2010

Double and single recycled pulsars: an evolutionary puzzle?

K. Belczynski

D. R. Lorimer

J. P. Ridley

S. J. Curran

Double and single recycled pulsars: an evolutionary puzzle?

K. Belczynski[1,2,3*], D.R. Lorimer[4,5], J.P. Ridley[4] and S.J. Curran[6]
[1] *Los Alamos National Laboratory, New Mexico, USA*
[2] *Astronomical Observatory, University of Warsaw, Al. Ujazdowskie 4, 00-478 Warsaw, Poland*
[3] *Oppenheimer Fellow*
[4] *Department of Physics, West Virginia University, Morgantown, WV 26506, USA*
[5] *Green Bank Observatory, PO Box 2, Green Bank, WV 24944, USA*
[6] *School of Physics, University of New South Wales, Sydney, NSW 2052, Australia*

15 June 2018

ABSTRACT
We investigate the statistics of isolated recycled pulsars and double neutron star binaries in the Galactic disk. Since recycled pulsars are believed to form through accretion and spinup in close binaries, the isolated objects presumably originate from disrupted progenitors of double neutron stars. There are a comparable number of double neutron star systems compared to isolated recycled pulsars. We find that standard evolutionary models cannot explain this fact, predicting several times the number of isolated recycled pulsars than those in double neutron star systems. We demonstrate, through population synthesis calculations, that the velocity distribution of isolated recycled pulsars is broader than for binary systems. When this is accounted for in a model for radio pulsar survey selection effects, which include the effects of Doppler smearing for the double neutron star binaries, we find that there is a small ($\sim 25\%$) bias towards the detection of double neutron star systems. This bias, however, is not significant enough to explain the observational discrepancy if standard ($\sigma = 265$ km s^{-1}) neutron star natal kick velocities are invoked in binary population syntheses. Population syntheses in which the 1D Maxwellian velocity dispersion of the natal kick is $\sigma \sim 170$ km s^{-1} are consistent with the observations. These conclusions further support earlier findings the neutron stars formed in close interacting binaries receive significantly smaller natal kicks than the velocities of Galactic single pulsars would seem to indicate.

Key words: methods: statistical; stars: neutron; stars: kinematics; pulsars: general

1 INTRODUCTION

The pulsar population is an important tool to study various aspects of stellar evolution, supernova rates, birth properties of neutron stars and the evolution of massive binary systems. Of particular interest are the double neutron star (DNS) binary systems whose inspirals are one of the key events expected by the gravitational wave detectors now in operation (see, e.g., Abbott et al. 2006). DNS binaries consist of an older neutron star with a short spin period (typically in the range 20–100 ms) formed in the supernova explosion of the initially more massive star in the binary system (the primary). The first-born neutron star initially behaves as a regular radio pulsar, but subsequently becomes spun up (recycled) via the accretion of matter during Roche lobe overflow (RLOF) from the secondary star once it leaves the main sequence. Following the supernova explosion of the secondary, the resulting DNS consists of a recycled pulsar and a younger second-born neutron star.

While a number of studies have addressed the population, lifetime and merger rate of DNS binaries (e.g., Phinney 1992; Kim et al. 2003; Chaurasia & Bailes 2005; Ihm et al. 2006), less attention has been given to those binary systems which disrupt during the second supernova (see, however, Kalogera & Lorimer 2000). Of particular significance are the statistics of the recycled pulsars released from these binary systems, with their distinct spin properties. As discussed by Lorimer et al. (2004), these so-called 'disrupted recycled pulsars' (DRPs) directly probe the fraction of DNS binaries which do not survive the second supernova explosion and can therefore provide an independent constraint on population synthesis models which predict a certain fraction of DRPs relative to DNS binaries.

As pointed out by Lorimer et al. (2004), there is an apparent conundrum posed by the observed DNS/DRP statistics. Given our current understanding of binary evolution, the ratio of the *underlying* number of DNS systems to DRPs

* Email:kbelczyn@nmsu.edu

observed should equal the survival fraction for binary systems during the second supernova event, i.e. those which remained bound after the explosion. Lorimer et al. (2004) estimated this fraction to be around 0.1 based on scale-factor analysis of DNSs and DRPs and appeared to be in reasonable accord with theoretical estimates of the survival fraction taken from the literature (Portegies Zwart & Yungelson 1998). Assuming that the luminosities and radio lifetimes of the recycled pulsars observable in DNS binaries are identical to the DRPs, the above estimate implies that we should see roughly ten DRPs for every DNS binary. However, this expectation is not confirmed in the observed sample discussed in Section 2 where there are comparable numbers of DRPs and DNS binaries.

In light of these issues, the relationship between DNS binaries and DRPs is an interesting problem which we address in this paper using Monte Carlo simulations of binary populations and observational selection effects. The goal of this work is to understand the relationship between the observed and underlying ratios of DNS binaries to DRPs. This can be summarized by the expression

$$r_{\rm obs} = r_{\rm int} f_{\rm obs}, \quad (1)$$

where $r_{\rm obs}$ is the observed ratio of DNS binaries to DRPs, $r_{\rm int}$ is the underlying (intrinsic) ratio and $f_{\rm obs}$ is a correction factor which takes account of observational selection effects. As we discuss in Section 2, we find that $r_{\rm obs} \sim 1$. In Sections 3 and 4, we use state-of-the-art binary population synthesis models to explore the possible predicted ranges of r. We investigate observational selection effects in radio pulsar surveys to evaluate $f_{\rm obs}$ in Section 4. Finally, in Section 5, we summarize the main findings of this study.

2 THE OBSERVATIONAL SAMPLE

Table 1 summarizes the observational data for the known DNS binaries and DRPs in the Galactic disk. In Fig.1, we present an updated version of the magnetic field–period ($B-P$) diagram from Lorimer et al. (2004) showing both samples of objects. There are currently nine DNS binaries which can be identified based on their orbital parameters where measurements of multiple post-Keplerian parameters (see, e.g. Lorimer 2008) suggest the presence of two neutron stars in each system. For the purposes of this paper, where the focus is on recycled pulsars produced during binary evolution, we do not select PSR J1906+0746 (Lorimer et al. 2006) where the observed radio pulsar is likely the young second-born neutron star formed in the binary. The resulting sample therefore consists of eight objects. We define a DRP as an isolated pulsar in the Galactic disk with $B < 3\times10^{10}$ G and $P > 20$ ms. The latter criterion ensures that no isolated millisecond pulsars, which are thought to have had a different evolutionary history, are included in our sample. The actual value of the limiting spin period was chosen such that recycled pulsars in the known DNS sample would have been selected had their hosting binaries been disrupted. The isolated millisecond pulsars with $B < 3\times10^{10}$ G and $P < 20$ ms (about 28 known) are believed to accreted from a low mass companion (e.g., a white dwarf) over long period of time ($\sim 10^8$ yr) and then the companion was evaporated (e.g., Lorimer et al. 2004 and references therein). The population

Table 1. Spin and spatial properties of DNS binaries and DRPs currently known in the Galactic disk. From left to right, the columns list pulsar name, spin period (P in ms), the base-10 logarithms of characteristic age ($\tau = P/(2\dot{P})$ in yr) and inferred magnetic field strength ($B \propto (P\dot{P})^{1/2}$ in Gauss), distance (d in kpc) and height above the Galactic plane (z in pc). The latter two quantities are based on the pulsar dispersion measure and the Cordes & Lazio (2002) model for the Galactic distribution of free electrons. The right-hand column lists the discovery paper for each pulsar.

