The possible companions of young radio pulsars

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ABSTRACT

We discuss the formation of pulsars with massive companions in eccentric orbits. We demonstrate that the probability for a non-recycled radio pulsar to have a white dwarf as a companion is comparable to that of having an old neutron star as a companion. Special emphasis is given to PSR B1820–11 and PSR B2303+46. Based on population synthesis calculations we argue that PSR B1820–11 and PSR B2303+46 could very well be accompanied by white dwarfs with mass $\gtrsim 1.1\,M_\odot$. For PSR B1820–11, however, we can not exclude the possibility that its companion is a main-sequence star with a mass between $\sim 0.7\,M_\odot$ and $\sim 5\,M_\odot$.

Key words: binaries: close – stars: neutron – pulsars: general – pulsars: individual: PSR B1820–11 pulsars: individual: PSR B2303+46

1 INTRODUCTION

High mass binary pulsars are binaries in which a radio pulsar is accompanied by an unseen companion that is approximately as massive as the pulsar. Although the companion is generally believed to be another neutron star, it appears to be likely that some of the high-mass binary pulsars are not accompanied by neutron stars but are instead accompanied by white dwarfs or low-mass main-sequence stars.

PSR B1820-11 (J1823-1115), for example, is a radio pulsar in a binary with an orbital period $P_{\text{orb}} \approx 357.8$ days and an eccentricity $e \approx 0.795$ (Lyne & McKenna 1989). The derived mass function $f = 0.068\,M_\odot$ indicates that the mass of the companion exceeds $\sim 0.7\,M_\odot$. The small spin-down age of the pulsar ($\tau = 6.5$ Myr) and its strong magnetic field ($B \approx 6 \times 10^{11}$ G) suggest that it is a young – non-recycled – pulsar (Phinney & Verbunt 1991).

Based on the mass function and the orbital eccentricity, Lyne & McKenna (1989) suggest that the most likely companion to PSR B1820-11 is a neutron star. The companion is unlikely to be a massive hydrogen star or a black hole due to the low mass function. Lyne & McKenna argue that the observed orbital eccentricity excludes the companion as a white dwarf or a low-mass helium star. Phinney & Verbunt (1991) suggest that the companion of PSR B1820-11 may be a $\sim 1\,M_\odot$ main-sequence star, which will make the system a precursor of low-mass X-ray binary.

Also PSR B2303+46 may contain a non-recycled pulsar ($P = 1.06\,s$, $\tau = 30$ Myr, $B = 8 \times 10^{11}$ G) in a binary with $P_{\text{orb}} = 12.34$ day and $e \approx 0.66$ (Stokes et al. 1985). The total mass of the binary is $2.64 \pm 0.05\,M_\odot$ (Thorsett & Chakrabarty 1999) and no optical counterpart was detected down to $R = 26''$ (Kulkarni 1988). Recently van Kerkwijk & Kulkarni (1999), however, discovered an object which coincides with the timing position of PSR B2303+46 and the properties of this object are consistent with those of a massive white dwarf with a cooling age close to the age of pulsar.

With population synthesis calculations we demonstrate that the birth rate of binaries in which the neutron star is born after the white dwarf is comparable to the birth rate of binaries with two neutron stars. In the former case the binary will have a high eccentricity eccentric and the radio pulsar will be accompanied by a white dwarf with a mass $\gtrsim 1.1\,M_\odot$. In this paper we argue that both PSR B1820–11 and PSR B2303+46 systems may be formed via such a scenario (see § 2.2). The calculations, however, do not rule out that the companion of PSR B1820–11 is either another neutron star or a main-sequence star. In the latter case, the mass of the main-sequence star would most likely be between $\sim 0.7\,M_\odot$ and $\sim 5\,M_\odot$.

