Formation of binary millisecond pulsars with relatively high surface dipole magnetic fields

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Abstract. We have carried out numerical evolutionary calculations of binary systems to investigate the formation of binary millisecond pulsars (pulsars with white dwarf companions). We apply a "standard scenario" in which the binary pulsars are formed from low-mass and intermediate-mass X-ray binaries as well as an alternative scenario in which the neutron stars are formed by accretion-induced collapse (AIC) of white dwarfs. The mass transfer processes are carefully followed by taking into account a number of binary interactions. Assuming that the magnetic fields of the neutron stars decay due to the accretion, we calculate the pulsar surface dipole magnetic field strength at the end of the mass transfer as a function of the final orbital period. We find that while the observed data of the majority of pulsars are compatible with the derived relations, we fail to produce binary pulsars with relatively high magnetic fields and short orbital periods (such as PSR B0655+64). We conclude that those systems are most likely formed through common-envelope phase.

Key words: stars: evolution – stars: neutron – stars: pulsars: general – stars: binaries: general

1. Introduction

It has been suggested that binary pulsars with white dwarf companions (binary millisecond pulsars or BMSPs) are the descendants of low-mass X-ray binaries (LMXBs; Joss & Rappaport 1983, Savonije 1983, and Paczynski 1983) or intermediate-mass X-ray binaries (IMXBs; Podsiadlowski & Rappaport 2000; Tauris, et al. 2000). The white dwarf companions of the pulsars are the remnants of the donor stars which have dumped matter onto the neutron stars during the X-ray phase. The nearly circular orbits observed in the systems support the view that extensive mass transfer has happened in the systems (before mass transfer the orbits must have been eccentric due to the supernova explosions which have formed the neutron stars, tidal effects become effective to circularize the orbits when the donor stars swell up

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Table 1. Binary millisecond pulsars with relatively strong magnetic fields. f(M) is the mass function and $M_{\rm wd}$ is the mass of the white dwarf companion assuming $i = 60°$ (Tauris & Savonije 1999, Tauris et al. 2000)

PSR	$P_{\rm orb}$ (days)	$P_{\rm spin}$ (ms)	$\log(B)$ (G)	f(M) ($M_\odot$)	$M_{\rm wd}$ ($M_\odot$)
B1831-00	1.811	520.95	10.94	0.000124	0.075
B0655+64	1.029	195.67	10.07	0.0714	0.814
J1232-6501	1.863	88.3	9.97	0.0014	0.175
J1157-5112	3.507	43.6	< 9.80	0.2546	> 1.2
J1803-2712	406.781	334.42	10.89	0.0013	0.170
B0820+02	1232.47	864.87	11.48	0.003	0.231

to fill up their Roche lobes). Hence, pulsars in those systems will have accreted some amount of mass and have been recycled by the accretion. The millisecond spin periods observed in many of the pulsars (despite their old ages, as the nondegenerate companions need some $10^8 - 10^9$ yr to become white dwarfs) indicate that they are indeed recycled pulsars.

Magnetic fields of isolated pulsars do not decay significantly during their lifetime (Bhattacharya et al. 1992). However, many pulsars which are, or have been members of binary systems have relatively weak surface magnetic fields ($10^8 - 10^9$ G). This leads to the suggestion that the magnetic field of neutron stars decays due to accretion (Taam & van den Heuvel 1986, Shibazaki et al. 1989) or related effects, such as spin up and spin down (Srinivasan et al. 1990). However, a number of BMSPs is observed to have relatively strong fields ($\sim 10^{10} - 10^{11}$ G; see Table 1) which implies that those neutron stars have accreted only a small amount of matter. We investigate a number of evolutionary models of binary systems which lead to the formation of BMSPs and examine whether such high-magnetic field BMSPs can be formed. In Sect. 2 we discuss the "standard scenario" in which the systems are formed from LMXBs or IMXBs. In Sect. 3 we discuss an alternative scenario in which the pulsars are formed by accretion-induced collapse (AIC) of white dwarfs. The discussion and conclusion are given in Sect. 4.

