

Can eccentric binary millisecond pulsars form by accretion-induced collapse of white dwarfs?

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Accepted 2010 August 12. Received 2010 August 11; in original form 2010 June 6

ABSTRACT

Binary radio pulsars are generally believed to have been spun up to millisecond periods (i.e. recycling) via mass accretion from their donor stars, and they are the descendants of neutron star low-mass X-ray binaries. However, some studies indicate that the formation of pulsars from the accretion-induced collapse (AIC) of accreting white dwarfs (WDs) cannot be excluded. In this work, we use a population-synthesis code to examine if the AIC channel can produce eccentric binary millisecond pulsars (BMSPs) in the Galaxy. Our simulated results indicate that only when the natal MSPs receive a relatively strong kick ($\gtrsim 100 \text{ km s}^{-1}$), can the AIC channel produce ~ 10 – 180 eccentric ($e > 0.1$) BMSPs in the Galaxy, most of which are accompanied by a helium star. Such a kick seems to be highly unlikely in the conventional AIC process, hence the probability of forming eccentric BMSPs via the AIC channel can be ruled out. Even if a high kick is allowed, the AIC channel cannot produce eccentric BMSPs with an orbital period of $\gtrsim 20$ d. Therefore, we propose that the peculiar BMSP PSR J1903+0327 cannot be formed by the AIC channel. However, the AIC evolutionary channel may produce some fraction of isolated MSPs, and even submillisecond pulsars if they really exist.

Key words: pulsars: general – Galaxy: stellar content – stars: white dwarfs – binaries: close – stars: evolution – stars: formation.

1 INTRODUCTION

Millisecond pulsars (MSPs) are characterized by short pulse periods ($P \lesssim 20$ ms), low spin-down rates ($\dot{P} \sim 10^{-19}$ to $10^{-21} \text{ s s}^{-1}$), old characteristic ages [$\tau = P/(2\dot{P}) \sim 10^9$ – 10^{10} yr] and weak surface magnetic fields ($B \sim 10^8$ – 10^9 G) (Manchester 2004). About 80 per cent of the MSPs are in binaries, but only $\lesssim 1$ per cent of the total pulsars (Bhattacharya & van den Heuvel 1991; Lorimer 2008). Standard models proposed that MSPs are formed in neutron star (NS) low-mass X-ray binaries (LMXBs), in which the NS has accreted the mass and angular momentum from its companion, and been spun up to a short spin period (Alpar et al. 1982; Tauris & van den Heuvel 2006). Meanwhile, mass accretion on to the NS induces its initial magnetic field ($B_0 \sim 10^{12}$ – 10^{13} G) to decline to $B \sim 10^8$ – 10^9 G.¹ When the mass transfer ceases, a binary millisecond pulsar (BMSP) is formed.

However, the origin of the MSPs still presents some controversial puzzles. First, can the known NS LMXBs evolve into the observed MSPs in the Galactic disc (Kulkarni & Narayan 1988)? Statistical analyses show that the birth rate of LMXBs is ~ 1 – 2 orders of magnitude lower than that of MSPs (Cote & Pylyser 1989; Lorimer 1995). Secondly, it is hard to understand how the isolated MSPs in the Galactic disc were formed via the standard recycling scenario. Although evaporation of the donor stars by the high-energy radiation of the MSPs might account for the origin of the isolated MSPs, the observed time-scales for evaporating a companion star seem too long. Thirdly, in standard model the strong tidal effects operating in the binary during the mass transfer serve to circularize the orbit. However, the discovery of the eccentric ($e = 0.44$) BMSP PSR J1903+0327 in the Galactic plane has challenged the standard scenario (Champion et al. 2008).

As an alternative evolutionary channel, BMSP may originate from the accretion-induced collapse (AIC) of an accreting white dwarf (WD; Michel 1987). Ivanova & Taam (2004) suggested that AIC may occur by thermal time-scale mass transfer in such binaries with orbital periods of a few days. Once the accreting ONe WD grows to the Chandrasekhar limit, the electron-capture process may induce gravitational collapse rather than Type Ia supernova. As a

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¹ As an alternative mechanism of accretion-induced field decay, the magnetic field of the NS may be screened or buried by the accreted material (Taam & van den Heuvel 1986; Cumming, Zweibel & Bildsten 2001).

result of angular momentum and magnetic flux conservations, an MSP with rapid spin and low magnetic field may be produced. To account for its observed characteristics, the bursting pulsar GRO J1744–28 was suggested to be originated from the AIC of a massive ONe WD (van Paradijs et al. 1997; Xu & Li 2009). Recently, the estimated birth rate of MSPs by population-synthesis calculations shows that the often-neglected AIC channel cannot be ignored (Hurley et al. 2010).