PSR	P	log τ	log B	d	$\|z\|$	Ref.[1]
Compact DNS systems (binary period < 1 day)						
J0737−3039	22.7	8.3	9.8	0.6	40	1
B1534+12	37.9	9.4	10.0	0.9	670	2
J1756−2251	28.5	8.6	9.7	2.9	50	3
B1913+16	59.0	8.0	10.4	7.1	260	4
Wide DNS systems (binary period > 1 day)						
J1518+4904	40.9	10.4	9.0	0.7	570	5
J1753−2240	95.1	9.2	10.0	3.0	90	6
J1811−1736	104.2	9.0	10.1	5.9	50	7
J1829+2456	41.0	10.1	9.2	0.8	200	8
DRPs ($B < 3.0 \times 10^{10}$ G)[2]						
J0609+2130	55.7	9.6	9.6	1.8	30	9
J1038+0032	28.9	9.8	9.1	2.4	1800	10
J1320−3512	458.5	9.6	10.5	0.9	430	11
J1333−4449	345.6	10.0	10.1	2.3	690	12
J1339−4712	137.1	9.6	9.9	1.8	450	12
J1355−6206	276.6	9.1	10.5	8.0	20	13
J1548−4821	145.7	9.5	10.0	3.8	310	13
J1611−5847	354.6	9.4	10.4	2.4	230	14
J1753−1914	63.0	8.7	10.1	2.7	160	14
J1816−5643	217.9	9.2	10.3	3.1	940	12
B1952+29	426.7	9.6	10.4	0.4	10	15
J2235+1506	59.8	9.8	9.5	1.2	680	16

[1] – The references used in this compilation are 1: Burgay et al. (2003), 2: Wolszczan (1991), 3: Faulkner et al. (2005), 4: Hulse & Taylor (1975), 5: Nice et al. (1996), 6: Keith et al. (2009), 7: Lyne et al. (2000), 8: Champion et al. (2004), 9: Lorimer et al. (2004), 10: Burgay et al. (2006), 11: Manchester et al. (1996), 12: Jacoby et al. (2007), 13: Kramer et al. (2003), 14: Lorimer et al. (2006), 15: Davies et al. (Davies et al. 1970), 16: Camilo et al. (1993).

[2] – This population of 12 single NSs may be contaminated by $\sim$ 4 regular (non recycled) NSs, and therefore the number of known DRPs (binary origin) is ~ 8 (see Sec.2.2).

Table 2. Results of population synthesis calculations for the DNS and DRP populations. From left to right, the columns give the name of evolutionary model, natal kick velocity dispersion, intrinsic numbers of DNS ($n_{\rm DNS}$) and DRPs ($n_{\rm DRP}$), and the intrinsic ratio $r = n_{\rm DNS}/n_{\rm DRP}$. The range of values corresponds to changing evolutionary assumption on common envelope evolution.

Model	$\sigma_{\rm CC}$ km s^{-1}	$n_{\rm DNS}$	$n_{\rm DRP}$	r
A	265	3854–2977	13418–10085	0.29–0.30
B	199	5798–4295	11166–8316	0.52–0.53
C	133	9587–7252	8476–5911	1.13–1.23
D	66	18042–13572	8141–3166	2.22–4.36
E	0	42145–36316	46817–15263	0.90–2.38

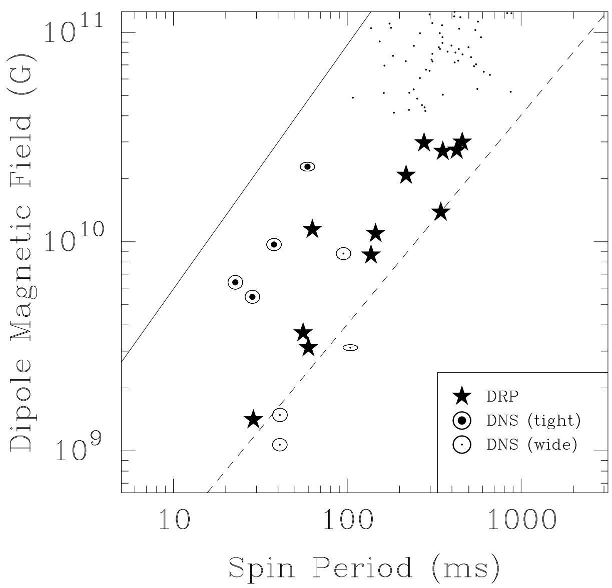

Figure 1. Magnetic field–period ($B - P$) diagram showing the samples of DNS binaries, DRPs and other isolated radio pulsars. The DNS systems are highlighted by ellipses with the eccentricity of the ellipse representing the orbital eccentricity. Compact DNS binary systems which will merge within a Hubble time are marked with larger dots. DRPs, defined as isolated pulsars with $B < 3 \times 10^{10}$ G and $P > 20$ ms, are shown as filled stars. The solid line is the limiting spin-up period for Alfvèn accretion at the Eddington limit. The dashed line is the locus of points with characteristic age equal to 10 Gyr.

of isolated pulsars with small magnetic field ($B < 3\times10^{10}$ G) but larger spin periods ($P > 20$ ms) is believed to accreted from a high mass companion over relatively short period of time ($\sim 10^{6-7}$ yr) and then the companion was ejected from a binary while undergoing supernova explosion. There are a dozen such objects. We now discuss possible selection biases present in these samples, and draw some simple conclusions based on the available data.

2.1 The DNS sample

In Table 1, we subdivide the DNS sample into "compact systems" with orbital periods less than one day which will merge due to gravitational wave emission within a Hubble time and "wide systems" with longer orbital periods that will effectively never merge on relevant timescales. Despite the small-number statistics, it is apparent, both from Table 1 and Fig. 1 that the compact systems appear to be younger than the wide systems. As noted by several previous authors (Phinney 1992; Arzoumanian et al, 1999; Chaurasia & Bailes 2005), this is a selection effect caused by the shorter coalescence time compared to the radio lifetimes of these systems. The wide DNS binaries and DRPs effectively spin-down until they reach the so-called "death line" at which radio emission is thought to become ineffective and cease for all radio pulsars Chen & Ruderman (1993). In our simulations of the underlying and observed DNS sample described below, we will account for this important selection effect by carefully modeling both the orbital evolution (Section 3) and Doppler smearing (Section 4) of such systems.

2.2 The DRP sample

Our choice of a maximum magnetic field of 3×10^{10} G to select DRPs is determined by the maximum magnetic field observed for a recycled pulsar in a DNS: 2.3×10^{10} G for B1913+16 (Hulse & Taylor 1975). This cut-off is valid, provided that higher magnetic field objects do not evolve into either sample during their observational lifetimes. Given the lack of observational evidence for magnetic field decay in recycled pulsars (Faucher-Giguére & Kaspi 2006), there is no reason to suspect that this cutoff will impose any significant bias into the *relative* numbers of pulsars in each sample.

