A Fallback Disk Accretion Involved Formation Channel to PSR J1903+0327

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ABSTRACT

The discovery of the eccentric binary and millisecond pulsar J1903+0327 has raised interesting questions about the formation mechanisms of this peculiar system. Here we present a born-fast scenario for PSR J1903+0327. We assume that during the supernova (SN) explosion that produced the pulsar, a fallback disk was formed around and accreted onto the newborn neutron star. Mass accretion could accelerate the neutron star’s spin to millisecond, and decrease its magnetic field to \( \sim 10^8 - 10^9 \) G, provided that there was sufficient mass (\( \sim 0.1 M_\odot \)) in the fallback disk. The neutron star became a millisecond pulsar after mass accretion terminated. In the meanwhile the binary orbit has kept to be eccentric (due to the SN explosion) for \( \sim 10^9 \) yr. We have performed population synthesis calculations of the evolutions of neutron stars with a fallback disk, and found that there might be tens to hundreds of PSR J1903+0327 like systems in the Galaxy. This scenario also suggests that some fraction of isolated millisecond pulsars in the Galactic disk could be formed through the same channel.

Key words: accretion, accretion disks – pulsars: general – pulsars: individual (PSR J1903+0327) – stars: neutron

1. INTRODUCTION

There are now around 100 binary and millisecond pulsars (BMPSRs) known in the Galaxy. Most of them are characterized by short spin periods (\( P < 15 \) ms), weak magnetic fields (\( B \sim 10^8 - 10^9 \) G), and circular orbits with companions of mass \( \sim 0.15 M_\odot - 0.45 M_\odot \). In the recycling scenario, these systems are thought to be the descendants of low-mass X-ray binaries (Bhattacharya & van den Heuvel 1991; Tauris & van den Heuvel 2006). The evolutionary path is briefly described as follows. A high-field (\( B \sim 10^{12 - 10^{13}} \) G), rapidly rotating neutron star (NS) is born in a binary with a low-mass (\( \sim 1 M_\odot \)) main-sequence (MS) companion star. During the supernova (SN) that produces the NS, mass loss and a kick imparted on the NS cause the orbit to be eccentric. The NS spins down as a radio pulsar for \( \sim 10^6 - 10^7 \) yr until passing by the so-called “death line” in the magnetic field–spin period (\( B-P \)) diagram (Ruderman & Sutherland 1975). When the companion evolves to overflow its Roche lobe, mass transfer occurs by way of an accretion disk, and tidal friction serves to circularize the orbit. Mass accretion onto the NS gives rise to X-ray emission, induces magnetic field decay (the mechanisms for the field decay induced by accretion are, however, not well understood), and accelerates the NS up to short (millisecond) period. When the companion loses almost all of its envelope and mass transfer ceases, the endpoint of the evolution is a circular binary containing an NS visible as a low-field, millisecond radio pulsar, and a He or CO white dwarf (WD), the remaining core of the companion. A fast-growing population of eccentric (\( e > 0.1 \)) BMPSRs have been recently revealed in globular clusters (GCs; Freire et al. 2007). These high eccentricities are likely to be attributed to the dynamical interactions in the central regions of GCs.

Most recently Champion et al. (2008) reported the discovery of an eccentric BMPSR PSR J1903+0327 in the Galactic plane. With a spin period of 2.15 ms, the pulsar lies in an eccentric (\( e = 0.44 \)), 95 day orbit around a \( \sim 1 M_\odot \) companion. The mass of the pulsar was estimated to be 1.74 ± 0.04 \( M_\odot \), about 30% larger than that of other binary NSs in the Galactic disk. Infrared observations identified a possible MS companion star. Preferred formation scenarios may include (see van den Heuvel 2008; Champion et al. 2008): (1) the pulsar was recycled in a GC, then the original donor star was replaced by the present MS companion via one or more exchange interactions, and the binary was displaced from the GC due to either ejection or the disruption of the GC; (2) the pulsar is part of a primordial hierarchical triple system, recycled by accretion from the progenitor of a massive (\( \sim 0.9 - 1.1 M_\odot \)) WD, which is seen in the timing measurement, while the detected infrared counterpart, the third star, is in a much wider and highly inclined orbit around the inner binary. The eccentricity of the inner binary is caused by the perturbation of the outer MS star; (3) in an alternative triple-star model, the WD in the inner binary system was evaporated by the pulsar’s energy flux, or coalesced with it, such that the present binary remained.

