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He star evolutionary channel to intermediate-mass binary pulsar PSR J1802-2124

W.-C. Chen[1,2,4], X.-D. Li[3,4], and R.-X. Xu[1]

[1] School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, PR China
[2] Department of Physics, Shangqiu Normal University, Shangqiu 476000, PR China
[3] Department of Astronomy, Nanjing University, Nanjing 210093, PR China
[4] Key Laboratory of Modern Astronomy and Astrophysics (Nanjing University), Ministry of Education, Nanjing 210093, PR China
e-mail: chenwc@nju.edu.cn

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ABSTRACT

Context. The intermediate-mass binary pulsars (IMBPs) are characterized by relatively long spin periods (10−200 ms) and massive ($\gtrsim$0.4 $M_\odot$) white dwarf (WD) companions. Recently, precise mass measurements have been performed for the pulsar and the WD in the IMBP PSR J1802-2124. Some observed properties, such as the low mass of the pulsar, the high mass of the WD, the moderately long spin period, and the tight orbit, imply that this system has undergone a peculiar formation mechanism.
Aims. In this work, we attempt to simulate the detailed evolutionary history of PSR J1802-2124.
Methods. We propose that a binary system consisting of a neutron star (NS, of mass 1.3 $M_\odot$) and an He star (of mass 1.0 $M_\odot$), and with an initial orbital period of 0.5 d, may have been the progenitor of PSR J1802-2124. Once the He star overflows its Roche lobe, He-rich material is transferred onto the NS at a relatively high rate of $\sim 10^{-7}-10^{-6}$ $M_\odot$ yr^{-1}, which is significantly higher than the Eddington accretion rate. A large amount of the transferred material is ejected from the vicinity of the NS by radiation pressure and results in the birth of a mildly recycled pulsar.
Results. Our simulated results are consistent with the observed parameters of PSR J1802-2124. Therefore, we argue that the NS + He star evolutionary channel may be responsible for the formation of most IMBPs with orbital periods $\lesssim$3 d.

Key words. pulsars: general – stars: evolution – stars: mass-loss

1. Introduction

In the standard recycling theory, a neutron star (NS) in a low-mass X-ray binary (LMXB) accretes mass from its companion star, and the transferred angular momentum causes it to be spun up to a short spin period (Alpar et al. 1982; Bhattacharya & van den Heuvel 1991). The endpoint of the evolution is a binary consisting of a millisecond radio pulsar with spin period $\lesssim$10 ms, and an He white dwarf (WD). This population is called low-mass binary pulsars (LMBPs) (Tauris & van den Heuvel 2006). In comparison with LMBPs, another population is that of the intermediate-mass binary pulsars (IMBPs), which contain a pulsar with a spin period of tens of milliseconds and a massive CO or ONeMg WD with mass of $\gtrsim$0.4 $M_\odot$ (Camilo et al. 1996; Camilo et al. 2001).

It is noticeable that the spin periods, magnetic field strengths, and orbital eccentricities of IMBPs are considerably greater than those of LMBPs (Li 2002), implying that these pulsars are mildly recycled. So far, the formation mechanisms of IMBPs have not been fully understood. Van den Heuvel (1994) suggests that these objects originate in low/intermediate-mass X-ray binaries (L/IMXBs) with a donor star on the asymptotic giant branch. When the donor star overflows its Roche-lobe, the unstable mass transfer onto the NS will lead to the formation of a common envelope (CE). During the spiral-in process, the NS experiences a short timescale, super-Eddington accretion and is partially spun up (van den Heuvel & Taam 1984; Stairs 2004). More recent works indicate that IMBPs are likely to evolve through a (sub)thermal timescale mass transfer in IMXBs without experiencing CE evolution (King & Ritter 1999; Podsiadlowski & Rappaport 2000; Kolb et al. 2000; Tauris et al. 2000; Podsiadlowski et al. 2002; Pfahl et al. 2003, See also Pylyser & Savonije 1988). Li (2002) proposes that the thermal-viscous instability of the accretion disks in some IMXBs may reduce the amount of mass transferred onto the NS and result in the birth of a mildly recycled pulsar.