In the AIC channel the puzzles in the standard recycling model mentioned above might disappear. First, the AIC of accreting WDs has been raised to interpret the birth-rate discrepancy (Bailyn & Grindlay 1990), and the AIC process may be associated with the r -process nucleosynthesis of heavy (baryon number $A > 130$) nuclei (Qian & Wasserburg 2003). Secondly, a kick velocity caused by asymmetric collapse may be produced during AIC of WDs. An appropriate kick can disrupt the binary system and result in the birth of isolated MSPs. Otherwise, the binary survives and an eccentric BMSP is formed.

Ferrario & Wickramasinghe (2007) argued that the AIC channel could form BMSPs of all of the observed types. Champion et al. (2008) proposed that the AIC of a massive and rapidly rotating WD could produce the observed orbital parameters of PSR J1903+0327. In this work, employing the binary population-synthesis approach we attempt to investigate if the AIC evolutionary channel can produce a population of eccentric BMSPs, as well as isolated MSPs. In Section 2, we describe the population-synthesis approach and the evolution model of MSPs. The simulated results by population synthesis are given in Section 3. Finally, we present a brief discussion and summary in Section 4.

2 INPUT PHYSICS

2.1 Population synthesis

Using an evolutionary population synthesis based on the rapid binary star evolution (BSE) code (e.g. Hurley, Pols & Tout 2000; Hurley, Tout & Pols 2002), we attempt to study the statistical properties (such as the birth rate, total number, the distributions of orbital period and eccentricity) of MSPs formed via the AIC process of a massive ONe WD in the Galaxy. In calculation, we consider the evolution of single stars with binary star interactions, which includes the mass transfer and accretion via stellar winds and Roche lobe overflow, common envelope (CE) evolution, supernovae and AIC kick, tidal friction and orbital angular momentum loss containing gravitational wave radiation and magnetic braking.

All stars are assumed to be born in binary systems, and start with zero eccentricities and a solar metallicity ($Z = 0.02$). We adopt the following input parameters for the simulation: (1) a constant star formation rate $S = 7.6085 \text{ yr}^{-1}$, i.e. one binary with $M_1 \geq 0.8 M_\odot$ is born in the Galaxy per year; (2) the primary mass distribution $\Phi(\ln M_1) = M_1 \xi(M_1)$, in which the initial mass function $\xi(M_1)$ is given by Kroupa, Tout & Gilmore (1993); (3) the secondary mass distribution $\Phi(\ln M_2) = M_2/M_1 = q$, which corresponds to a uniform distribution of the mass ratio $q = 0-1$ and (4) a uniform distribution of $\ln a$ for the binary separation a , namely $\Phi(\ln a) = k = \text{constant}$ (normalization results in $k = 0.12328$; see Hurley et al. 2002). The input parameter space for the primary mass M_1 , the secondary mass M_2 and the separation a are set to be $0.8-80 M_\odot$, $0.1-80 M_\odot$ and $3-10\,000 R_\odot$, respectively. For each initial parameter χ (M_1 , M_2 and a), we set n_χ grid points in

logarithmic space, so we have

$$\delta \ln \chi = \frac{\ln \chi_{\max} - \ln \chi_{\min}}{n_\chi - 1}. \quad (1)$$

During the evolution, if a binary appears as BMSP, it makes a contribution to the birth rate as

$$\delta r = S \Phi(\ln M_1) \Phi(\ln M_2) \Phi(\ln a) \delta \ln M_1 \delta \ln M_2 \delta \ln a. \quad (2)$$