2 THE BINARY COMPANIONS OF PSR B1820–11 AND PSR B2303+46

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2.1 Hiding a main-sequence star

At a distance of 6.3 kpc and a height above the Galactic plane of ~100 pc (Taylor, Manchester, & Lyne 1993), PSR B1820–11 is heavily obscured by the interstellar medium. A star with an absolute magnitude of $M_V \sim -4''$0 could easily be missed in a survey with a limiting magnitude of 20''0 (assuming an interstellar absorption of $A_V = 1''6$ kpc$^{-1}$). In the USNO-A v1.0 catalog (Monet et al. 1997), based on the Palomar Sky Survey, the object closest to PSR B1820–11 is located at a distance of 5.9 seconds of arc and therefore cannot be associated with PSR B1820–11. There is no indication for other forms of radiation (X-rays, infrared, etc.) from the direction of PSR B1820–11. These suggest that the companion can not be a very massive star or have a strong stellar wind.

The presence of radio emission indicates that the rate of mass loss by the companion star is modest. An upper limit to $\dot{M}$ in the stellar wind of the companion can be estimated from the expression for the optical depth of the stellar wind for free-free absorption (e.g., Eq. 16 in Illarionov & Sunyaev 1975). By assuming that the wind of the accompanying star is transparent at $\lambda = 75$ cm (and a temperature of the stellar plasma of $10^8$ K) we obtain

$$\dot{M} \lesssim 4.8 \times 10^{-12} \frac{M_{\text{tot}}}{M_\odot} \frac{P_{\text{orb}}}{\text{day}} (1 - e)^{2/3} [M_\odot \text{yr}^{-1}],$$

(1)

where $M_{\text{tot}}$ is the mass of the binary. The estimate for $\dot{M}$ depends on the eccentricity; substitution of $(1 + e)$ for $(1 - e)$ in Eq. (1) gives the lower limit for the mass loss rate given that the radio pulsar is only visible at apocenter. We illustrate this limit in Fig. 1 for two typical combinations of $M_{\text{tot}}$ and $M$.

A binary with more or less similar orbital characteristics is PSR B1259-63 ($P_{\text{orb}} = 1237 \pm 24$ days, $e = 0.8699$, $M_{\text{opt}} = 10 \pm 3 M_\odot$, $\dot{M} = 5 \times 10^{-9} M_\odot \text{yr}^{-1}$; Johnston et al. 1992, 1994) which contains a radio pulsar and a Be-type star. The pulsar is visible at apastron but not at periastron. This is understood from Eq. (1) as an effect of shielding of the radio signal from the pulsar by the stellar wind. Another known radio pulsar in a long-period binary is PSR J0045-7319 ($P_{\text{orb}} = 147.8$ days, $e = 0.808$) with a B1 V ($M = 8.8 \pm 1.8 M_\odot$) companion with $\dot{M} < 3.4 \times 10^{-11} (v_{\text{rot}}/v_{\text{esc}}) M_\odot \text{yr}^{-1}$ (McConnell et al. 1991; Bell et al. 1995; Kaspi, Tauris & Manchester 1996). This pulsar is visible along its entire orbit due to a more tenuous wind of the companion star, which is typical for a lower metallicity star in the Large Magellanic Cloud.

The absence of eclipses and of X-rays from accretion or shocks generated by the interaction between the pulsar wind with wind of the Be star (as are observed in PSR B1259-63, Grove et al. 1995) also indicates that the companion of PSR B1820–11 is not likely to be a massive star. An upper limit to the mass-loss rate of the companion star in PSR B1820–11 may be set by measuring variations in the dispersion measure of the radio pulsar when it is close to periastron (see Melatos, Johnston, & Melrose 1995).

2.2 Can the companion to a radio pulsar be a massive white dwarf?

The eccentricity of a binary orbit can either be primordial or induced by the sudden mass loss by one of the stars (Blauw 1961). The latter is expected to occur in a supernova in which the exploding star loses a considerable fraction of its mass leaving behind a neutron star. The orbital periods of PSR B1820–11 and PSR B2303+46 prohibit the observed eccentricity from being primordial; these binaries have experienced a phase of mass transfer which circularized the orbit. The orbital eccentricities of these binaries are therefore induced by a supernova which may have produced the currently observed pulsar.