An important selection effect for DRPs, however, is the "contamination" in the sample from the isolated population of non-recycled pulsars (Kalogera & Lorimer 2000). To quantify this effect, we have used the results of recent studies of the normal pulsars (Faucher-Giguére & Kaspi 2006; Ridley & Lorimer 2010) which predict the fraction of non-recycled pulsars in the observed sample with $B < 3\times10^{10}$ G to be about 0.3%. Given the present sample of ~ 1500 non-recycled objects, we therefore expect 4–5 of these to have no binary origin. We conclude that the best estimate for the observational ratio of the DRP to DNS systems is therefore currently $r_{\rm obs} \sim 1$.

2.3 Ages

Our population synthesis of the DNS and DRP samples discussed below requires some estimate of the likely radio lifetime of the mildly recycled pulsars produced in these systems. With their relatively weak magnetic fields, DNS and DRPs are expected to have longer radio lifetimes by comparison to normal pulsars which are thought to be a few 10s of Myr (e.g. Lyne, Manchester & Taylor 1985). For all 20 objects listed in Table 1, the characteristic ages range between 100 Myr and 50 Gyr with mean and median values of 5.4 and 3.0 Gyr respectively. As recently discussed by Kiziltan & Thorsett (2009). The characteristic ages of recycled pulsars are likely to both significantly underestimate and overestimate the true ages. The underestimate is caused by secular accelerations which contribute to the observed $\dot{P}$, while overestimates arise due to sub-Eddington accretion in the progenitor phase (Kiziltan & Thorsett 2009) which result in a birth period that is close to the current value. Taken as a whole, the characteristic ages suggest a typical lifetime for the population that is close to 10 Gyr, and we adopt this number in our evolutionary simulations described in Section 3.3.

2.4 Scale heights

Despite the small-number statistics present in Table 1, it is immediately apparent that the height above/below the Galactic plane z is, on average, significantly larger for DRPs than for DNS binaries. Taking the z values from Table 1, we find $|z| = 200$ pc for the DNS systems compared to $|z| = 480$ pc for the DRPs. This difference between the two populations could be explained by a larger velocity dispersion for DRPs and/or longer radio lifetimes. We have already remarked that the radio lifetimes of DRPs are likely to be longer than the DNSs. In the following section, we will also show on evolutionary grounds that the expected velocity distributions of the two populations are indeed fundamentally different.

3 BINARY POPULATION SYNTHESIS

The population synthesis code we use, `StarTrack`, was initially developed to study double compact object mergers in the context of gamma-ray burst progenitors (Belczynski, Bulik & Rudak 2002b) and gravitational-wave inspiral sources (Belczynski, Kalogera, & Bulik 2002a). In recent years `StarTrack` has undergone major updates and revisions in the physical treatment of various binary evolution phases, and especially the mass transfer phases. The new version has already been tested and calibrated against observations and detailed binary mass transfer calculations (Belczynski et al. 2008a), and has been used in various applications (e.g., Belczynski & Taam 2004; Belczynski et al. 2004; Belczynski, Bulik & Ruiter 2005; Belczynski et al. 2006; Belczynski et al. 2007). The physics updates that are most important for compact object formation and evolution include: a full numerical approach for the orbital evolution due to tidal interactions, calibrated using high mass X-ray binaries and open cluster observations, a detailed treatment of mass transfer episodes fully calibrated against detailed calculations with a stellar evolution code and updated stellar winds for massive stars (e.g., decreased mass loss from Wolf-Rayet stars that accounts for clumping; Hamann & Koesterke 1998).

3.1 Helium star evolution

For helium star evolution, which is of crucial importance for the formation of DNS binaries (e.g. Ivanova et al. 2003; Dewi & Pols 2003), we have applied a treatment matching closely the results of detailed evolutionary calculations. If the helium star fills its Roche lobe, the systems are examined for the potential development of a dynamical instability, in which case they are evolved through a common envelope phase, otherwise a highly non-conservative mass transfer ensues. We treat common envelope events using the energy formalism (Webbink 1984), where the binding energy of the envelope is determined from the set of He star models calculated with the detailed evolutionary code by Ivanova et al. (2003). For the case when the common envelope is initiated by a star crossing the Hertzsprung gap, the outcome of the common envelope is highly uncertain. Such stars do not yet have well developed core-envelope structure and once the inspiral process starts it may never end (whether there is enough of binary orbital energy or not to eject the envelope) leading to the binary component merger. If a merger is assumed, the evolution leads to a very dramatic decrease of number of BH-BH binaries and a less pronounced decrease for DNS systems (Belczynski et al. 2007). In this study we allow either survival or we assume a merger in case the Hertzsprung gap star is a donor in common envelope evolution. The results are presented for both cases to test the influence of this evolutionary uncertainty on recycled pulsar populations.

3.2 Neutron star formation

The full description of remnant mass calculation is given in Belczynski et al. (2008; see their Sec. 2.3.1), and here we report only the most important details. Neutron stars form in a wide range of initial progenitor masses. For zero-age main sequence (ZAMS) single stars, neutron star formation begins at $M_{\rm ZAMS} \sim 7.5 - 8.5$ with low mass neutron stars ($M_{\rm NS} \sim 1.2\,{\rm M}_{\odot}$) being formed via electron capture supernovae that involves core collapse of ONeMg core (e.g., Podsiadlowski et al. 2004). For higher initial masses, neutron stars form through core collapse of FeNi core; for $M_{\rm ZAMS} \sim 8.5 - 18\,{\rm M}_{\odot}$ neutron stars form with mass $M_{\rm NS} \sim 1.3\,{\rm M}_{\odot}$, while for heavier progenitors, $M_{\rm ZAMS} \sim 18 - 20\,{\rm M}_{\odot}$, neutron stars form with $M_{\rm NS} \sim 1.8\,{\rm M}_{\odot}$. Such a bimodal distribution is explained by the different element burning in the cores of massive stars that results in the formation of lower mass FeNi cores for lighter stars where the central temperature is not high enough for more effective burning (Timmes, Woosley & Weaver 1996). Although the majority of neutron stars with mass determinations fall in the range $\sim 1.2 - 1.4\,{\rm M}_{\odot}$ there are a number of pulsars for which higher masses are likely exist (e.g., $\sim 1.9\,{\rm M}_{\odot}$, Vela X-1, Barziv et al. 2001; $\sim 1.7 - 1.8\,{\rm M}_{\odot}$ for Terzan 5 I and J, Ransom et al. 2005), although the error bars are still large (e.g., Lorimer 2008). For progenitors with $M_{\rm ZAMS} \gtrsim 20\,{\rm M}_{\odot}$, the fallback of material (e.g., Fryer & Kalogera 2001) during supernova explosion may increase a proto neutron star mass such that it collapses to a black hole. We assume the maximum neutron star mass to be $M_{\rm NS,max} = 2.5\,{\rm M}_{\odot}$, and then progenitors with masses $M_{\rm ZAMS} \gtrsim 21\,{\rm M}_{\odot}$ form black holes.