If this system lives for a time Δt as a member of BMSPs, it makes a contribution to the number

$$\delta n = \delta r \delta t. \quad (3)$$

During the CE evolution, the parameter $\alpha_{\text{CE}} = E_{\text{bind}}/(E_{\text{orb,f}} - E_{\text{orb,i}})$ describes the efficiency that the orbital energy is transferred to expel the envelope (Hurley et al. 2002). Here E_{bind} is the total binding energy of the envelope and $E_{\text{orb,f}}$ and $E_{\text{orb,i}}$ are the final and the initial orbital energy of the cores, respectively. There exists some diversity in calculating the initial orbital energy, hence Hurley et al. (2010) suggest that in this formulation $\alpha_{\text{CE}} = 3$ should be consistent with $\alpha_{\text{CE}} = 1$ adopted by Pfahl, Rappaport & Podsiadlowski (2003). Both the estimated velocity of individual pulsars and the pulsar velocity distribution indicate that the nascent NSs should have received a kick velocity, which may root in the asymmetric collapse of massive progenitors of NSs (Burrows & Hayes 1996; Lai & Goldreich 2000). The kick plays an important role in determining the fate of the binaries, whether surviving or disruptive. Noticeably, it is widely accepted that the NS formed by the AIC may receive a lower kick velocity (e.g. $\sigma_{\text{AIC}} = 20 \text{ km s}^{-1}$ in the standard model of Hurley et al. 2010). However, some works presented the opposite point of view (Harrison & Tademaru 1975; Lai, Chernoff & Cordes 2001; also see Section 4). In our standard model, a relatively stronger kick dispersion for NSs by core collapse supernovae is taken to be $\sigma_{\text{CC}} = 265 \text{ km s}^{-1}$ (Hobbs et al. 2005),² while $\sigma_{\text{AIC}} = 150 \text{ km s}^{-1}$ (a ultrahigh kick dispersion) for NSs via the AIC. To study the influence of AIC kick on the formation of MSPs, other kick dispersions such as $\sigma_{\text{AIC}} = 10\,050 \text{ km s}^{-1}$ are also included. Unless we particularly mention, the BSE input parameters in table 3 of Hurley et al. (2002) are used.

2.2 Evolution of MSPs

When the mass of the accreting WD reaches the Chandrasekhar limit, the process of electron capture may dominate, and induce the WD to collapse to be an NS or explode as a Type Ia supernova (Canal, Isern & Labay 1980; Isern et al. 1983), depending on the WD mass and the accretion rate. Nomoto & Kondo (1991) pointed out that if the accretion rate $\dot{M}_{\text{wd}} > 10^{-8} M_\odot \text{ yr}^{-1}$, an ONe WD with an initial mass of $1.2 M_\odot$ is very likely to collapse to be an NS rather than experience a Type Ia supernova explosion. By 2.5-dimensional radiation-hydrodynamics simulations of the AIC of WDs, Dessart et al. (2006) proposed that the spin periods of the natal NSs are 2.2–6.3 ms. Therefore, in our calculations all NSs formed by AIC are assumed to be rapidly rotating objects with millisecond period and low magnetic field. In the input parameters, the initial magnetic field strengths of the MSP are chosen from a lognormal distribution of mean 9 and standard deviation 0.4, and its initial spin periods P_1 are distributed uniformly between 1 and 10 ms. If the donor star

² To match the observed intrinsic ratio between disrupted recycled pulsars and double NSs, the simulated results by population synthesis show that the natal kick of NS formed in close-interacting binaries is $\sim 170 \text{ km s}^{-1}$ (Belczynski et al. 2010).

fills its Roche lobe after the AIC, the NS should appear as an X-ray pulsar (Stairs 2004; Freire 2009), and radio emission is suppressed. However, even if for a detached binary with a He star or a massive companion, accretion may occur due to capture of the stellar winds, which may strongly influence the radio emission of MSPs. Based on the simplified version of the theoretical model given by Davies & Pringle (1981), we consider the MSP's spin evolution as follows.

(i) Radio pulsar phase: after the birth of MSP via AIC, it appears as a radio pulsar due to the rapid rotation, which causes its radiation to be strong enough to expel the winds coming from the He star beyond the radius of the light cylinder r_{lc} or the Bondi accretion radius r_{acc} (Dai, Liu & Li 2006). As a result of magnetic dipole radiation, the spin angular momentum loss rate of the MSP is

$$\dot{J}_m = -\frac{2\mu^2\Omega^3}{3c^3}, \quad (4)$$

where Ω and $\mu = 10^{30}\mu_{30} \text{ G cm}^3$ are the angular velocity and the magnetic dipole moment of the MSP, respectively.