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2. Binary pulsars formed from LMXBs or IMXBs ("standard scenario")

We will first discuss the "standard" evolutionary scenario in which BMSPs are formed from LMXBs and IMXBs. We used an updated version of the numerical stellar evolution code of Eggleton (1971, 1972, 1973) to keep track of the evolution of the donor star in which the mass-transfer process is carefully followed by taking into account a number of binary interactions (see Tauris & Savonije 1999 for the description of the code). The initial parameters are chosen such as to avoid spiral-in and common-envelope (CE) evolution (Tauris et al. 2000). We assume models of systems in which the initial mass of the donor star is between 1 and 4.5 $M_\odot$ and the initial orbital period is between 1–20 days. The initial mass of the neutron star is assumed to be 1.3 $M_\odot$. Accretion onto the neutron star is limited by the Eddington limit ($10^{-8}\,M_\odot\mathrm{yr}^{-1}$). Above this limit, matter which cannot be accepted by the neutron star is ejected isotropically carrying the specific angular momentum of the neutron star ("isotropic reemission"). We also take into account the loss of angular momentum due to gravitational radiation and magnetic braking. We neglect the possible mass loss from the accretion disk due to the centrifugal propeller effect as this effect is not precisely known. We follow the evolution of the systems starting from the zero-age main-sequence phase of the donor until the end of the mass transfer phase. We also take into account mass loss prior to the Roche lobe overflow. The calculations are technically similar to those carried out by Tauris & Savonije (1999) and Tauris et al. (2000).

Using population synthesis calculation, Bhattacharya et al. (1992) indicate that isolated pulsars with high magnetic field do not undergo significant magnetic field decay during their lifetime ($\sim 10^7$ yr). On the other hand, binary and millisecond pulsars which are members, or have been members of binaries, have low magnetic field strength ($10^8 - 10^9$ G). These facts lead to the conclusion that the magnetic fields of those pulsars decay due to the interaction in the binaries. More specifically, Taam & van den Heuvel (1986) and Shibazaki et al. (1989) suggest that the magnetic field decay is induced by the mass transfer which has happened in the systems. Cheng & Zhang (1998), by assuming the frozen field and incompressible fluid approximations, derive a relation for the surface dipole magnetic field strength and the amount of matter accreted by the neutron star:

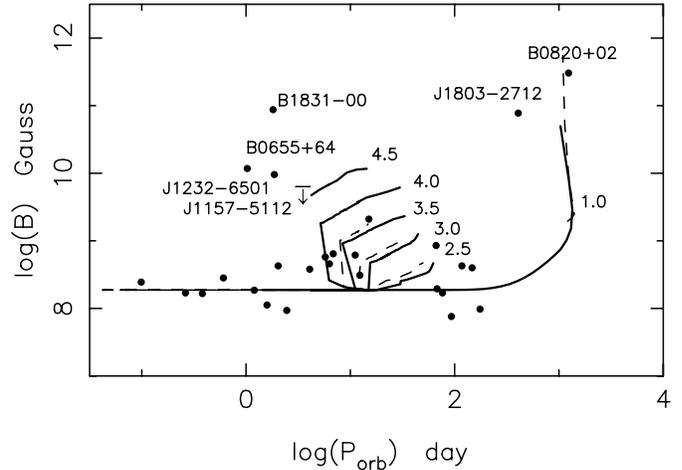$$B = \frac{B_f}{\left(1 - C\exp\left(-\frac{\Delta M}{M_{\mathrm{cr}}}\right)\right)^{\frac{7}{4}}} \tag{1}$$

where,

$$B_f = 4.3 \times 10^8 \alpha (\dot{M}/\dot{M}_{\mathrm{Ed}})^{1/2}(M/M_\odot)^{1/4}R_6^{-5/4}$$

and,

$$C = 1 - \left(\frac{B_f}{B_o}\right)^{4/7}$$

α is an adjustment factor of the order of unity, $\dot{M}_{\mathrm{Ed}}$ is the Eddington mass accretion rate, ΔM is the amount of matter ac-

Fig. 1. Pulsar magnetic field strength as a function of the orbital period. The solid curves show the relation for BMSPs formed from LMXBs and IMXBs ("standard scenario"), the dashed curves indicate the relation for binary pulsars formed by AIC of white dwarfs (see text for further explanations). The initial mass of the donor star is shown on each curve. The dots represent the observed binary pulsars in the galactic disk with circular orbits; for PSR J1157-5112 only the upper limit of $\log(B)$ is shown (we do not include binary pulsars in globular clusters since they may have different evolutionary history).

creted by the neutron star, M_{cr} is the mass of the crust, R_6 is the radius in units of 10^6 cm, and B_o is the initial magnetic field strength of the neutron star. From this formula one can show that a neutron star with $B_o \sim 10^{12}$G can decrease its surface magnetic field to $B \sim 10^9$G by accreting only a few hundredths of $M_\odot$.