At present, 16 known IMBPs exist, and only two of them have relatively precise measurements of the pulsar masses. For PSR J0621+1002 the measured mass is $M_{\rm NS} = 1.70^{+0.10}_{-0.16}$ $M_\odot$ (Nice et al. 2008). The other well-studied IMBP, PSR J1802-2124, was discovered by the Parkes Multibeam Pulsar Survey (Faulkner et al. 2004). It has a spin period of 12.6 ms and is in a 16.8 hr circular orbit with a massive WD companion. By measuring the general relativistic Shapiro delay, Ferdman et al. (2010) estimate the NS mass to be 1.24(±0.11) $M_\odot$ and WD mass to be 0.78(±0.04) $M_\odot$ (68% confidence).

Tauris et al. (2000) have calculated the nonconservative evolution of IMXBs and find that IMBPs with a wide orbit ($P_{\rm orb}$ $\gtrsim$ 3 d) can be formed through a short-lived highly super-Eddington mass transfer phase. However, this scenario may not work for IMBPs with a short orbital period, such as PSR J1802-2124, PSRs B0655+64 (Jones & Lyne 1988; Lorimer et al. 1995), J1232-6501, J1435-6100 (Camilo et al. 2001; Manchester 2001), and J1756-5322 (Edwards & Bailes 2001). The CO WD may be formed when the donor star evolves to be a He star (van den Heuvel 1994), which means the NSs have undergone a short timescale ($\sim 10^3$ yr) accretion from the donor star in the

CE evolution phase (Ferdman et al. 2010). However, the detailed evolutionary histories of IMBPs with a short orbital period like PSR J1802-2124 have not been explored, so will be investigated in this work. Employing the observed parameters of PSR J1802-2124, we simulate its evolutionary history by using a detailed stellar evolution code. We argue that a binary system consisting of an NS and an He star may be its progenitor. In Sect. 2, we describe the formation processes of NS + He star systems and obtain the initial parameter space of NS + He star systems. In Sect. 3 we present a detailed evolutionary path of PSR J1802-2124. We give a brief summary and discussion in Sect. 4.

2. Formation of NS + He star systems

The primordial binaries that formed NS + He star systems consist of a massive primary and an intermediate-mass secondary that produce the NS and the WD, respectively. We used an evolutionary population synthesis approach based on the rapid binary star evolution (BSE) code developed by Hurley et al. (2000, 2002) to derive the initial parameter space of NS + He star systems. For the NS formation, there are two main evolutionary channels: iron core-collapse (ICC) supernovae (SNe) and electron-capture (EC) SNe. The former is believed to form a higher mass ($\sim$1.35 $M_\odot$) population, while the latter produces a lower mass ($\sim$1.25 $M_\odot$) population (Podsiadlowski et al. 2005; Schwab et al. 2010). In calculation, we distinguish ICC SNe of massive stars from EC SNe or accretion-induced collapse (AIC) of ONeMg WDs. Some input parameters including the star formation rate, the initial mass functions, the CE ejection efficiency parameter, the kick velocity dispersion, the distributions of initial orbital separations, masses, and the eccentricities are described as follows[1].