Considering the interaction between the magnetic field of the MSP and the wind material from the donor star, Davies & Pringle (1981) proposed that if the spin period P of the NS is greater than either

$$P_{ac} = 1.2\dot{M}_{15}^{-1/4}\mu_{30}^{1/2}v_8^{-1/2} \text{ s} \quad (5)$$

or

$$P_{ab} = 0.8\dot{M}_{15}^{-1/6}\mu_{30}^{1/3}v_8^{-5/6}\left(\frac{M}{M_\odot}\right)^{1/3} \text{ s}, \quad (6)$$

then the radio phase stops. Here $\dot{M} = 10^{15}\dot{M}_{15} \text{ g s}^{-1}$ is the rate of mass flow on to the NS, $v = 10^8v_8 \text{ cm s}^{-1}$ is the wind velocity relative to the NS and M is the mass of the MSP.

Based on the criterion for the radio phase mentioned above, a NS formed via AIC is assumed to be an MSP until its spin period $P > 10$ ms, or it crosses the so-called death line, i.e. $B_{12}/P^2 < 0.17 \text{ G s}^{-2}$ (Bhattacharya et al. 1992), where $B = 10^{12}B_{12} \text{ G}$ is the surface magnetic field of the NS.

(ii) Propeller phase: with the spin-down of the NS, the light cylinder moves outwards, and the magnetosphere radius

$$r_m = 1.6 \times 10^8 B_{12}^{4/7} \dot{M}_{18}^{-2/7} \text{ cm} \quad (7)$$

is less than r_{lc} , and is greater than the corotation radius $r_c = 1.5 \times 10^8 (M/M_\odot)^{1/3} P^{2/3} \text{ cm}$. Subjecting to the centrifugal barrier, the wind material is assumed to be ejected at r_m , and exerting a propeller spin-down torque on the NS (Illarinov & Sunyaev 1975). The spin angular momentum loss rate via the propeller effect is given by

$$\dot{J}_p = 2\dot{M}r_m^2\Omega_K(r_m)[1 - \Omega/\Omega_K(r_m)], \quad (8)$$

where $\Omega_K(r_m)$ is the Keplerian angular velocity at r_m .

(iii) Accretion phase: we neglect the influence of the wind accretion on the spin of the MSP owing to small spin angular momentum of wind material.

3 RESULTS

Based on the theoretical model described in Section 2, we calculated the evolution of n_χ^3 binaries to an age of 12 Gyr using the BSE code, as well as additions for MSP evolution which will affect the lifetime, δt , used to calculate BMSP numbers (see equation 3). To explore the effect of input parameters, we have calculated the evolutionary results for six models (see Table 1), which are determined by the CE parameter α_{CE} , the kick dispersion σ_{CC} of core collapse and the kick dispersion σ_{AIC} via AIC channel. We collect the evolutionary stages of MSPs as follows: (1) binary MSPs with a main-sequence

Table 1. Model parameters for binary population synthesis.

| Model | α_{CE} | σ_{CC} | σ_{AIC} |
|-------|---------------|---------------|----------------|
| A | 3 | 265 | 150 |
| B | 1 | 265 | 150 |
| C | 3 | 265 | 100 |
| D | 1 | 265 | 100 |
| E | 3 | 265 | 50 |
| F | 1 | 265 | 50 |

(MS), red giant (RG) or subgiant (SG) companion (BMSP-MG); (2) BMSPs with a He star companion (BMSP-He) and (3) isolated MSPs. In Table 2, we summarize the predicted numbers and birth rates of various types of MSPs via AIC channel in the Galaxy.

To evaluate the uncertainties in the birth rates and numbers for various types of BMSPs, in Table 2 we also present the simulated results for the same model under different random number seeds and grid points n_χ . We find that the predicted numbers have considerable uncertainties, especially the numbers of BMSP-He in models D and F for different random number seeds, as well as the numbers of BMSP-MG in models A, C and E for different grid points. However, the birth rates besides BMSP-MG show only small variations (with uncertainties of $\lesssim 20$ per cent). The uncertainties in the numbers seem to originate from various random number sequences under different seeds or grid points. The reasons are as follows. First, the random number sequence can influence the kick received by the natal MSP, which can affect the evolutionary fate of binaries. Secondly, the spin evolution of MSPs is related to the distribution of the initial period and magnetic field. Both parameters strongly depend on the random number sequence, which can result in the different evolutionary histories of MSPs (see equation 3).