Using Eq. (1) and ΔM which we obtained from the evolutionary calculations, we can derive the surface dipole magnetic field strength of the neutron stars as a function of the orbital period. The results are shown as the solid curves in Fig. 1. Here we assume that $\alpha = 0.4$ (this value is chosen to get the best fit to the observed data based on the eye estimate), $R_6 = 1$, $\dot{M}/\dot{M}_{\mathrm{Ed}} = 1$, $M_{\mathrm{cr}} = 0.1\,M_\odot$, and $B_o = 10^{12}$ G. The results are not sensitive to the values of B_o and M_{cr}, but depend on the choice of α. The apparent discontinuities for large donor masses reflect the "jump" of the evolutionary timescale when the donors fill the Roche lobe while crossing the Hertzsprung gap. Also in Fig. 1, we plot the observed data of galactic binary pulsars with circular orbits ($e < 0.01$) for comparison. We do not include binary pulsars in globular clusters as they may have had a different history. Note that the majority of pulsars, except a group of pulsars at the upper left, can be fitted nicely with the curves. This suggests that the "standard scenario" is the most plausible way to form most systems.

3. Binary pulsars formed by accretion-induced collapse of white dwarfs

We will investigate an alternative scenario to form BMSPs in which the neutron stars are formed by accretion-induced collapse (AIC) of white dwarfs (van den Heuvel & Bitzaraki 1995).

AIC is expected to happen in systems consisting of a normal star and a ~ 1.0–1.2 M$_\odot$ ONeMg white dwarf (van den Heuvel 1994). If the white dwarf can accrete enough matter to increase its mass up to the Chandrasekhar limit, it will collapse to a neutron star. In this process, about 0.2 M$_\odot$ is converted into the binding energy of the neutron star (some amount of mass may also be ejected), hence the total mass of the system is reduced. As a result, the orbit somewhat widens and the donor is temporarily detached from its Roche lobe. Mass transfer is resumed when the donor, which is continuing its evolution, again fills up its Roche lobe. At this stage the system can be observed as an LMXB. As in the "standard scenario", the system will eventually end up as a binary pulsar with a white dwarf companion. The difference with the "standard scenario" is that, here the donor star is already an evolved star at the birth of the neutron star (since it must have filled its Roche lobe to initiate the mass transfer which induces the collapse of the white dwarf), while in the "standard scenario" the donor star is essentially an unevolved star when the neutron star is born. Since in this scenario the neutron stars are born when the donors have already been losing mass, one may expect that those neutron stars will accrete less matter than those formed from the "standard scenario". Consequently, they may have stronger magnetic fields. We will examine this notion.

Not all accreting white dwarfs can reach the Chandrasekhar limit. Li & van den Heuvel (1997) show that there are two groups of systems in which the white dwarf can grow up to the Chandrasekhar limit. One is close binaries with ~ 2 to 3.5 M$_\odot$ main-sequence or subgiant companions, and an initial orbital period of several tenth of a day to several days. The other is wide binaries with low-mass (~ 1 M$_\odot$) red giant companions with long (ten to hundred day) orbital period. Although the result of Li & van den Heuvel is aimed for seeking the progenitors of Type Ia supernovae, it applies to AIC as well. In this work we take into account these constraints. We assume that the initial mass of the white dwarf is 1.2 M$_\odot$.

During the collapse about 0.2 M$_\odot$ ($\Delta M_{\rm be}$) is converted to the binding energy of the neutron stars. Some amount of mass ($\Delta M_{\rm ej}$) may also be ejected from the system. This will result to the widening of the system:

$$a = a_{\rm o} \frac{M_{\rm donor} + M_{\rm wd}}{M_{\rm donor} + M_{\rm ns}} \qquad (2)$$

where $a_{\rm o}$ and a are, respectively, the orbital separations before collapse and after tidal circularization; $M_{\rm donor}$ and $M_{\rm wd}$ are, respectively, the masses of the donor and the white dwarf; $M_{\rm ns}$ is the mass of the neutron star ($M_{\rm ns} = M_{\rm wd} - \Delta M_{\rm aic}$ where $\Delta M_{\rm aic} = \Delta M_{\rm be} + \Delta M_{\rm ej}$). We assume $\Delta M_{\rm aic} = 0.2$ M$_\odot$ for all models. We neglect any ki ck velocity which may be received by the neutron star due to asymmetric processes during the collapse.

We keep track of the evolution of the systems by following the accretion onto the white dwarf and subsequently onto the neutron star. The results are shown as the dashed curves in Fig. 1 and we find that those are essentially the same as those of the "standard scenario". This is due to the fact that to maintain

relatively high surface magnetic field ($\gtrsim 10^9$ G) the neutron star must accrete only a small fraction (at most a few percent) of the transferred mass, so this condition is not affected so much by whether the neutron star already exists at the beginning of the mass transfer or whether it exists somewhat later when the donor is already losing some amount of mass. Van den Heuvel & Bitzaraki (1995) suggest that PSR B1831-00 is a candidate for a system formed from this scenario. But, as can be seen from Fig. 1, our results seem to rule out this possibility.