If the companions to PSR B1820–11 or PSR B2303+46 are white dwarfs they must have been formed before the neutron stars. This possibility was never studied in detail since the progenitor of a white dwarf is expected to live longer than the progenitor of a neutron star. However, it was noticed by Tutukov & Yungelson (1993) and by Portegies Zwart & Verbunt (1996) that a reversal of evolution can be accomplished if both stars are similar in mass and if the masses of both stars are only slightly smaller than the mass limit for forming a neutron star. If this is the case, the secondary star may still gain enough mass in a phase of mass transfer to pass the limit for forming a neutron star. For this to happen mass transfer should proceed rather conservatively, which will be the case since the initial mass ratio is close to unity. In the second, unstable, phase of mass transfer the white dwarf (original primary star) will spiral-in into the envelope of the secondary as this star ascends the giant branch. This phase causes the orbital period to decrease dramatically by using orbital energy to carry the common envelope to infinity. If the white dwarf and the core of the giant stay detached after the common envelope is ejected, a close binary consisting of a white dwarf and a helium star remains.

If the helium star is massive enough, the binary experiences a supernova and a young radio pulsar is formed. If the system survives the supernova the companion of the radio pulsar will be a white dwarf in an eccentric orbit. The mass of the white dwarf will be $\gtrsim 1.1 M_\odot$, in such a case, because it originated from a star that was rather massive.

2.3 Binary population synthesis

We use the population synthesis program for binary stars SeBa† (Portegies Zwart & Verbunt 1996) for evolving a million binaries with a primary mass between $8 M_\odot$ and 100 $M_\odot$. We used model B from Portegies Zwart & Yungelson (1998; henceforth PZY98), which satisfactorily reproduces the properties of observed high-mass binary pulsars (with neutron star companions). For a single star we adopt a minimum zero-age mass of $8 M_\odot$ for forming a neutron star, which coincides with estimates based on observations (Koester & Reimers 1996, see however Ritossa, Garcia-Berro, & Iben 1996) who show that a single star with a mass

† The name SeBa is adopted from the Egyptian word for ‘to teach’, ‘the door to knowledge’ or ‘(multiple) star’. The exact meaning depends on the hieroglyphic spelling.
of $10 \, M_\odot$ may still evolve into a oxygen-neon-magnesium white dwarf). If a star is stripped of its envelope in an early phase this lower limit may become as large as $12 \, M_\odot$. Coincidence of the lower limits of the initial primary mass for our simulation with the minimum mass for the progenitors of neutron stars results in an underestimate in the formation of binaries in which the secondary star experiences a supernova. By comparing our results with those of Portegies Zwart & Verbunt (1996, see their Tab. 4), who take lower mass primaries into account, we evaluate that this affects our results with $\lesssim 20\%$.

While referring the reader to PZY98 for details, we list here the most crucial assumptions. The masses of the primaries obey a power-law with exponent 2.5 (Salpeter $\equiv 2.35$). The initial mass function is normalized to the current Galactic star-formation rate of $4 \, M_\odot \, \text{yr}^{-1}$ (van den Hoek & de Jong 1997). We assume that all stars are born in binaries with a semi-major axis up to $a = 10^6 \, R_\odot$. The distribution was chosen to be flat in log a. Roche-lobe contact at zero age sets the minimum to the distribution of initial separations. The mass of the secondary is selected to be between 0.1 $M_\odot$ and the mass of the primary from a flat mass ratio distribution. The eccentricity for each binary is taken from the thermal distribution between zero and unity.

Neutron stars receive a kick upon birth. The velocity of the kick is taken randomly from the distribution function proposed by Hartman (1997) and in a random direction. Black holes (from stars initially more massive than $40 \, M_\odot$) receive a kick velocity which is scaled by $M_{\text{ini}}/M_{\text{bh}}$.