In model A, we take a strong kick of $\sigma_{AIC} = 150 \text{ km s}^{-1}$ for the AIC channel and $\alpha_{CE} = 3$. Our results show that there exist ~ 360 BMSPs, which formed via AIC channel. In our standard model, BMSPs with a He star companion have a number that is ~ 10 – 100 times higher than that with a MS, RG or SG companion, and the birth rate also shows the same tendency.³ In addition, the AIC channel can result in the formation of $\sim 5.0 \times 10^5$ isolated MSPs, which is compatible with the estimation by observations (Lorimer 1995). As a result of large kick, ~ 100 – 200 BMSPs with an eccentric orbit ($e \gtrsim 0.1$) is produced.

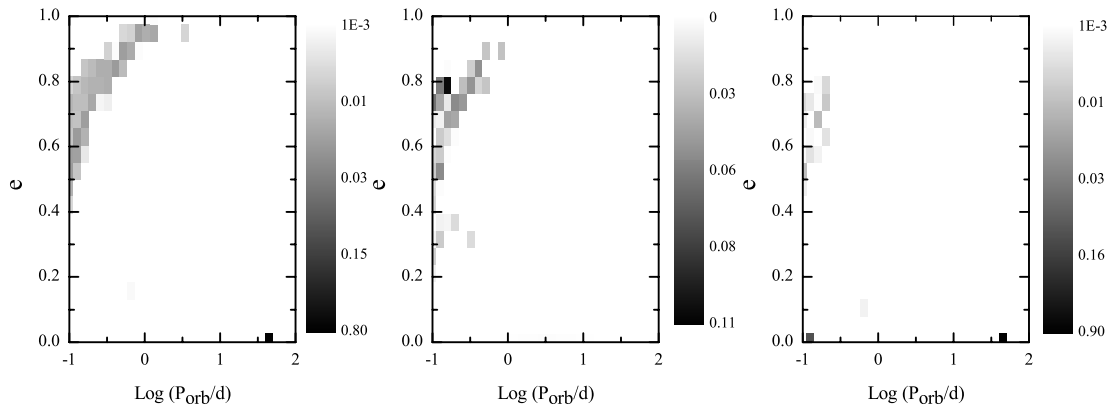
The results of model B show that for the same kick, a lower α_{CE} results in fewer BMSPs. Other models also have the same tendency. This difference originates from the influence of α_{CE} on the evolution of close binaries. A high α_{CE} can prevent coalescence during the CE stage, significantly increasing the formation rate of BMSPs (Liu & Li 2006). In models E and F, we take a low kick for AIC channel, and find that more BMSPs are produced, whereas almost no eccentric BMSPs are formed. In addition, most models predict that the number of BMSPs with a RG or SG companion (no BMSPs with MS donor star) is less than 10 (besides models A, C and E when $n_\chi = 120$), and their eccentricities are close to 0.

In Fig. 1, we plot the distribution of BMSP-He binaries in the e – P_{orb} diagram for models A, B and C under seed 1 and $n_\chi = 100$. It is seen that in model B most BMSP-He binaries are in tight orbits ($P_{orb} < 1 \text{ d}$) with eccentricities of $e > 0.4$. For models A and C, the

³ Tutukov & Yungelson (1996) suggested that binaries with non-degenerate He star may be the origin of the most vast AIC, and outnumber binaries with H MS star.

Table 2. Predicted numbers and birth rates of various types of MSPs via the AIC channel for differential models in the Galaxy.