Since there is no strong evidence for the GC or triple star origin of PSR J1903+0327, in this paper, we seek an alternative, born-fast scenario for PSR J1903+0327, which was already mentioned by Champion et al. (2008). These authors argued that the pulsar was not likely to be formed spinning rapidly at the time of SN with a small magnetic field, due to the following reasons: (1) there are no pulsars like PSR J1903+0327 in any of the \( > 50 \) young SN remnants in which an NS has been directly inferred or detected; (2) the 18 isolated MPSRs detected in the Galactic disk have spin distributions, space velocities, and energetics indistinguishable from those of recycled BMPRSs and their space velocities and scale heights do not match those of nonrecycled pulsars; (3) magnetic fields in young pulsars are unlikely to be less than \( 10^{10} \) G. However, as we have shown below, if it experienced accretion from a SN fallback disk, the newborn pulsar could be accelerated to a period of several milliseconds, together with the magnetic field decayed to \( \sim 10^8 \) G from an initial value, say \( \sim 10^{12} \) G. When the disk becomes neutral after \( \sim 10^3 - 10^4 \) yr (Menou et al. 2001) and accretion ceases, the NS becomes an MPSR. The orbit, if not being disrupted by the SN explosion, will remain eccentric for \( > 10^5 \) yr before it is circularized (see Hurley et al. 2002). The binary consists of a recycled pulsar and an MS companion in an eccentric orbit, just like PSR J1903+0327. Hence this scenario could produce a population of eccentric BMPSRs as well as isolated MPSRs.
2. SPIN EVOLUTION OF AN NS WITH A FALBACK DISK

Following the formation of an NS through the core collapse of its progenitor, a small amount of mass could fall back onto the compact object (Colgate 1971; Chevalier 1989; Lin et al. 1991). Some of the fallback material may carry sufficient angular momentum to form an accretion disk of mass \( M_d \) around the NS. The initial transient phase lasts for a local viscous timescale \( t_0 \approx 6.6 \times 10^{-5} (T_{e,6})^{-1} R_d^{-2}(t_0) \) yr, on which a thin disk forms (Cannizzo et al. 1990; Menou et al. 2001). Here \( T_{e,6} \) is the typical temperature in the outermost disk annulus during this early phase in units of \( 10^6 \) K and \( R_d(t_0) \) is the initial disk radius in units of \( 10^8 \) cm. We set \( T_{e,6} = 1 \) throughout this paper. The subsequent evolution of the disk obeys the self-similar solution (Cannizzo et al. 1990), i.e.,

\[
M_d(t) = \begin{cases} 
M_d(t_0), & 0 < t < t_0, \\
M_d(t_0) \left( \frac{t}{t_0} \right)^{-p}, & t \geq t_0,
\end{cases}
\]

where the power index \( p = 1.25 \) (Francischelli & Wijers 2002), \( M_d(t_0) \) is a constant that we normalize to the total mass of the disk \( M_d = \int_0^\infty M_d dt \), by \( M_d/(5t_0) \) (Chatterjee et al. 2000).

The subsequent evolution of the NS can be divided into three phases:

1. The accretor phase. When the magnetosphere radius \( R_m \simeq 1.6 \times 10^6 B_{12}^{-1/2} M_{18}^{7/2} \) cm is less than the corotation radius defined by \( R_c = (GM/\Omega)^{1/3} \), the fallback matter is allowed to be accreted onto the surface of the NS. Here \( B_{12} = B/10^{12} \) G, \( M_{18} = M/10^{18} \) g s\(^{-1}\), and \( \Omega \) is the angular velocity of the NS. To evaluate the accretion torque, we divide this phase further into two subphases: (a) if \( R_m \lesssim \) the NS radius \( R_{NS} \), the torque exerted on the star is assumed to be \( J = \dot{M} R_{NS}^2 \Omega_{K}(R_{NS}) \), where \( \Omega_{K}(R) \) is the Keplerian velocity at \( R \); (b) if \( R_{NS} < R_m \lesssim R_c \), the accretion torque is given by \( J = 2\dot{M} R_m^2 \Omega_{K}(R_{m})[1 - \Omega/\Omega_{K}(R_{m})] \).