From computations presented in PZY98 one may infer that our conclusions concerning birth rates and $P_{\text{orb}} - e$ distributions for various combinations of neutron star and companion are robust with respect to reasonable variations in the most crucial model parameters and initial conditions, such as the kick velocity distribution and common envelope parameter, initial mass function and initial distribution in orbital periods. The criteria for the stability of mass transfer and the adopted rate of mass lost via a stellar wind and the amount of momentum lost per unit mass, however, may affect the details of our calculations rather significantly.

From the output of the computer simulations we select binaries with at least one neutron star. Within these constraints three orbital-period ranges are considered: $P_{\text{orb}} \geq 10, 100,$ and 1000 days. Table 1 gives the model birth rates for the binaries in various groups depending on the nature and the mass of the companion of the neutron star. Figures 1 and 2 give the probability distributions for these binaries in the orbital period - eccentricity plane.

The birth rates in Table 1 reflect the initial distributions of the binary parameters and the complicated evolutionary history via several phases of mass transfer and at least one supernova. It is therefore not surprising that the most common companion to a pulsar is a rather massive ($\gtrsim 5M_\odot$) main-sequence star in a relatively wide binary $(10 \lesssim P_{\text{orb}} \lesssim 1000 \, \text{days}, \text{Fig. 1})$. As argued above, the presence of such a massive companion in PSR B1820-11 may be excluded by the absence of an optical counterpart and the unlikely inclination of the orbit; hiding a companion of $M \gtrsim 3M_\odot$ demands $i \lesssim 0.95$ (Lyne & McKenna 1989). The observed radio emission also makes it unlikely that the mass of the companion to PSR B1820-11 is $\gtrsim 5M_\odot$. Such a companion star with a mass loss in the stellar wind of $\lesssim 10^{-9} \, M_\odot \, \text{yr}^{-1}$ (which is chosen on the high side to account for the enhanced wind mass loss for Be stars) would easily shield the radiation of the radio pulsar along its entire orbit (see Fig. 3).

In the range of orbital periods $P_{\text{orb}} \geq 100$, days the birth rates of neutron stars accompanied either by another neutron star ($ns$), a white dwarf ($wd$), a low mass ($M \lesssim 1.4M_\odot$) main-sequence star ($ms$) or a black hole ($bh$) are comparable (Table 1). The relatively large population of ($bh$, $ns$) systems and their distribution in orbital periods is a result of the evolutionary history of massive stars which is dominated by stellar wind mass loss rather than Roche lobe overflow and by the lower kick velocities imparted to black holes. However, the mass function of PSR B1820-11 makes a black hole with mass exceeding several $M_\odot$ as a companion unlikely, and for PSR B2303+46 such a massive companion is excluded by the measured total mass.

Figure 3 compares the probability distributions for binaries with a radio pulsar which is accompanied by a white dwarf (upper panel) and an older neutron star (lower panel) in the orbital period - eccentricity diagram.

Our model calculations reveal that the binaries in which a young pulsar is accompanied by a massive white dwarf are generally rather eccentric ($e \sim 0.6$) and that their orbital periods are distributed with more or less equal probability in $\log P_{\text{orb}}$ between a few hours and about one hundred days. In Fig. 3 PSR B1820-11 appears at the edge of the area with highest probability, while the orbital parameters of PSR B2303+46 fall nicely in the densely populated area of the $P_{\text{orb}} - e$ diagram. This suggests, together with the

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**Table 1.** Results of the model computations for binaries with at least one radio pulsar. The first column identifies the various binary components. Cols. (2) and (3) give the mass limits for the companion of the pulsar (black holes have a mass $> 2M_\odot$). Col. (4) gives the total Galactic birth rate (BR) of such binaries. Cols. (5), (6) and (7) give the birth rate of binaries with an orbital period larger than 10, 100, and 1000 days, respectively, in the units of $10^{-5} \, \text{yr}^{-1}$.