During formation, a neutron star receives a natal kick that along with the mass loss from the exploding star may lead to disruption of a binary system, if an exploding star is a binary component. Since natal kicks are a major factor in the disruption of binaries, we can also expect them to play a crucial role in determining the DNS/DRP ratio. To investigate this issue in detail, we use our standard evolutionary model and vary the spread of the underlying natal kick distribution. In a recent analysis of the pulsar birth velocity distribution, Hobbs et al. (2005) found that the observed sample could be well described by a single Maxwellian with $\sigma_{\rm Hobbs} = 265$ km s^{-1}. It is not clear whether this distribution may be directly applied for stars in binaries since the observed pulsars are single and we do not know how many have originated from binaries. Also, if a given single pulsar originates from a binary, mass loss and orbital velocity at the time of the supernova explosion disrupting a binary will factor into the final pulsar velocity (in addition to the natal kick it has received). Therefore, we employ the observed distribution just in one of our calculations (model A) assuming that all neutron stars that form in FeNi (regular) core collapse supernovae receive a natal kick drawn from a distribution with $\sigma_{\rm CC} = \sigma_{\rm Hobbs}$, and then we decrease the kicks for the sequence of models: $\sigma_{\rm CC} = 0.75\sigma_{\rm Hobbs} = 199$ km s^{-1} (model B), $\sigma_{\rm CC} = 0.5\sigma_{\rm Hobbs} = 133$ km s^{-1} (model C), $\sigma_{\rm CC} = 0.25\sigma_{\rm Hobbs} = 66$ km s^{-1} (model D), and $\sigma_{\rm CC} = 0$ km s^{-1} (model E). In each of the above models, we assume that there is no natal kick in the case of neutron star formation through electron capture supernova ($\sigma_{\rm ECS} = 0$) as recent numerical simulations indicate that explosion energy may be much smaller in such a case (e.g., Dessart et al. 2006; Kitaura, Janka & Hillebrandt 2006).

3.3 Mass accretion

In the evolutionary scenarios for DNS and DRP progenitor binaries we consider the amount of mass accretion onto the neutron star to be relatively modest. This naturally follows from the fact that a first born neutron star always has a (much) more massive companion. In the event of RLOF, most often it proceeds on a thermal timescale of the massive donor and with super-Eddington mass transfer rates and only a small fraction of the transferred material ($\sim 1\%$) is usually accreted onto a neutron star. Even in case of mass transfer on a nuclear timescale of the donor, the duration of RLOF is usually so short that not much is accumulated on a neutron star (short lifetime of massive donor). Additionally, in the case of dynamically unstable events that lead to common envelope evolution it was pointed out (e.g., Ruffert 1999; Ricker & Taam 2008) that only a small amount of mass may be accreted onto a compact object (a black hole or a neutron star). We calculate a Bondi-Hoyle accretion rate onto a compact object during a specific common envelope event (Belczynski et al. 2002a) and then allow for accretion at the level of only 10% of the calculated rate. Such an approach leads to the formation of DNS population with a neutron star of low mass $1.2 - 1.4\,{\rm M}_\odot$ that reproduces rather well the observed systems (e.g., Belczynski et al. 2008b). First born neutron stars in DNS and DRP populations usually accrete (if any RLOF/common envelope was encountered) $\sim 0.01 - 0.1\,{\rm M}_\odot$. Although an exact amount of mass to recycle a pulsar is not well established (e.g., Zdunik, Haensel & Gourgoulhon 2002; Jacoby et al. 2005), we assume that if a neutron star accreted over $0.05\,{\rm M}_\odot$ it becomes a mildly recycled pulsar with a lifetime of 10 Gyr as discussed above.

3.4 Simulation specifics

In each calculation we evolve 2×10^6 massive binaries ($6 < M_1 < 150\,{\rm M}_\odot$, $4 < M_2 < 150\,{\rm M}_\odot$), in which the primary mass (M_1) is drawn from power-law initial mass function with slope -2.7, and the secondary is chosen via a flat mass ratio distribution ($q = M_2/M_1$). All binaries are allowed to be initially eccentric ($f(e) \propto 2e$), while their separations are drawn from a flat distribution in logarithm (i.e., $\propto 1/a$) and reaching maximum of $10^5 R_\odot$. All stars are evolved with solar-like metallicity ($Z = 0.02$) and are assumed to form in the Galactic disk (i.e., continuous star formation through the last 10 Gyr). We perform a time cut at the present time and count the numbers of DNS and DRP hosting an active recycled pulsar. The numbers presented throughout our study are not calibrated as we are mostly concerned with the ratio of DNS to DRP. However, very easy calibration may be performed on these numbers to represent the entire synthetic population of active recycled pulsars in Galaxy. The presented numbers need to be multiplied by a factor of ~ 40 to give the star formation rate observed currently in the disk of the Galaxy ($\sim 3.5\,{\rm M}_\odot$ yr^{-1}) or result in supernova II and Ib/c rate estimated for a Milky Way-type Galaxy (~ 0.02 yr-1).

We consider only the formation of recycled pulsars in massive star populations, i.e., stars that can form neutron stars/black holes. Recycled pulsars can also be formed in binaries with a companion star that is not massive enough to form a second neutron star/black hole, e.g., neutron star low- or intermediate-mass main sequence star, neutron star low mass-mass helium star or neutron star white dwarf binaries. However, any of these binaries cannot form a single recycled pulsar (or one in a DNS), unless some rather exotic scenarios are considered (e.g., evaporation of a white dwarf by a neutron star).

In the first scenario, two stars of similar mass ($\sim 10 - 20\,{\rm M}_\odot$) start the evolution. The more massive primary initiates the first (stable) RLOF episode, potentially rejuvenating the secondary before forming the first neutron star. Very often this is a low-mass neutron star ($\sim 1.2\,{\rm M}_\odot$) formed through electron capture supernova. The secondary then initiates a second RLOF episode. This time, due to high mass ratio ($q \gtrsim 5$; the ratio of the secondary star and neutron star masses), the common envelope phase is initiated. The system emerges as a close neutron star–helium star binary. The neutron star has accreted some material while moving through the envelope of the secondary ($\sim 0.05\,{\rm M}_\odot$). The helium star expands and initiates the third RLOF. This time it may be either a dynamically stable or unstable event. In the case of the common envelope there is a large uncertainty whether such a system survives or not. Frequently the helium donor is crossing the helium Hertzsprung gap and has not yet developed a clear core-envelope structure that is needed to halt an inspiral during this phase (for details see Belczynski et al. 2007).