1. We adopt a constant star formation rate $S = 7.6085$ yr^{-1}, which implies that one binary with $M_1 \geq 0.8\ M_\odot$ is born in the Galaxy per year.
2. The primary star mass distribution function is taken to be $\Phi(\ln M_1) = M_1\xi(M_1)$, in which the initial mass function $\xi(M_1)$ is given by Kroupa et al. (1993).
3. The secondary star mass distribution function is taken to be $\Phi(\ln M_2) = M_2/M_1 = q$, which corresponds to a uniform distribution of the mass ratio q between 0 and 1[2].
4. We take a uniform distribution of $\ln a$ for the binary separation a, namely $\Phi(\ln a) = 0.12328$ (Hurley et al. 2002).
5. The CE ejection efficiency parameter $\alpha_{\rm CE}$, which describes the fraction of the released orbital energy used to eject the envelope during the CE evolution, i. e. $\alpha_{\rm CE} = E_{\rm bind}/(E_{\rm orb,f} - E_{\rm orb,i})$ (Hurley et al. 2002). Here $E_{\rm bind}$ is the total binding energy of the primary's envelope, $E_{\rm orb,f}$, and $E_{\rm orb,i}$ are the final and initial orbital energies of the secondary, respectively. In this work, we adopt $\alpha_{\rm CE} = 3$ in our standard model and $\alpha_{\rm CE} = 1$ for comparison.
6. The kick velocity dispersion received by the natal NS. For NSs formed by ICC SNe, we adopt relatively stronger kick velocities with a dispersion $\sigma_{\rm ICC} = 190$ km s^{-1} (Hansen & Phinney 1997)[3]. However, for the EC SNe or AIC channel, the explosive energies of electron-capture SN explosion are significantly lower than those of ICC SNe (Dessart et al. 2006; Kitaura et al. 2006; Jiang et al. 2007). Therefore, it is usually believed that the natal NSs formed by both channels may receive a smaller kick (Podsiadlowski et al. 2004; Scheck et al. 2004; Poelarends et al. 2008; for a review, see van den Heuvel 2010). Therefore, we take a moderately weak velocity dispersions with $\sigma_{\rm EC,AIC} = 20$ km s^{-1} [4].
7. All stars are assumed to be members of binaries in a circular orbit, and they have metallicity of $Z = 0.02$. In our simulations, the primary mass M_1, the secondary mass M_2, and the binary separation a range in 0.8–80 $M_\odot$, 0.1–80 $M_\odot$, and 3–10 000 $R_\odot$, respectively.

First, we show an example of the formation process of an NS + He star system. Using the BSE code we calculated the evolution of a primordial binary consisting of a primary (star 1) of mass $M_1 = 8.5\ M_\odot$ and a secondary (star 2) of mass $M_2 = 4.4\ M_\odot$ ($Z = 0.02$) in an $a = 100.7\ R_\odot$ orbit. At $t = 33.11$ Myr the primary evolves to fill its Roche lobe, and transfers its material to star 2. Because of the relatively high-mass ratio, the mass transfer is dynamically unstable, resulting in the formation of a CE. After the envelope is ejected, the primary becomes an He star ($M_1 = 1.738\ M_\odot$), the donor star is still on the main sequence ($M_2 = 6.837\ M_\odot$), but the orbit shrinks to $a = 33.19\ R_\odot$. At $t = 40.03$ Myr, the He star overflows its Roche lobe once more, and the product of the subsequent evolution is a binary consisting of an ONeMg WD ($M_1 = 1.035\ M_\odot$) and a main sequence star ($M_2 = 7.456\ M_\odot$), in an orbit of $a = 70.915\ R_\odot$. At $t = 71.77$ Myr, Star 2 starts to overflow its Roche lobe, initiating the second CE evolution. After the CE is ejected, a close binary system consisting of an ONeMg WD ($M_1 = 1.035\ M_\odot$) and an He star ($M_2 = 1.459\ M_\odot$) is formed in a tight orbit with $a = 0.725\ R_\odot$ (see also Belczynski & Taam 2004). When the He star (the descendant of Star 2) fills its Roche lobe and transfers the He-rich material onto the ONeMg WD, the WD may grow to the Chandrasekhar limit and collapse to be an NS because of the electron capture process (Nomoto 1984)[5]. Therefore, through two CE phases a compact binary including an NS and a low-mass He star ($M_2 = 1.049\ M_\odot$) can be produced. Meanwhile, with the sudden increase in the orbital separation caused by the received kick during the AIC, the mass transfer ceases.