The accretion rate \( \dot{M} \) of the NS is assumed to be limited by the Eddington accretion rate \( \dot{M}_E \simeq 1 \times 10^{18} \) g s\(^{-1}\) for a 1.4 \( M_\odot \) NS. However, during the early phase of accretion, the accretion rate may be so high that the radiation is trapped in the flow and neutrino losses are important close to the NS surface (Colgate 1971; Chevalier 1989). The gravitational energy generated by infalling matter is mainly released by neutrino losses. Hence the Eddington limit does not work in this phase. According to Chevalier (1989), when the accretion rate drops to about \( 3 \times 10^{-4} \) \( M_\odot \) yr\(^{-1}\), the reverse shock reaches the radiation trapping radius so that the photons can begin to diffuse out from the shocked envelope. A luminosity of Eddington limit is expected now, and this luminosity can reduce or even reverse the inflow outside the shocked envelope. Hence we adopt the Eddington-limited accretion only when \( \dot{M} < 3 \times 10^{-4} \) \( M_\odot \) yr\(^{-1}\). Otherwise we assume all the mass is accreted by the NS.

Along with mass accretion, we assume that the magnetic field evolution follows the relation, \( B = B_0(1 + \Delta M/M_0) \), where \( B_0 \) is the initial magnetic field strength, and \( M_0 \) is a parameter that determines the rate of decay with its typical value of \( \sim 10^{-5} \) to \( 10^{-4} \) \( M_\odot \) (Taam & van den Heuvel 1986; Shibasaki et al. 1989; Romani 1990).

2. The propeller phase. This phase begins when \( R_c < R_m \). The infalling matter is assumed to be accelerated outward owing to the centrifugal barrier, taking away the angular momentum of the NS (Illarionov & Sunyaev 1975). In this phase we use the same formula as in the accretor phase (b) to estimate the propeller spin-down torque.

3. The radio pulsar phase. As \( \dot{M} \) decreases further, \( R_m \) exceeds the light cylinder radius \( R_{lc} = c/\Omega \), or the disk becomes neutral, the accretion ceases and the NS becomes a radio pulsar. The neutral timescale of a fallback disc is \( t_n = [R_d(t_0) \times 10^{16} \) g s\(^{-1}\)/\( M_d(t_0) \)]\(^{-1} \times 2.75 t_0 \) (Menou et al. 2001), where \( R_d(t_0) \) is the disk radius in units of \( 10^{10} \) cm. In this work, when either \( R_m > R_{lc} \) or \( t > t_n \), we assume that the radio pulsar phase turns on and the subsequent NS spin evolution follows the magnetic dipole radiation prescription, until the NS crosses the “death line,” i.e., \( B_{12}/P^2 < 0.17 \).

In Figure 1 we show several examples of the calculated evolutions of the NS spin and magnetic field under typical conditions according to the scheme described above. The model parameters are listed in Table 1. For the spin evolution, the thick solid, solid, and dotted lines represent the accretor, propeller, and radio pulsar phases, respectively. In Case 1 we adopt the initial parameters as \( M_d = 0.28 \) \( M_\odot \), \( P_0 = 14 \) ms,
Table 1

| Model No. | $M_d (M_⊙)$ | $R_d,10^{-6}$ | $P_d$, ms | $B_0 (10^{12}$ G) | $M_d (10^{-6} M_⊙)$ |
|-----------|-------------|-------------|----------|-----------------|-------------------|
| 1         | 0.28        | 0.1         | 14       | 3               | 1                 |
| 2         | 0.02        | 0.1         | 14       | 3               | 1                 |
| 3         | 0.28        | 0.01        | 14       | 3               | 1                 |
| 4         | 0.28        | 0.1         | 14       | 3               | 1                 |
| 5         | 0.28        | 0.1         | 14       | 10              | 1                 |
| 6         | 0.01        | 0.01        | 14       | 10              | 1                 |

$B_0 = 3 \times 10^{12}$ G, $M_d = 10^{-5} M_⊙$, and $R_d = 10^9$ cm. The NS is found to be spun-up to a period of 2.88 ms in 72 yr, when the disk becomes neutral.\(^3\) In the meanwhile, the magnetic field decreases dramatically to $4.2 \times 10^9$ G. This is a strongly spun-up pulsar, demonstrating a possible way for the formation of PSR J1903+0327.

