate to system parameters (Lasota 2001), and may also evolve with the orbital period and mass transfer rate. Thirdly, in our input physics the magnetosphere radius relates to the field decay model, while their relation is not sensitive. Some uncertainties mentioned above may be responsible for the discrepancy between our simulated results and observational data in Figure 4. A large duty cycle and a weak magnetic braking model may produce BMSps with a short spin period (3-8 ms) and a moderate long orbital period ($\gtrsim 70 - 80$ days). Certainly, if our evolutionary model is correct, there may be other evolutionary channel to BMSps such as AIC process of massive white dwarfs.

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