To investigate the initial parameter space of NS + He star systems, we calculated the evolution of 1×10^6 binaries to an age of 12 Gyr. Figure 1 shows the distribution of natal NS + He star systems in the $M_{\rm He} - P_{\rm orb}$ diagram when $\sigma_{\rm EC,AIC} = 20$ km s^{-1}. It is clear that most systems have initial orbital periods of $P_{\rm orb,i} \sim$ 0.01–1 d and initial He star masses $M_{\rm He,i} \sim 0.5$–3.0 $M_\odot$. For the same kick, a lower $\alpha_{\rm CE}$ results in fewer NS + He star systems. This difference develops out of the influence of $\alpha_{\rm CE}$ on the evolution of close binaries. A high $\alpha_{\rm CE}$ can prevent coalescence during the CE stage, significantly increasing the formation rate of NS + He star systems (Liu & Li 2006; Chen et al. 2011).

[1] For other parameters, we refer to Table 3 of Hurley et al. (2002) if not mentioned.

[2] Recently, Pinsonneault & Stanek (2006) proposed that two components in 50% of detached binaries have similar masses, i.e. $q > 0.87$.

[3] Hobbs et al. (2005) find that the observed pulsars could be described by a Maxwellian distribution with a dispersion $\sigma = 265$ km s^{-1}. However, the population synthesis by Belczynski et al. (2010) suggests that, only when the kick velocity dispersion of natal NS formed in close interacting binaries is $\sim$170 km s^{-1}, can the simulated results fit the observed intrinsic ratio between disrupted recycled pulsars and double NSs.

[4] For the natal NS via EC SN, Dewi et al. (2006) proposes that the kick is a Maxwellian distribution with a dispersion of 30 km s^{-1}.

[5] Here, we present an evolutionary example of an NS + He star system. However, the NS may also be formed directly by an electron-capture supernova of the He-star that originated from a close binary by Case B mass transfer, and its progenitor star should have a mass in the range 8 to 12 $M_\odot$ (Podsiadlowski et al. 2004).

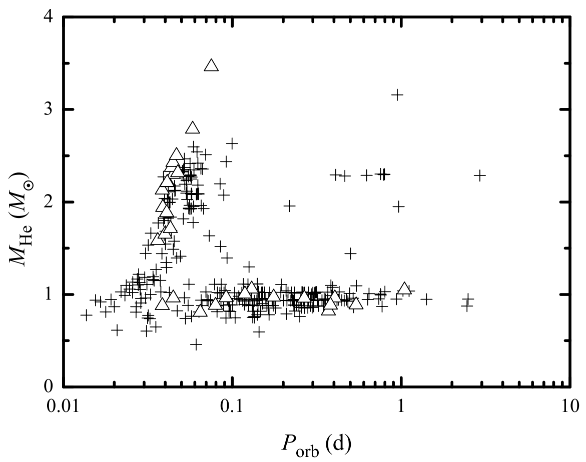

Fig. 1. Distribution of initial NS + He star systems in the $M_{He} - P_{orb}$ diagram when σ_{ICC} = 190 km s^{-1}, and $\sigma_{EC,AIC}$ = 20 km s^{-1}. The crosses and the open triangles correspond to the CE ejection efficiency parameters α_{CE} = 3, and 1, respectively.

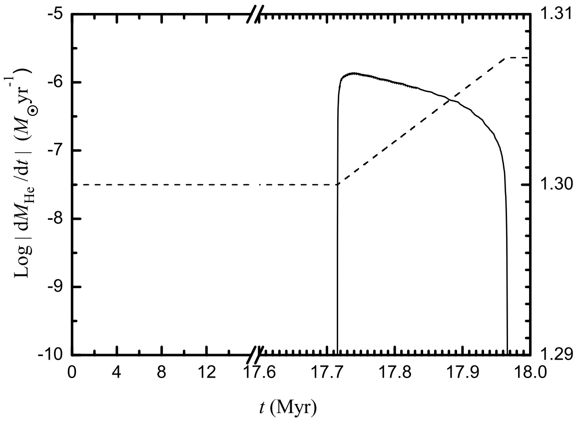

Fig. 2. Evolution of an NS + He star system with $M_{NS,i}$ = 1.3 $M_\odot$, $M_{He,i}$ = 1.0 $M_\odot$, and $P_{orb,i}$ = 0.5 d. The solid and dashed curves denote the evolutionary tracks of the mass transfer rate and the NS mass, respectively.