In Case 2 we lower the initial disk mass $M_d$ to 0.02 $M_⊙$, while keeping all other parameters same as in Case 1. This leads to a lower $M_d(t_0)$, so that the spinning-up efficiency also becomes lower. The NS enters the radio pulsar phase with a relatively longer period of 11.26 ms and a higher magnetic field of 6.8 $\times 10^9$ G. In Case 3 we lower the initial disk radius $R_d$ by a factor of 10 compared with Case 1. This gives a lower value of $t_0$ and a higher value of $M_d(t_0)$, and the NS is spun-up to a period of 3.63 ms. In Case 4 we choose a slower decay of the magnetic field than in Case 1 by setting a higher value of $B_0 = 10^{-6} M_⊙$. It is shown that the period evolution remains almost unchanged, but the magnetic field decays to $4.2 \times 10^9$ G, about 10 times of that in Case 1. A similar feature can be seen in Case 5, if we increase the initial magnetic field to $B = 1 \times 10^{13}$ G. Finally, in Case 6 $M_d$ is further decreased to 0.01 $M_⊙$, now the NS is spun-up to a period of 11.82 ms during the first 39 yr and then spun-down during the propeller phase to a period of 11.92 ms during the subsequent 88 yr. After that time the disk becomes neutral and the radio pulsar phase begins. In the meanwhile the magnetic field decays to $6.6 \times 10^{10}$ G. This is a mildly spun-up pulsar.

3 The neutral time is given by $t_n \propto [R_d^3 M_d(t_0)]^{1/2.75} \times R_d^{0.3}$ (Menou et al. 2001). The value $t_n = 72$ yr used here is much less than that ($\sim 10^3$–$10^4$ yr) in Menou et al. (2001). This is because (1) we calculated $M_d(t_0)$ by normalizing it to the total disk mass, while Menou et al. (2001) estimated it by assuming $M_d(t_0) = M_d/t_0$, which gives a larger value of $M_d(t_0)$ than ours; (2) the adopted value of $R_d = 10^9$ cm is larger than the value in Menou et al. (2001).
and has an MS binary companion. Since the pulsar evolution can be strongly influenced by the stellar winds from the companion, which are intensive for massive stars, we only consider the MPSR low-mass main-sequence (MPSR-LMS) binaries, in which the companion star has a mass less than 1.5 $M_\odot$. Alternatively the pulsar is formed by core collapse of the secondary, and already has an NS/BH binary companion. They are called NS/BH-MPSRs binaries. Finally, a single MPSR could form during either the first or the second SN that disrupts the binary.

To investigate the influence of the model parameters on the final results, we design nine models by changing the values of the CE parameter $\alpha_{\text{CE}}$, the field decay parameter $R_d$, the lower and upper limit of the fallback disk mass $M_{\text{d,low}}$, $M_{\text{d,upp}}$ in case of subenergetic SNe, and the disk radius $R_d$ (listed in Table 2). The calculated numbers and formation rates of various types of binary and single MPSRs in our Galaxy are listed in Table 3, and briefly described as follows.

In model A (regarded as our control model) we adopt $\alpha_{\text{CE}} = 1.0$, $M_0 = 10^{-5}$ $M_\odot$, $M_d = 10^{-5}$–0.1 $M_\odot$, and $R_d = 10^6$ cm. It is predicted that in the Galaxy there are $\sim 200$ MPSR-LMS (PSR J1903+0327 may be one of them) and 10 times more NS/BH-MPSR systems. Moreover, $\sim 10^5$ single MPSRs are produced. This number is comparable with that estimated from observations (e.g., Lorimer 1995), suggesting that some fraction of the single MPSRs might form from the fallback disk accretion rather than the traditional recycling channel in binary systems. Since their formation rate is 100 times lower than normal pulsars, it is not surprising that no MPSRs have been detected in young SN remnants.