In the above example we have presented our most efficient scenario for the DNS/DRP formation. However, in our population synthesis calculations we include a number of various formation channels (for example see Table 3 of Belczynski et al. 2002a). In particular, we include the "Brown" channel (Brown 1995) of the DNS formation of two almost equal mass stars that avoids common envelope with a NS accretor (e.g., see channel NSNS:09 of Belczynski et al. 2002a). This channel was also followed by other groups (e.g. Dewi, Podsiadlowski & Sena 2006) and it was found that the rates are generally smaller than predicted in the original work. This study predicts much lower rates for this particular channel as compared with the original Brown work. The difference stems from the fact that the early estimates on the amount of accretion ($\sim 1\,\mathrm{M}_\odot$; Bethe & Brown 1998) onto NS in the common envelope phase were most likely overestimated. With high accretion rates, in all the classical channels (like the one we presented above) that involve a common envelope phase, a NS accreted enough to collapse to a BH avoiding the NS-NS formation. As discussed in section 3.3 we follow recent estimates of accretion in common envelope ($\sim 0.1\,\mathrm{M}_\odot$; Ruffert 1999; Ricker & Taam 2008) and allow for the NS-NS formation along variety of channels.

In our modeling, and in particular in the presented example of the DNS/DRP formation, the first NS forms predominantly in electron-capture supernova while the second NS is formed either in regular core-collapse or electron capture supernova. This is consistent with the original ideas of Pfahl et al. (2002a) who argued that neutron stars formed in some specific high-mass X-ray binaries are formed with a low kick. The DNS/DRP progenitors evolve through a high-mass binary phase after the first NS formation. The potential explanation was discussed by Podsiadlowski et al. (2004), who pointed out that depending on initial binary orbital period, the first star may either form a NS via electron capture or regular (FeNi) core-collapse supernova. Our result stems from the fact, that majority of the DNS/DRP progenitors are still found on relatively wide orbits at the first SN explosion and if any significant kick is imparted on a NS a given system is most likely disrupted, barring the formation of either DNS or DRP. Hence, the systems that are in the mass range of electron-capture NS formation at the time of the first supernova are naturally selected in the DNS/DRP formation. At the time of the second supernova the progenitors are usually very close binaries, and the effect of kicks is not as severe on the system survival as during the first SN. In our simulations it is found that the second SN is dominated by regular core-collapse with smaller contribution of the electron-capture NS formation. Some known DNS have significant eccentricities (B1913+16: $e = 0.617$; J1811-1736: $e = 0.828$) that are indicative of a significant natal kick at the second SN. Even for some moderate eccentricity systems (e.g. B1534+12: e=0.274) high natal kicks are derived (e.g., Stairs et al. 2006). For some low-eccentricity systems (e.g., J0737-3039: $e = 0.088$) the low kicks are claimed (e.g., Piran & Shaviv 2005), but high kicks at the second SN can not yet be excluded (Willems et al. 2006). If it will turn out that the second supernova in DNS binary progenitors is predominantly electron-capture SN with a low (or no) kick, it will allow us to put strong constrains on the initial mass range (broader than assumed in this study) for this mode of NS formation.

3.5 Results

The results of two models are presented. In the first model, we allow for such a survival. In the second model, such systems are assumed to merge. During the third RLOF episode the neutron star accretes some more material from its companion ($\sim 0.05\,\mathrm{M}_\odot$). The first neutron star, which accreted about $\sim 0.1\,\mathrm{M}_\odot$, has most probably become a recycled pulsar. After (or during) the third RLOF the companion star explodes forming the second (non-recycled) neutron star. The second neutron star is formed in regular supernova explosion/core collapse. Regular core collapse supernovae (stars forming FeNi cores) are more massive than stars forming neutron stars through electron capture supernovae (semi-degenerate ONeMg cores). Early on in the evolution of a progenitor (first RLOF) there is a mass ratio reversal, and in fact it is expected that the secondary is in the end the more massive star. After the third RLOF, the system becomes very close and many such systems have a good chance of supernova explosion survival. The systems that are disrupted at the second supernova produce two single neutron stars, while surviving systems form DNS binaries. Depending upon the amount of accretion onto a first-born neutron star either a DRP or a DNS recycled pulsar may form.

In the second scenario, the evolutionary history is almost the same as presented in scenario 1 with the difference being that the secondary star forms a black hole. The stars are initially more massive, and then during the first RLOF episode the secondary accretes enough mass to form a black hole at the end of its evolution. As before, the primary forms a neutron star and it is the first formed compact object in a system. Such a scenario may lead to the formation of either a NS-BH binary or, if a system is disrupted upon black hole formation, a single recycled pulsar. This scenario is rather inefficient ($\sim 0.2\%$) as compared to scenario 1 ($\sim 98.8\%$) in the formation of DRPs. This is due to the fact that scenario 2 is allowed for only very specific combinations of progenitor masses, i.e. both component masses need to be very close to the mass limiting neutron star and black hole formation.

3.5.1 DNS/DRP numbers

In Table 2 we list the intrinsic (i.e. with no detection biases accounted for) numbers of DNS with recycled pulsar, DRP, and their ratio as obtained in the population synthesis calculations. Numbers are listed for all our models (natal kick velocity varied), and within each model we give a range corresponding to common envelope uncertainty; the high numbers of DRP/DNS correspond to calculations in which survival through the common envelope is allowed for Hertzsprung gap donors, while the low numbers correspond to the assumption of a merger during such a phase.

The predicted number of DNSs increases with decreasing natal kicks, as the kicks are very effective in disrupting potential DNS progenitors. For model A (high kicks) most of the potential DNS progenitors are disrupted in the first supernova explosion (98%), while a much smaller fraction are disrupted at the second supernova (1.8%), and only a very small fraction (0.2%) survive and form DNSs. For model C (intermediate kicks) the disruption is 97.6%, and 1.9% in first and second supernova, and 0.5% of the systems survive to form DNSs. The very high disruption rate at the first supernova comes from the fact that many binaries at that time still have rather wide orbits. At the second supernova, not only the wide binaries were eliminated by first supernova disruptions, but also consecutive RLOF and/or common envelope phases decrease the separation between binary components. For model E (no natal kicks) in which disruptions are due only to mass loss during supernova explosion, we find 16.3%, and 79.5% disruptions occurring in the first and second supernova, and 4.2% systems survive as DNS binaries. From the virial theorem, disruption by mass loss alone requires about 50% of the total binary mass to be lost. It is therefore much easier to disrupt binaries at the second supernova during which time a first born neutron star is a less massive binary component. For the DNS population, most of the first born neutron stars ($\gtrsim$ 80%) accreted enough mass to host a recycled pulsar, and only these systems are listed in Table 2.

The number of DRPs at first decreases with decreasing kick velocity as the smaller kicks are less effective in releasing recycled pulsars from progenitor binaries. However, for very low kicks ($\sigma < 100$ km s^{-1}) the number of DRPs increases with decreasing kick velocity. This is a natural effect of the higher disruption rate during the second supernova (high release of recycled neutron stars from binaries) relative to the first supernova for low or zero kicks as explained above. Progenitors of disrupted binaries are on average wider (easier to disrupt) than progenitors of a DNS. Since they are wider, the stars interact less (less mass transfer) and in the end not so many first born neutron stars are recycled. If we consider just progenitors that are disrupted at the second supernova (so the ones that have a chance to produce a solitary recycled pulsar) we find that only $\sim 1 - 20$% of the disrupted binaries form a DRP. Smaller fractions are found for models with no or low natal kicks as wider non-interacting systems more readily survive the first supernova.