4. Discussion and conclusion

We have derived the relations between the surface magnetic field strengths and the final orbital periods of BMSPs. The observed data of BMSPs mostly fit well with the derived relations. This is compatible with the view that those systems are indeed the descendants of LMXBs or IMXBs. The existence of high-magnetic field pulsars with long orbital periods (PSR B0820+02 and J1803-2712) can naturally be explained by their having originated from long period LMXBs. In such long period systems the red giant donors have a deep convective envelope at the onset of the mass transfer, hence the mass transfer happens violently (super Eddington) and occurs on a short timescale (van den Heuvel 1994) such that the neutron stars can only accrete a small fraction of the transferred mass. As a result, the pulsars only experience a mild decay of the magnetic field.

However, we fail to produce high-magnetic field pulsars with short orbital periods such as PSR B0655+64 and PSR B1831-00. We conclude that those systems cannot be formed from either "standard" or AIC scenario. Tauris et al. (2000) also reach a similar conclusion that binary pulsars with high-mass CO/ONeMg white dwarf companions (PSR B0655+64 belongs to this category as it has a ~ 0.8M$_\odot$ companion) and short orbital periods cannot be formed from LMXBs or IMXBs. Then, the most plausible scenario for forming those systems is that they are formed from the common-envelope (CE) evolution as was originally suggested by van den Heuvel & Taam (1984) for PSR B0655+64. In this scenario, the initial mass of the companion star is considerably larger than the mass of the neutron star (say 5M$_\odot$) and the initial orbital period is very long (~ 1000 days). The companion will fill up its Roche lobe when it ascends the asymptotic giant branch (AGB), i.e. after helium exhaustion in its core. Mass transfer from such an evolved and massive companion tends to be unstable. Such a system undergoes a common envelope (CE) phase in which the neutron star spirals into the envelope of the primary and both stars are embedded in a common envelope. During the spiral-in of the neutron star, the envelope is blown off at the expense of the orbital energy (and probably also in combination with some other energy sources; i.e., accretion energy, recombination energy etc.). At the end of the CE phase, the system consists of a ~ 1M$_\odot$ CO white dwarf (initially the CO core of the primary) and a neutron star. As a large fraction of the orbital energy is used to expel the envelope, the orbital separation of the system is very small ($P_{\rm orb} \lesssim 1$d). The system resembles closely PSR B0655+64. Since the duration of the CE phase is short ($\sim 10^3 - 10^5$ yr), the neutron star

will not accrete much matter, so it will maintain its high magnetic field. However, Chevalier (1993) and Brown (1995) have suggested that a spiral-in neutron star may experience a hypercritical accretion to become a black hole. Despite this suggestion, we argue that the existence of short orbital period BMSPs with relatively strong dipole fields indicates that CE evolution is still an attractive way to form binary pulsars.

The remaining problem is that, the small mass function of PSR B1831-00 may imply a small mass of the white dwarf ($\sim 0.075 M_\odot$ if we assume $i = 60°$). This mass is much too small to be reconciled with the CE evolution. In this respect, the small mass function may indicate, instead, a small inclination angle. However, if we require $M_{\mathrm{wd}} \gtrsim 0.6 M_\odot$ then $i \lesssim 7.5°$. Assuming a random orientation of the orbit, the probability of observing a binary with such a small inclination angle is only 0.8%. Another possibility is that the system may result from AIC of a 1+1.2 $M_\odot$ main-sequence and white dwarf system with unstable mass transfer (Li & Wang 1998). But the outcome is highly speculative. We conclude therefore that the history of PSR B1831-00 is indeed very special and it needs further studies.

We have used a specific relation between magnetic field strength B and amount of matter accreted by the neutron star ΔM, as given in Eq. (1). This relation well reproduces the observed relation between B and orbital period of BMSPs originating from LMXBs and IMXBs. This is certainly a strong argument in favour of a relation of the type of Eq. (1), however it is not necessarily a confirmation for this type of relation. In the literature, at least two other relations have been suggested (see e.g. Shibazaki et al. 1989 and Urpin & Geppert, 1995). The field decay described by these relations are more slow or rapid compared to that by Eq. (1). But, evidently, they will give similar "good fitting" for the vast majority of the BMSPs (Li & Wang, 1998) in which PSR B0655+64 and PSR B1831-00 will always remain the exceptions.

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