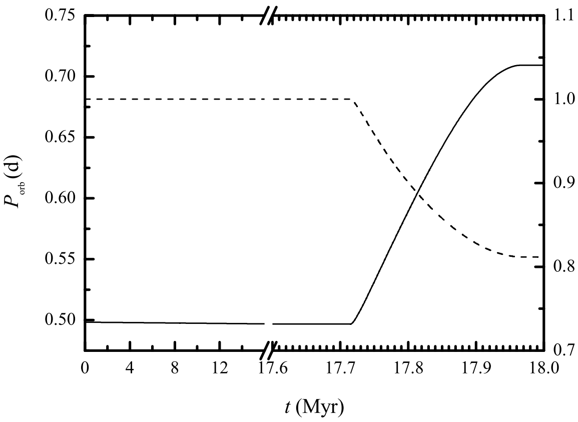

Fig. 3. Evolution of an NS + He star system with $M_{NS,i}$ = 1.3 $M_\odot$, $M_{He,i}$ = 1.0 $M_\odot$, and $P_{orb,i}$ = 0.5 d. The solid and dashed curves denote the evolutionary tracks of the orbital period and the He star mass, respectively.

3. An example evolutionary path to PSR J1802-2124

In this section we show an example of an evolutionary path to PSR J1802-2124, to reproduce its observed parameters. We used the stellar evolution code developed by Eggleton (1971,1972,1973) to calculate the evolutionary sequences of an NS + He star system. In the calculations, we adopted the stellar OPAL opacities for a low temperature given by Rogers & Iglesias (1992) and Alexander & Ferguson (1994) and take the ratio of the mixing length to the pressure scale height to be 2.0. The overshooting parameter of the He star (with a chemical abundance Y = 0.98, Z = 0.02) is set to 0 (Wang et al. 2009).

When the He star overflows its Roche lobe and transfers He-rich material onto the NS, the maximum accretion rate of the NS should be limited by the Eddington accretion rate, which is twice that of hydrogen accretion, i. e. $\dot{M}_{Edd} \simeq 3.0\times10^{-8}$ $M_\odot$ yr^{-1}. If the mass transfer rate $-\dot{M}_{He}$ from the He star is greater than $\dot{M}_{Edd}$, the radiation pressure from the NS will cause the excess mass to be lost from the system at a rate $\dot{M} = \dot{M}_{He} + \dot{M}_{Edd}$. In our calculations, we consider three types of orbital angular momentum loss from the binary system: (1) gravitational-wave radiation; (2) magnetic braking: we adopt the induced magnetic braking prescription given by Sills et al. (2000); (3) isotropic winds: the transferred matter in excess of the Eddington accretion rate is assumed to be ejected from the vicinity of the NS in the form of isotropic winds and to carry away the specific orbital angular momentum of the NS (Tauris & Savonije 1999).

Based on the results of Fig. 1, we calculated the evolution of an NS + He star system with initial masses $M_{NS,i}$ = 1.3 $M_\odot$, $M_{He,i}$ = 1.0 $M_\odot$, and initial orbital period $P_{orb,i}$ = 0.5 d. Figures 2 and 3 show the evolution of the mass transfer rate, the NS mass, the orbital period, and the He star mass. At $t \simeq$ 17.71 Myr, the He star fills its Roche lobe and transfers mass at a high rate of $\sim10^{-7}$–10^{-6} $M_\odot$ yr^{-1} onto the NS, which is significantly higher than the Eddington limit. A large amount of the transferred material is ejected by radiation pressure, so the mass of the NS hardly gains anything. Because the material is transferred from the less massive He star to the more massive NS, the orbital period continuously increases. The mass exchange lasts ~0.25 Myr, during which the NS has accreted ~4% of the transferred mass, or ~0.01 $M_\odot$. This amount of material is, however, sufficient to spin the NS up to ≲16 ms and cause the magnetic field to decay (Taam & van den Heuvel 1986; van den Heuvel 1994). The endpoint of the evolution is an IMBP consisting a mildly recycled pulsar and a CO WD with a mass of 0.81 $M_\odot$ in an orbital period of 0.71 d. This evolution provides a plausible path that leads to the formation of PSR J1802-2124.