3.5.2 DNS/DRP spatial velocities

In Fig. 2 we present the resulting velocity distributions for DNS and DRP populations. Results for models with high (model A), intermediate (C) and zero (E) natal kicks are presented. The presented distributions are obtained for evolutionary models that allow for the survival through the common envelope phase with Hertzsprung gap donor (i.e., they correspond to the higher numbers in Table 2). The distributions for alternative treatment of such a phase are qualitatively very similar. The velocities we present are those that the DNSs and DRPs obtain during the two supernova explosions from mass loss and/or natal kicks. In other words they can be understood as an extra velocity component that should be added to a typical Galactic velocity for a given object.

As can be seen from Fig. 2, that velocities of DRPs are higher than the velocities gained by DNSs. Also the distributions are broader for DRPs. These general features hold for all considered models. Progenitors of DRPs are disrupted at the second supernova explosion mostly due to a rather high and/or unfavorably (e.g., perpendicular to orbital plane: high disruption probability) placed kick. Additionally, mass loss from an exploding star and its orbital speed at the time of explosion factor into the final DRP velocity (the full description of the velocity calculation is given in Belczynski et al. 2008; see their Section 6.3). The progenitors of a DNS survive two supernova explosions and tend to receive smaller or favorably (for survival) placed kicks and their final velocities are on average smaller than these of DRPs.

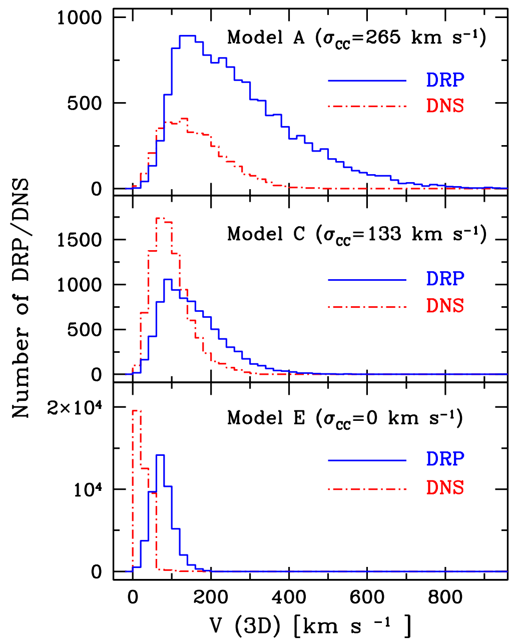

Figure 2. Predicted velocity distributions for DRP and DNS populations for different models. The presented distributions correspond to evolutionary calculations in which common envelope phase with Hertzsprung gap donor is allowed (the shape of distributions is virtually the same for calculations in which such phase is assumed to lead always to a merger).

We can see that the natal kicks play the major role in setting the spatial velocities of both populations. If no natal kicks are applied at supernova explosions (model E) we see that the mean velocities are rather small: 26 and 76 km s^{-1} for DNS and DRP populations, respectively. However, if even intermediate kicks are applied (model C) we note a significant increase of the mean velocity: 99 and 154 km s^{-1} for DNS and DRP populations, respectively.

The substantial differences in the DNS and DRP velocity distributions may lead to a different detection probability for both populations. If there is any observational bias against detecting either DNSs or DRPs we need to take it into account and revise our intrinsic ratio $r_{\rm int}$ before attempting a comparison with the observed ratio $r_{\rm obs}$ below.

3.5.3 Orbital period distributions of DNS binaries

In Fig. 3 we present the orbital period distributions for the DNS population (only binaries hosting a recycled pulsar are shown) for models A, C, E. For all of the models, the orbital periods extend to high values (see mean and standard deviations for the distributions), although the majority of systems are found at small periods (medians are in the range $\sim$ 10–25 hr). In the following text we explain the shape of the orbital period distributions for DNS for various natal kick

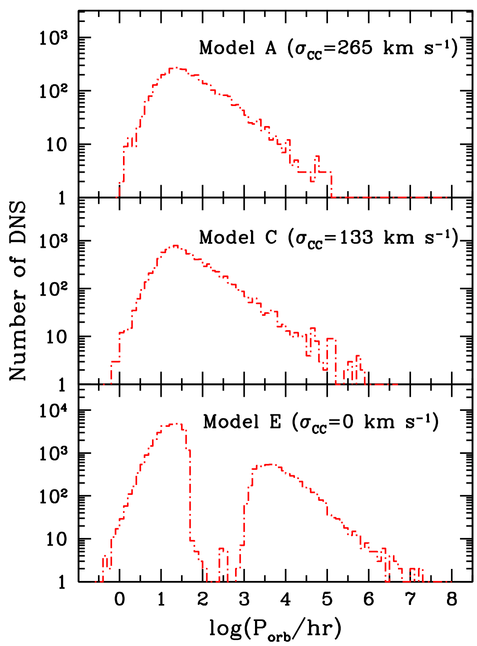

Figure 3. Predicted period distribution for DNS binaries hosting a recycled pulsar for the same models as in Fig. 2.

models. In particular, it is interesting that models that involve natal kicks (A-D) have continuous distributions, while model E which has no natal kicks shows a bimodal bimodal period distribution (see Fig. 3).

Prior to the second SN explosion (i.e. just before DNS formation), the period distribution is bimodal for all models. Long-period systems ($P_{\rm orb} \sim 100$ hr) originate from progenitors evolving via classical DNS formation channels (e.g., Bhattacharya & van den Heuvel 1991) that involve only two RLOF episodes, while short-period systems ($P_{\rm orb} \sim 10$ hr) originate from new DNS formation scenarios (Belczynski & Kalogera 2001; Ivanova et al. 2003; Dewi & Pols 2003) that involve three RLOF phases. The extra RLOF phase (that is the last phase before the second SN and the DNS formation) tends to make orbital separation (and orbital period) decrease and thus creating a bimodal period distribution prior the second SN. There is also an additional effect; for the binaries evolving through the extra RLOF the donor star that is just about to explode in SN and form the second NS is of a very low mass (mass loss in the RLOF). At the time of the second SN explosion, the exploding star loses on average $\sim 0.5\,{\rm M}_\odot$ in the new formation scenarios, while it loses $\sim 2.5\,{\rm M}_\odot$ for classical formation channels.

The bimodality, in orbital period and mass ejection, at the second SN leads to the bimodal distribution of DNS orbital periods for model with no natal kicks (E). The systems with short pre-SN orbital periods have small mass ejection and thus they tend to survive the SN with not much change of orbital parameters and they end up as close DNS with $P_{\rm orb} \lesssim 100$ hr (the new DNS). On the contrary, the binaries with the long pre-SN periods have significant mass ejection and thus the orbit increases and gains high eccentricity at the second SN and these binaries form rather long-period DNS binaries ($P_{\rm orb} \gtrsim 1000$ hr).