In model B we increase the $\alpha_{\text{CE}}$ to 3.0, and find that higher $\alpha_{\text{CE}}$ produces more MPSR-LMS binaries. This is because binaries with a higher $\alpha_{\text{CE}}$ tend to survive during the CE evolution, especially for low-mass, close binaries, which are more likely to be subject to coalescence during CE evolution. For the same reason, lower $\alpha_{\text{CE}}$ (model C) leads to fewer MPSRs (see Liu & Li 2006 for more detailed discussions). In model D we adopt a slower magnetic field decay, resulting in a shorter duration of the accretor phase, hence significantly reducing the numbers of all three types of MPSRs. In model E we choose a lower value of $R_d$ than in model A. As mentioned in Section 2, this will cause longer final periods of the pulsars (compare the curves of P1 and P3 in Figure 1), and produce fewer MPSRs. In model F the lower limit of the fallback disk masses is increased by a factor of 3, but the numbers of MPSRs change little, since MPSRs are produced only in the case of heavy disk accretion. This effect can also be illustrated in model G: when the upper limit of disk masses become half in model A, the numbers of MPSRs decrease by a factor of 10. To constrain the possible ranges of MPSR numbers, models H and I represent two extremely favorable and unfavorable cases for the production of MPSRs, respectively. It is found that the number of MPSR-LMS binaries may range from less than 1 to nearly 1000 in the Galaxy.

We plot the eccentricity versus orbital period distributions of the MPSR-LMS binaries for models A, B, and C in Figure 2. The distributions of the other three models are similar to that of model A. It is seen that in both models A and C most MPSR-LMS binaries are in wide orbits ($P_{\text{orb}} > 10^3$ days) with eccentricities $e > 0.3$. For model B, the binary population seems to be distributed into two groups. One is similar to that in models A and C, the other stretches across large ranges of $e (\sim 0–1)$ and $P_{\text{orb}} (\sim 1–10^3$ day) with a tendency of larger $e$ accompanied with larger $P_{\text{orb}}$.

4. DISCUSSION AND CONCLUSIONS

In this paper we suggest a born-fast formation channel for MPSRs in the Galaxy. In this scenario, a newborn NS may experience spinning-up and field decay phase via accretion from a fossil disk, established as a result of fallback following an SN explosion. For appropriate choices of initial parameters, the NS could become a low-field MPSR within $< 10^3$ yr. In particular, this scenario can naturally explain the properties (millisecond spin and eccentric orbit) of the recently discovered BMPSR PSR J1903+0327, without invoking stellar interactions within a GC or peculiar triple system.

Our population synthesis calculations also suggest a population of single FDAI MPSRs in the Galaxy. The formation of single MPSRs has not been well understood, especially how the pulsar has lost its binary companion after mass transfer. The conventional explanation is that the pulsar was recycled in a binary located in a GC, and then ejected out due to stellar encounters, or that the high-energy radiation from the pulsar has evaporated its companion (e.g., Ruderman et al. 1989). The latter explanation may also require a GC origin of the binary (King

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### Table 2

Model Parameters for Binary Population Synthesis

| Model | $\alpha_{\text{CE}}$ | $M_0$ ($10^{-5}$ $M_\odot$) | $R_d$ | $M_{\text{d,low}}$ ($10^{-5}$ $M_\odot$) | $M_{\text{d,upp}}$ (0.1 $M_\odot$) |
|-------|---------------------|-----------------------------|-------|---------------------------------|---------------------------------|
| A     | 1                   | 1                           | 1     | 1                               | 1                               |
| B     | 3                   | 1                           | 1     | 1                               | 1                               |
| C     | 0.5                 | 1                           | 1     | 1                               | 1                               |
| D     | 1                   | 10                          | 1     | 1                               | 1                               |
| E     | 1                   | 0.1                         | 1     | 1                               | 1                               |
| F     | 1                   | 1                           | 1     | 3                               | 1                               |
| G     | 1                   | 1                           | 1     | 1                               | 0.5                             |
| H     | 3                   | 1                           | 1     | 1                               | 1                               |
| I     | 0.5                 | 0.1                         | 1     | 0.5                             | 1                               |