| Model | Item | BMSP-He | | BMSP-MG | | Isolated MSP | | BMSP | BMSP |
|-------|-------------|---------|----------------------|---------|----------------------|-------------------|----------------------|-------------------------|--------------------------|
| | | Number | Birth rate | Number | Birth rate | Number | Birth rate | ($e > 0.1$) Number | ($e < 0.01$) Number |
| A | Seed 1, 100 | 363 | 2.3×10^{-4} | 4 | 4.3×10^{-6} | 5.0×10^5 | 2.1×10^{-4} | 107 | 260 |
| | Seed 2, 100 | 368 | 2.4×10^{-4} | 3 | 4.2×10^{-6} | 4.0×10^5 | 2.1×10^{-4} | 115 | 256 |
| | Seed 1, 120 | 305 | 2.4×10^{-4} | 50 | 1.1×10^{-6} | 4.5×10^5 | 2.0×10^{-4} | 184 | 170 |
| B | Seed 1, 100 | 21 | 5.5×10^{-5} | 1 | 2.0×10^{-6} | 2.1×10^5 | 9.3×10^{-5} | 21 | 1 |
| | Seed 2, 100 | 12 | 5.1×10^{-5} | 3 | 2.0×10^{-6} | 2.6×10^5 | 9.6×10^{-5} | 11 | 3 |
| | Seed 1, 120 | 28 | 5.1×10^{-5} | 1 | 0.9×10^{-6} | 2.2×10^5 | 8.1×10^{-5} | 28 | 1 |
| C | Seed 1, 100 | 301 | 2.1×10^{-4} | 3 | 4.6×10^{-6} | 4.0×10^5 | 1.8×10^{-4} | 14 | 290 |
| | Seed 2, 100 | 503 | 2.1×10^{-4} | 2 | 4.2×10^{-6} | 3.6×10^5 | 1.8×10^{-4} | 11 | 493 |
| | Seed 1, 120 | 274 | 2.2×10^{-4} | 62 | 1.5×10^{-6} | 3.9×10^5 | 1.8×10^{-4} | 58 | 277 |
| D | Seed 1, 100 | 4 | 4.6×10^{-5} | 2 | 2.0×10^{-6} | 2.0×10^5 | 9.0×10^{-5} | 4 | 2 |
| | Seed 2, 100 | 61 | 4.7×10^{-5} | 2 | 4.1×10^{-6} | 2.4×10^5 | 8.5×10^{-5} | 8 | 54 |
| | Seed 1, 120 | 7 | 4.2×10^{-5} | 1 | 2.0×10^{-6} | 2.2×10^5 | 7.6×10^{-5} | 6 | 2 |
| E | Seed 1, 100 | 553 | 1.6×10^{-4} | 4 | 5.3×10^{-6} | 3.6×10^5 | 1.7×10^{-4} | <1 | 556 |
| | Seed 2, 100 | 610 | 1.6×10^{-4} | 4 | 6.6×10^{-6} | 3.4×10^5 | 1.7×10^{-4} | <1 | 612 |
| | Seed 1, 120 | 210 | 1.7×10^{-4} | 45 | 1.7×10^{-6} | 3.4×10^5 | 1.7×10^{-4} | 11 | 244 |
| F | Seed 1, 100 | 40 | 3.0×10^{-5} | 1 | 1.9×10^{-6} | 2.2×10^5 | 8.3×10^{-5} | <1 | 40 |
| | Seed 2, 100 | 320 | 3.0×10^{-5} | 4 | 4.2×10^{-6} | 2.4×10^5 | 8.3×10^{-5} | 2 | 322 |
| | Seed 1, 120 | 52 | 3.1×10^{-5} | 4 | 2.4×10^{-6} | 2.2×10^5 | 7.4×10^{-5} | <1 | 55 |

**Figure 1.** Orbital period and eccentricity probability distribution of BMSPs formed via the AIC channel for models A, B and C, from left to right, respectively.

binary population seems to be distributed into two regions. Similar to model B, the first group has a short orbital period of $\lesssim 1$ d and a large eccentricity of $e \gtrsim 0.4$. While contrary to the first group, the second group consists of BMSPs with a long orbital period of $\gtrsim 20$ d and an eccentricity of near 0.

The distribution of the primordial binary systems forming BMSPs in the M_1 - M_2 (left-hand panel) and M_1 - a (right-hand panel) diagrams are shown in Fig. 2 for models A and E. One can see that the parameter space of the primordial binaries forming BMSP-He is wider than that of BMSP-MG, and the latter has rigorous initial parameters. In addition, the initial parameter space of BMSP-He in model A is larger than that in model E, while the tendency is reversed for BMSP-MG. This difference results from various effects of the kicks on BMSP-He and BMSP-MG. The former usually has a narrow orbit, and high kick can prevent the merger of the two components. However, for BMSP-MG with a wide orbit high kick can lead to more binaries to be broken up during the AIC. The difference in the initial parameter space naturally accounts for the difference of birth rates. BMSPs with long orbital periods ($\gtrsim 20$ d) have evolved

from primordial binaries with $M_1 \sim 8$ – $11 M_\odot$, $M_2 \sim 2$ – $4 M_\odot$ and $a \sim 100$ – $1000 R_\odot$.