For models with natal kicks (A, B, C, D), the progenitor binaries follow similar evolutionary channels (the classical and new formation scenarios). At the time of the second SN there is similar mass ejection, however the additional natal kicks (with various directions and magnitudes) tend to smear the two peaks in pre-second SN period distribution out. The distributions peak at ~ 10 hr (preserving the shape of pre-SN period distribution for the closest binaries; the hardest to disrupt and change the orbit) and then it falls off with the increasing period. Additionally to the smearing, the effect of increasing natal kicks can be observed with distributions terminating at shorter periods and general decrease of DNS with increasing kicks (enhanced SN binary disruptions).

4 OBSERVATIONAL SELECTION EFFECTS

The evolutionary models described above do not take into account the observational selection biases which are known to be significant for the radio pulsar population (see, e.g., Lorimer et al. 1993). In this section, we investigate the various factors which might affect the relative populations of DRPs and DNS systems.

4.1 Basic assumptions

We begin by making an important assertion: the spin-down, luminosity and beaming evolution are the same for both DRPs and DNS binaries. This simplification should hold for any model in which the two populations follow an accretion phase that determines the initial spin period of the recycled pulsar. The subsequent spin-down evolution is the same regardless as to whether the binary system was disrupted at the end of mass transfer or not. The spin period, radio luminosity and beaming fraction of the recycled pulsar should be identical.

Given this premise, there are only two possible differences that affect the detectability of DRPs as opposed to DNS binaries. Firstly, Doppler smearing in the binary orbit during a survey integration time will significantly degrade the sensitivity to DNS binaries with the shortest orbital periods. Secondly, the different predicted velocity distributions for DRPs and DNS systems will result in a larger distance from Earth for the DRPs and hence smaller average flux density than the DNS binaries. These two effects act in opposite ways. Doppler smearing tends to select against the detection of DNS binaries relative to DRPs, while the higher velocities of DRPs compared to DNS systems selects against DRPs.

4.2 Monte Carlo simulation

To quantify the strength of these effects on the observed sample, we carried out a simple Monte Carlo simulation described in detail below which compares the relative detectability of DNS binaries to DRPs in radio pulsar surveys. The ratio of the numbers of detectable DNS binaries to DRPs then provides us with an estimate of the correction factor $f_{\rm obs}$ required to scale the intrinsic DNS/DRP ratios listed in Table 2 and compare them with the observed DNS/DRP ratio as defined in Equation 1.

The Monte Carlo code we use for this analysis, `psrpop`, is a freely available software package to model pulsar populations and radio survey selection effects (Lorimer et al. 2006). We have recently extended the scope of `psrpop` to model the kinematical and spin-down evolution of pulsars to investigate a number of issues in pulsar statistics (Ridley & Lorimer 2010). For the purposes of this study, we generated two populations with identical numbers of recycled pulsars. For both populations, we assumed a dipolar spin-down evolution from an initial spin period of 20 ms for a magnetic field strength of 2×10^{10} G. The radio luminosity of each pulsar at 1.4 GHz was assumed to be 10^3 mJy kpc^2. Each model pulsar was then allowed to move in a model of the Galactic gravitational potential for a random age of up to 1 Gyr, the typical radio lifetime of a recycled pulsar. The exact details of these assumptions have no effect on our results, since we are only concerned with the relative numbers of each population that are detectable and we are assuming that the spin-down, luminosity and beaming evolution are identical for each population.

To model the Doppler smearing due to binary motion for the DNS systems, we follow the approach of Johnston & Kulkarni (1991). In this framework, for a given survey integration time and set of orbital parameters, a signal-to-noise reduction factor γ is computed by comparing the response in the Fourier domain between an isolated pulsar and a binary system. We assumed a Fourier spectrum which is optimally summed for 16 harmonics (which is typical for pulsar search detections), and averaged over all orbital phases and inclinations assuming circular orbits with randomly inclined planes with respect to the line of sight. The circular orbit assumption is made for computational convenience and is an excellent approximation for DNS systems like J0737−3039 and J1906+0746. For the more eccentric systems such as B1936+16 and J1756−2251, this approach provides a more approximate but conservative measure of γ. We defer a full extension of Johnston & Kulkarni's analysis for elliptical orbits to a future study.

As described in Johnston & Kulkarni (1991), the factor γ can be computed for surveys with and without coherent acceleration searches. Most of the surveys considered below had relatively short integration times and did not adopt acceleration searches. However, the Doppler smearing effects can be significant for short orbital periods and this is taken into account in our simulations. For the Parkes multibeam pulsar survey of the Galactic plane which had 35-minute dwell times (Manchester et al. 2001), acceleration search techniques were applied (Faulkner et al. 2004). As discussed by Faulkner et al., the "stack search" method used in this analysis is typically 25% less efficient than a fully coherent acceleration search. We take this factor into account when computing γ for this survey. The two other surveys with fully coherent acceleration searches we consider are the ongoing Pulsar Arecibo L-band Feed Array (PALFA) survey (Lorimer et al. 2006) and the Green Bank 350-MHz drift scan survey (GBTDRIFT; Archibald et al. 2009).

4.3 Results

With the above set of assumptions, we considered two populations. For one population (model DNS) we drew velocities from the distribution predicted for the DNS binary systems produced in model A (see Fig. 2). The orbital period distribution we used for these systems was an analytic form of the predicted distribution of DNS orbital periods from model A shown in Fig. 3. For this model, we find that the cumulative number of systems as a function of orbital period is well approximated by the simple function $N(< P_b) = P_b/(1 + P_b)$, where P_b is the orbital period in days. For the second population (model DRP), we drew velocities from the distribution predicted for the DRPs from the same model. For both populations, we computed the final position and expected flux density of each model pulsar and used models of a variety of recent pulsar surveys to calculate the number of detectable pulsars.

Table 3. Results of simulation runs for the model DRP and DNS populations. From left to right, the columns give the survey name, integration time ($t_{\rm int}$), whether acceleration searches were used (AC), simulated number of detected DNS binaries ($N_{\rm DNS}$), number of detected DRPs ($N_{\rm DRP}$), and the correction factor $f_{\rm obs} = N_{\rm DNS}/N_{\rm DRP}$. The surveys considered are: an Arecibo drift-scan survey (AODRIFT), the Green Bank Telescope drift-scan survey (GBTDRIFT), the Parkes Multibeam surveys of the Galactic plane (PMSURV) and high latitudes (PHSURV), the 70-cm Parkes Southern Sky Survey (PKS70), the Pulsar Arecibo L-band Feed Array survey (PALFA) and the Swinburne Parkes Multibeam mid and high latitude surveys (SMMID and SMHI).