4. Discussion and summary

At present, the formation channel of IMBPs is not very well understood. The recent timing analysis of PSR J1802-2124 provides precise measurements of the pulsar and WD masses (Ferdman et al. 2010). The observed properties of this system, such as the low mass of the pulsar, the high mass of the WD, short orbital period, and moderately long spin period (in comparison with those of LMBPs) imply that this binary may have a specific evolutionary history. One possibility is that IMBPs like PSR J1802-2124 may have evolved from IMXBs. Because the material is transferred from the more massive donor star to the less massive NS in IMXBs, the mass transfer occurs on a short thermal timescale. Therefore, Podsiadlowski et al. (2002) suggest that IMXBs spend most of their X-ray active lifetime as LMXBs. In this phase some of the binaries would have undergone unstable accretion owing to an accretion disk instability during the LMXB phase, and thus the accretion efficiency was significantly decreased (Li 2002).

In this work, we attempted to explore whether the evolutionary channel of NS + He star system can reproduce the observed parameters of PSR J1802-2124. We first investigated the initial parameter space of NS + He star systems using a population synthesis approach. Our simulated results show that most NS + He star systems have initial orbital periods $P_{\rm orb,i} \sim 0.01{-}1$ d and initial He star masses $M_{\rm He,i} \sim 0.5{-}3.0\ M_{\odot}$. We then performed numerical calculations for the evolution of an NS + He star system with $M_{\rm NS,i} = 1.3\ M_{\odot}$, $M_{\rm He,i} = 1.0\ M_{\odot}$, and $P_{\rm orb,i} = 0.5$ d. Detailed evolutionary calculations shows that the NS + He star evolutionary channel can successfully reproduce the observed parameters of PSR J1802-2124. The NS + He star systems have a compact orbit, therefore we propose that the NS + He star evolutionary channel may be responsible for the formation of most IMBPs with orbital periods $\lesssim$3 d.

Obviously, two main uncertainties exist in our work. The first one is the CE evolution. As seen in Sect. 2, the initial parameter space of the NS + He star systems strongly depends on the CE ejection efficiency parameters $\alpha_{\rm CE}$, which should vary with stellar mass and evolution, but is still poorly known. Additionally, some works argue that, an NS may experience hypercritical accretion in the CE phase and collapse to be a black hole (see Chevalier 1993; Brown 1995; Brown et al. 2001). However, it has been found that ~60% NS with a mass greater than 2.0 $M_{\odot}$ can survive under hypercritical accretion (Belczynski et al. 2002). The second one is the EC SNe and AIC process. When the ONeMg core of an asymptotic giant branch star (Siess 2007; Poelarends et al. 2008) or an He star (Nomoto 1987) grows to a critical mass, EC SN would be triggered. However, the AIC process originates from an ONeMg WD accreting from the donor star or from the merger of two CO WDs (Nomoto & Iben 1985; Nomoto & Kondo 1991). Compared with the AIC channel, EC SN can also produce a detached NS + He star system. To obtain a long enough spin-down timescale for the natal NS, our evolutionary scenario favors detached binary systems. Therefore, it seems that also NS formed by EC SN are reasonable progenitors of mildly recycled pulsars. Podsiadlowski et al. (2004) suggest that the minimum mass of the NS progenitor may be 10−12 $M_{\odot}$ for single stars, while this value can be 6−8 $M_{\odot}$ in binaries. The progenitor masses of EC SNe are related to the amount of convective overshooting, and to the metallicity of the star (Podsiadlowski et al. 2004). A full population synthesis for the birthrates of NS + He star systems formed by EC SNe and AIC channels is beyond the scope of this paper, and will be addressed in future work.

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