4 DISCUSSION AND SUMMARY

The main goal of this work is to explore if the AIC channel can form a population of eccentric BMSPs. For a massive ONE WD that accretes material from its donor star, when its mass reaches Chandrasekhar limit, the process of electron capture may induce gravitational collapse of the WD rather than a Type Ia supernova explosion. As a result of AIC, an MSP with a weak surface magnetic field and low spin-down rate may be formed. Same as the formation of those NSs originated from the collapse of massive star, the nascent NSs via AIC may also receive a kick due to the asymmetric ejection of material or neutrinos from the newborn NSs. Our simulated results can be summarized as follows.

- (1) For a high kick velocity (150 km s^{-1}) during the AIC, there exist ~ 100 – 200 ($\alpha_{\text{CE}} = 3$) or ~ 10 – 30 ($\alpha_{\text{CE}} = 1$) eccentric

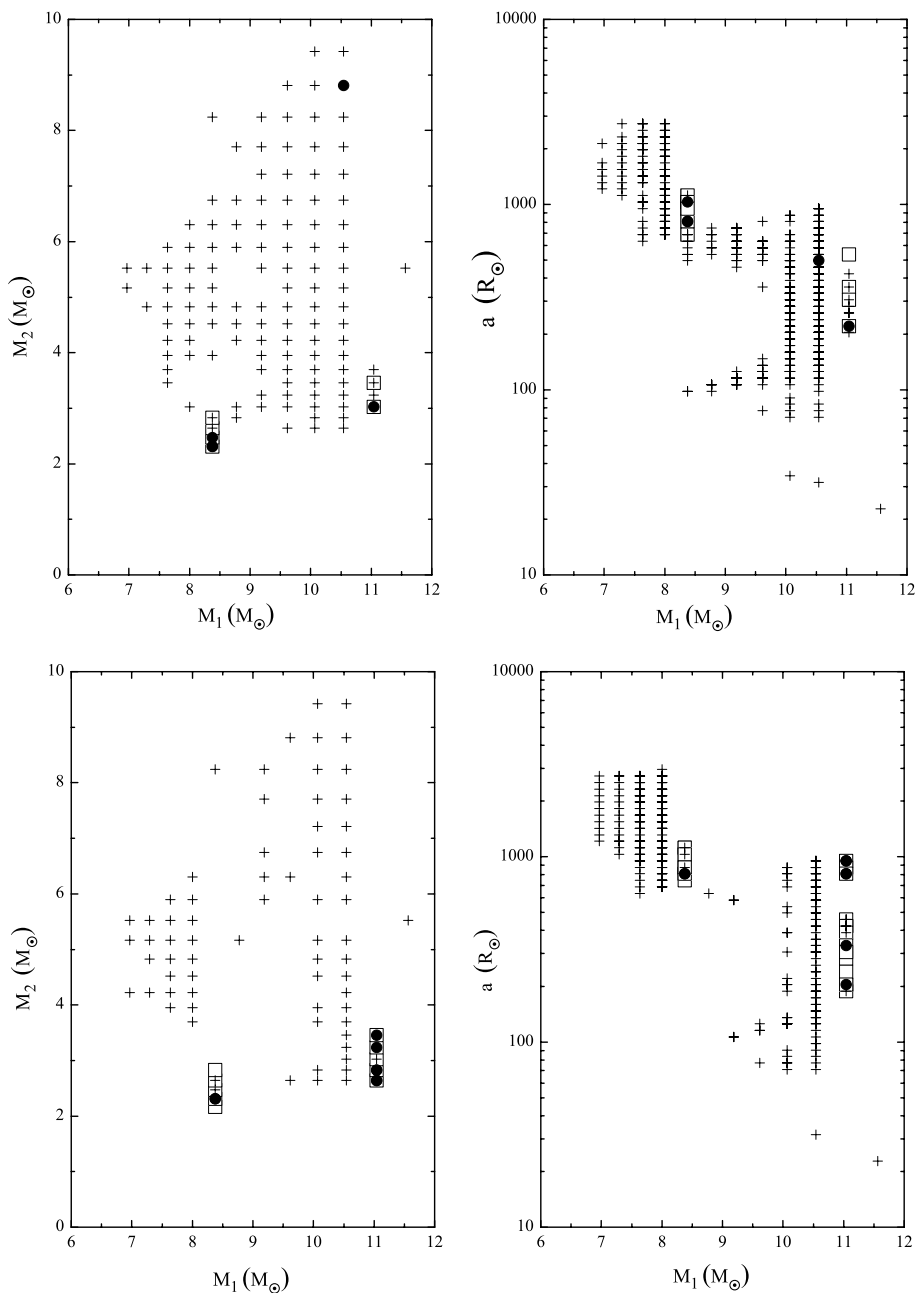


Figure 2. Distribution of primordial binary systems forming BMSPs in the M_1 – M_2 and M_1 – a diagrams for models A (top panels) and E (bottom panels), respectively. The open squares, crosses and solid circles correspond, respectively, to the progenitors of BMSP-MG, BMSP-He and BMSPs with long orbital periods.