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### Table 3

Predicted Numbers and Formation Rates in Our Galaxy of Various Types of FDAI MPSR Systems

| Model | Item       | MPSR-LMS | NS/BH-MPSR | Single MPSR |
|-------|------------|----------|------------|-------------|
| A     | Number     | 203      | 3.3 $\times$ 10^3 | 1.5 $\times$ 10^6 |
|       | Rate       | 6.0 $\times$ 10^{-7} | 3.1 $\times$ 10^{-6} | 3.1 $\times$ 10^{-4} |
| B     | Number     | 751      | 3.7 $\times$ 10^3 | 1.6 $\times$ 10^6 |
|       | Rate       | 1.3 $\times$ 10^{-6} | 4.0 $\times$ 10^{-6} | 3.2 $\times$ 10^{-4} |
| C     | Number     | 192      | 3.1 $\times$ 10^3 | 1.5 $\times$ 10^6 |
|       | Rate       | 6.5 $\times$ 10^{-7} | 3.0 $\times$ 10^{-6} | 3.1 $\times$ 10^{-4} |
| D     | Number     | 8        | 1.4 $\times$ 10^2 | 1.2 $\times$ 10^5 |
|       | Rate       | 6.2 $\times$ 10^{-7} | 3.3 $\times$ 10^{-6} | 2.7 $\times$ 10^{-4} |
| E     | Number     | 83       | 1.3 $\times$ 10^3 | 4.9 $\times$ 10^4 |
|       | Rate       | 3.9 $\times$ 10^{-7} | 2.0 $\times$ 10^{-6} | 1.9 $\times$ 10^{-4} |
| F     | Number     | 232      | 3.7 $\times$ 10^3 | 1.7 $\times$ 10^4 |
|       | Rate       | 6.9 $\times$ 10^{-7} | 3.5 $\times$ 10^{-6} | 3.4 $\times$ 10^{-4} |
| G     | Number     | 28       | 4.5 $\times$ 10^2 | 1.2 $\times$ 10^4 |
|       | Rate       | 3.5 $\times$ 10^{-7} | 1.7 $\times$ 10^{-6} | 2.0 $\times$ 10^{-4} |
| H     | Number     | 856      | 4.2 $\times$ 10^3 | 1.8 $\times$ 10^5 |
|       | Rate       | 1.5 $\times$ 10^{-6} | 4.5 $\times$ 10^{-6} | 3.6 $\times$ 10^{-4} |
| I     | Number     | 0.3      | 7           | 38           |
|       | Rate       | 9.9 $\times$ 10^{-8} | 4.6 $\times$ 10^{-7} | 3.9 $\times$ 10^{-5} |

### Notes

1. The CE parameter $\alpha_{\text{CE}}$ is defined as the ratio of total binding energy of the envelope $E_{\text{bound}}$, and the difference between the initial and final orbital energies of the cores, i.e., $\alpha_{\text{CE}} = E_{\text{bound}}/(E_{\text{orb, i}} - E_{\text{orb, f}})$, where $E_{\text{orb, i}}$ and $E_{\text{orb, f}}$ are the final and initial binding energy of the cores, respectively (see Hurley et al. 2002 for details).
et al. 2005). Although the fraction of BMPSRs and LMXBs in GCs is much larger with respect to the fraction in the Galactic field, it seems unlikely that all single MSPRs have originated from GCs. The fallback disk accretion scenario might provide a possible way for the formation of not only single MSPs (Miller & Hamilton 2001) but also planetary systems around them (Lin et al. 1991).

Obviously the formation scenario proposed in this work is subject to many uncertainties, so the results in Table 3 should be regarded as the optimistic cases. One of the biggest issues is to determine how much fallback material would have enough angular momentum at the time of collapse to allow the formation of a disk. Our population synthesis calculations suggest that there may be tens to hundreds of MSPR-LMS binaries lurking in our Galaxy. For PSR J1903+0327, a relatively large amount of fallback disk mass ($\gtrsim 0.1 \, M_\odot$) is required to produce the very short period ($\lesssim 3$ ms), implying that the progenitor star may have experienced an unusual SN-fallback history. It is interesting to note that the large mass ($\sim 1.74 \, M_\odot$) of the pulsar may suggest a massive ($\gtrsim 18 \, M_\odot$) progenitor star (Zhang et al. 2008) and probably intensive fallback during the SN explosion.