| $m_{\text{min}}$ | $m_{\text{max}}$ | BR | $P_{\geq 10}$ | $P_{\geq 100}$ | $P_{\geq 1000}$ |
|-----------------|------------------|----|-------------|-------------|-------------|
| $[M_\odot]$     |                  |    | $[10^{-5} \, \text{yr}^{-1}]$ |             |             |
| (1)             | (2)              | (3) | (4)         | (5)         | (6)         | (7)         |
| (ns, ns)        | 0.1              | 0.7 | 0.5         | 0.1         | 0.0         | 0.0         |
| (ns, ns)        | 0.7              | 1.4 | 4.4         | 1.2         | 0.3         | 0.0         |
| (ns, ns)        | 1.4              | 5.0 | 13.9        | 5.0         | 2.3         | 0.3         |
| (ns, ns)        | 5.0              | 10.0| 9.5         | 3.6         | 1.1         | 0.5         |
| (ns, ns)        | 10.0             | up  | 19.7        | 17.4        | 10.8        | 3.3         |
| (wd, ns)        | 1.1              | 1.4 | 4.4         | 1.3         | 0.3         | 0.0         |
| (ns, ns)        | 1.4              | 1.4 | 3.4         | 0.6         | 0.2         | 0.1         |
| (bh, ns)        | 2.0              | var| 0.6         | 0.3         | 0.2         | 0.1         |
rather high birth rate of such binaries, that PSR B2303+46 may well contain a white dwarf as a companion star. Recently van Kerkwijk & Kulkarni (1999) found evidence that PSR B2303+46 is accompanied by a white dwarf with a mass of about 1.2 M⊙.

PSR B1820–11 fits rather ill in either of the $P_{\text{orb}} - e$ diagrams for $(ns, ns)$, $(wd, ns)$, and low mass or moderate mass $(ns, ms)$ binaries. The relative birthrates for a population of binaries with long orbital periods increases by increasing the efficiency of the deposition of orbital energy into common envelopes during the spiral-in phase (see PZY98).

However, this would require us to relax the decisive criterion why we chose this specific set of model parameters; the coincidence of having the other high mass binary pulsars (PSR J1518+49, B1534+12, and B1913+16) in the most densely populated areas in the $P_{\text{orb}} - e$ diagram for $(ns, ns)$ binaries. There is no evidence for a strong selection against the discovery of a young pulsar which is accompanied by a dead pulsar or by a massive white dwarf with an orbital period $\gtrsim 10$ days (Johnston & Kulkarni 1991). The higher birth rate of binaries in which the radio pulsar is accompanied by a low mass main-sequence star and the better coincidence in the $P_{\text{orb}} - e$ diagram makes this possibility very attractive.

If the companion of PSR B1820–11 is indeed a low- or moderate mass main-sequence star it may be a precursor of a system similar to GX 1+4 = V2116 Oph, which shows the X-ray features of an accreting neutron star and which is identified with a symbiotic star (Davidson, Malina, & Bowyer 1977). The orbital period of GX 1+4 is $\gtrsim 100$ days (Chakrabarty & Roche 1997). The low birth rate of such binaries (Table 1) together with the short life time of a red giant explains the paucity of such X-ray binaries.
3 CONCLUSION

We have studied the nature of the companions of young radio pulsars in eccentric orbits. Our calculations reveal that the possibility that a young pulsar is accompanied by a white dwarf of mass \( \gtrsim 1.1 \text{M}_\odot \) cannot be neglected. The birth rate of such binaries is higher than the birth rate of of binaries in which a young pulsar is accompanied by a dead pulsar (i.e.: an old neutron star).

We argue therefore that PSR B1820–11 may be accompanied by a massive white dwarf, however the probability that its companion is a main-sequence star with a mass \( \lesssim 5 \text{M}_\odot \) (or even another neutron star) is similar to the probability of being a white dwarf.

Our calculations confirm the observation of van Kerkwijk & Kulkarni (1999) in the sense that it is likely that PSR B2303+46 is accompanied by a white dwarf with a mass \( \gtrsim 1.2 \text{M}_\odot \).

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