BMSPs in the Galaxy, accompanied by a He star. However, almost all BMSPs are in circular orbits when the natal kick velocity $\lesssim 100 \text{ km s}^{-1}$.

(2) The ONe WD + He star channel plays an important role in forming BMSPs. Except for model D, our predicted number and birth rate of BMSP-He are one to two orders of magnitude higher than those of BMSP-MG. In fact, this evolutionary channel has been noted by Tutukov & Yungelson (1996). Recently, Wang et al. (2009a,b) investigated the evolutionary channel of CO WD + He star to Type Ia supernovae, and found that this channel can interpret Type Ia supernovae with short delay times.

(3) It is difficult for the AIC channel to produce BMSPs with a MS, RG or SG companion, the number of which is less than 10, and

their eccentricities are near 0. If the companion of PSR J1903+0327 is really a MS star, the probability that it originated from the current binary can be ruled out. Both the recycled model and the AIC channel cannot produce this peculiar BMSP with a high eccentricity and a MS donor star, unless the natal NS had possessed a debris disc (Liu & Li 2009). We expect further detailed multiwaveband observations for PSR J1903+0327 to constrain the properties of its optical counterpart, and hence its formation channel.

(4) All the models can produce $\sim 10^5$ isolated MSPs in the Galaxy, without invoking the evaporation of donor stars by the high-energy radiation of the MSPs (Kluźniak et al. 1988; Ruderman, Shaham & Tavani 1989a; Ruderman et al. 1989b). In addition, AIC of WDs may form submillisecond pulsars in a quark star regime

(Du et al. 2009), which can hardly be formed in the scenario of normal NSs. In particular, the AIC channel seems to be related to the discrepancy between the birth rates of MSPs and LMXBs, the solution of which may need additional mechanisms forming MSPs (Bailyn & Grindlay 1990; Lorimer 1995). Certainly, it is interesting to investigate further in this alternative model.

(5) We note that the predicted numbers of various types of BMSPs have considerable uncertainties for different random number sequences. However, the birth rates and the numbers for BMSP-He in a given model show little or no variation. Since BMSP-He makes a significant contribution to the total numbers of BMSPs, our results are reliable in this respect.

Perhaps the biggest uncertainty in this work is the kick distribution during the AIC. It strongly depends on the kick velocity if the AIC channel can form the eccentric BMSPs. It is usually assumed that the natal NS formed by AIC may receive a small kick (Podsiadlowski et al. 2004; Scheck et al. 2004; Dessart et al. 2006; Kitaura, Janka & Hillebrandt 2006). Therefore, the possibility of forming the eccentric BMSPs via the AIC channel can be ruled out. In addition, even if the natal NS receives a strong kick,⁴ AIC channel also cannot produce the eccentric BMSPs with an orbital period of $\gtrsim 10$ d, and their companions are He stars. Based on the results by binary population synthesis, we demonstrate that the observed orbital parameters of PSR J1903+0327 cannot be produced by the AIC channel.

ACKNOWLEDGMENTS

We are grateful to the referee, Jarrod Hurley, for his constructive suggestion on improving this paper. This work was partly supported by the National Science Foundation of China (under grant nos 10873008, 10873011, 10973002 and 10935001), the National Basic Research Programme of China (973 Programme 2009CB824800), Programme for Science & Technology Innovation Talents in Universities of Henan Province, China Postdoctoral Science Foundation funded project and Scientific Research Foundation, Huazhong Agricultural University, China.

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⁴The natal NS via the AIC would lose a mass of $\sim 0.2 M_{\odot}$ in the form of neutrinos (van Paradijs et al. 1997). If the ejection of neutrinos is highly asymmetric, then a large kick may be produced. Alternatively, during AIC a large amount of mass ejection may occur as a result of the formation of a low-mass bare strange star (Xu 2005), and a large kick velocity may be received.

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