To form a centrifugally supported accretion disk around the NS, the specific angular momentum of the fallback matter should be larger than that needed for a circular orbit at the NS radius ($GM_{\rm NS} R_{\rm NS}^{1/2}$). Modern stellar evolution calculations suggest that there may be tens to hundreds of MSPR-LMS binaries lurking in our Galaxy. For PSR J1903+0327, a relatively large amount of fallback disk mass ($\gtrsim 0.1 \, M_\odot$) is required to produce the very short period ($\lesssim 3$ ms), implying that the progenitor star may have experienced an unusual SN-fallback history. It is interesting to note that the large mass ($\sim 1.74 \, M_\odot$) of the pulsar may suggest a massive ($\gtrsim 18 \, M_\odot$) progenitor star (Zhang et al. 2008) and probably intensive fallback during the SN explosion. To form a centrifugally supported accretion disk around the NS, the specific angular momentum of the fallback matter should be larger than that needed for a circular orbit at the NS radius ($GM_{\rm NS} R_{\rm NS}^{1/2}$).

Numerical calculations have been carried for a few mass and angular momentum configurations of massive stars (see Woosley & Bloom 2006, and references therein), which generally suggest highly super-Eddington accretion with a short time. Still lacking is a comprehensive picture of the conditions for fallback disk formation after SN explosions of massive stars. Highly super-Eddington accretion in a short period of $\sim 100$ yr in a radiation-trapped regime plays a key role in the formation of FDI MPSRs. This distinguishes our model from the standard type of accretion expected in the recycling scenario, which lasts for $\sim 10^8$–$10^{10}$ yr. In the standard pulsar recycling theory, the so-called “spin-up line” in the $B$–$P$ diagram shows the minimum period to which the NS can be spun-up in Eddington-limited accretion. This line is defined by the equilibrium period assuming the spin-up proceeding at the Eddington accretion rate. Although the pulsars in our scenario have experienced the highly super-Eddington accretion, since the mass accretion rate declines rapidly, the equilibrium period is never attained, unlike in the case of accreting NS in LMXBs. Thus our model does not necessarily predict any MPSRs sitting above the spin-up line.

It is also not known how accretion-induced field decay occurs in NSs. One possible way is via ohmic dissipation of the accreting NSs crustal currents, due to the heating of the crust which in turn increases the resistance in the crust (Romani 1990; Geppert & Urpin 1994; Konar & Bhattacharya 1997). Alternative scenarios consist of screening or burying the magnetic field with the accreted material (Bisnovatyi-Kogan & Komberg 1974; Taam & van den Heuvel 1986; Cumming et al. 2001), or outward moving vortices in the superfluid and superconducting core pushing magnetic fluxoids into the crust during pulsar’s spin-down (Srinivasan et al. 1990; Konar & Bhattacharya 1999). In this work we require a fast field decay during the hyperaccretion phase (within $\lesssim 10^5$–
10^7 yr). Screening or burying the magnetic field with the accreted material may be more appropriate for this scenario.

Finally we move to the uncertainties is the CE evolution. We have used a constant CE parameter $\alpha_{\text{CE}}$ to compute the orbital evolution during the spiral-in process, which is, however, very likely to change with the properties and evolutionary state of stars (Iben & Livio 1993; Taam & Sandquist 2000). From Figure 2 we find that model B with $\alpha_{\text{CE}} = 3$ seems to be preferred for the formation of PSR J1903. This value is compatible with other estimates by, e.g., van den Heuvel (1994), Portegies Zwart & Yungelson (1998), and Kalogera (1999), but in contradiction with Taam (1996), Sandquist et al. (1998, 2000), and O’Shaughnessy (2008). Here the controversial issue is that there are no strict criteria for defining binding energy of stellar envelopes and there is no clear understanding whether sources other than gravitational energy may contribute to unbinding common envelopes (Han et al. 1995).

A distinct feature of the born-fast scenario is that the companion star of PSR J1903+0327 is predicted to be a “young” ($\approx (1-2) \times 10^5$ yr, i.e., within the characteristic age of the pulsar) MS star. Future optical, IR, and radio observations could present strong constraints on the nature of the optical counterpart, and thus verify or falsify the born-fast scenario.

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