Survey	$t_{\rm int}$ (s)	AC	$N_{\rm DNS}$	$N_{\rm DRP}$	$f_{\rm obs}$
AODRIFT	45	No	13377	11559	1.16
GBTDRIFT	180	Yes	9553	8139	1.17
PMSURV	2100	Yes	26715	16435	1.63
PHSURV	524	No	2227	2141	1.04
PKS70	180	No	35783	32613	1.10
PALFA	278	Yes	4101	2391	1.72
SMMID	524	No	21641	17160	1.26
SMHI	524	No	9781	10364	0.94

Our results are summarized in Table 3 where we calculate the number of each model pulsar population detected ($N_{\rm DNS}$ and $N_{\rm DRP}$) and the ratio of the two populations $f_{\rm obs} = N_{\rm DNS}/N_{\rm DRP}$. The absolute values of $N_{\rm DNS}$ and $N_{\rm DRP}$ are, of course, arbitrarily high and chosen to be so to minimize statistical fluctuations. Given our assertion of that the spindown and beaming of the two populations should be identical, it is their ratio that is of astrophysical significance. As can be seen, depending on the survey parameters, there is a variation in the ratio in the range 0.9–1.7. Surveys along the Galactic plane (i.e. PMSURV and PALFA) show the largest bias in favor of detecting DNS systems over DRPs (i.e. the largest values of $f_{\rm obs}$), while surveys away from the plane (e.g. PHSURV and PKS70) show much less of a bias. Indeed, for the Swinburne high-latitude survey Jacoby et al. (2007), the bias is slightly tipped in favor of detecting DRPs. Taken as a whole, the average value of $f_{\rm obs} = 1.25$ in Table 3 suggests that we might expect to detect around 25% more DNS binaries than DRPs due to selection effects alone. Thus the observational bias is a relatively small perturbation on top of the intrinsic ratios found in the population syntheses listed in Table 2.

Although we have only explicitly considered the velocity and orbital period distributions from model A in this study, similar results are found when the other model parameters are used as input. In summary, while we find that observational biases exist which favor the detection of DNSs over DRPs, their magnitude is not sufficient to significantly skew any underlying ratios of the two populations.

This allows us to revisit the results from the population syntheses presented in Table 2. As discussed earlier the observed ratio is $r_{\rm obs} \sim 1$. If we fold this with observational bias factor ($f_{\rm obs} = 1.25$) the intrinsic ratio of DNS to DRPs is of the order $r_{\rm int} \sim 0.8$ (DRPs slightly dominate over DNS). The comparison with Table 2, that shows the predicted ratios r, shows two things. First, the model with natal kicks adopted from observations of single pulsars (model A) does not reproduce the intrinsic ratio ($r = 0.3$). Second, the models that are close to the intrinsic ratio (model B and C, $r = 0.5,\ 1.1$ respectively) indicate that the 1–D dispersion of kick velocity distribution is of the order of $\sigma_{\rm CC} \sim 170$ km s^{-1} (approximately the mid point between model B and C).

5 CONCLUSIONS

We have investigated the statistics of disrupted recycled pulsars (DRPs) and double neutron star (DNS) binaries where it is observed (see Section 2) that there are comparable numbers of DNS binary systems and DRPs. From a population synthesis of neutron star formation and evolution in binary systems (see Section 3), regardless of the assumed natal kick velocity distribution for neutron stars, we find that the velocity dispersion of DRPs is significantly higher than for DNS binaries. Using the resulting orbital period and velocity distributions in a model for radio pulsar selection effects (see Section 4), we found that there is a small ($\sim 25\%$) observational bias in favor of detecting DNS binaries over DRPs. The difference in velocity dispersions for the two populations lead to a bias towards observing DNS binaries which are, on average, closer to the Earth than DRPs. This conclusion holds even after taking into account that DNS binaries are harder to detect due to Doppler smearing.

Based on these results, we conclude that our models in which the natal kick velocity dispersion above 200 km s^{-1} (e.g. model A) or below 100 km s^{-1} (e.g. model D) are inconsistent with the observations. Model A predicts significantly more DRPs than are observed, while model D predicts significantly more DNS binaries than are observed. Models with intermediate natal kicks (e.g. models B and C) provide a better match to the observed sample. The typical kicks (from regular (FeNi) core collapse supernovae) that match the observed intrinsic ratio are of the order of $\sigma_{\rm CC} \sim 170$ km s^{-1}. In all our simulations we have included the formation of neutron stars through electron-capture supernovae with no natal kicks. The initial mass formation range for electron-capture NS formation was adopted from Hurley et al. (2000) and Eldridge & Tout (2004a,b) for single stars ($M_{\rm zams} = 7.6 - 8.3\,{\rm M}_{\odot}$; see Belczynski et al. 2008), and it is naturally extended by binary evolution. If the adopted range for electron-capture supernovae was much broader than adopted here, it would be possible to explain the the observed intrinsic ratio of DNS to DRPs with much higher regular (FeNi) core-collapse supernova kicks. Independent of details of the electron-capture NS formation, our results strongly indicate that NS natal kicks (whether formed via regular core collapse or electron-capture) are much lower in binaries than for single pulsar population.

The research into natal kicks and the formation of single recycled pulsars by supernova disruption has already a long history (e.g., Bailes 1989). The most recent study by Dewi et al. (2006) is not directly comparable to our results. Dewi et al. (2006) have studied only one (alternative) scenario of the DNS formation and based their conclusions on the information available at the time of their study (7 DNS and 2 DRP). However, it is interesting to note that the results from Dewi et al. (2006) show slightly higher DNS birth rates as compared to disruption rates (DRP formation) for example for the model in which natal kicks are drawn from distribution with $\sigma = 190$ km s^{-1} (see the first entry in their Table 1). This result is fully consistent with the current observational dataset, presented here, and it is similar to our finding for the two models B and C that also match the observations.

Our conclusion that small neutron star kicks are required to explain the DNS–DRP populations adds to the growing body of evidence that such kicks are required in the formation of close binaries. The original impetus for this idea was provided by Pfahl et al. (2002a) based on statistics of high-mass X-ray binaries with orbital periods longer than 30 days. A similar requirement was seen for the neutron star population in globular clusters (Pfahl et al. 2002b) in which the low escape velocities of the clusters predict many fewer pulsars than are observed (Drukier 1996). The notion of electron-capture supernovae, which naturally produce such neutron stars with lower velocity kicks was subsequently introduced by Podsiadlowski et al. (2004). More recent evidence for low-velocity kicks in binary systems has been inferred from the spin-eccentricity correlation seen in DNS binaries (Faulkner et al. 2005; Dewi et al. 2005) and in a starburst activity of high-mass X-ray binaries in the Small Magellanic Cloud (Linden et al. 2009).

The process of the formation of neutron stars via electron capture supernovae is highly uncertain; the magnitude of kicks (if any; e.g., Dessart et al. 2006; Kitaura et al. 2006), the initial star mass range for these explosions (e.g., Nomoto 1987) or physical conditions like rotation (e.g., Pfahl et al. 2002a) at which such a process may occur. We have included the possibility of formation of neutron stars via this process in our calculations and we have assumed that these types of explosions are not connected with any significant natal kicks. Still, our results indicated that there are too many DNS progenitor binary disruptions to reproduce the approximately equal observed numbers of DNSs and DRPs. The disruptions are mostly due to the natal kicks received by neutron stars in regular (FeNi) core collapse supernovae. It naturally led us to conclude that the regular core collapse natal kicks are smaller than it is usually believed in the case of close binaries. However, it needs to be noted that a similar effect (fewer disruptions) may be achieved via extended formation of neutron stars via electron capture supernova with negligible (or no) kicks (e.g. Podsiadlowski et al. 2004). Whether it is rather small regular core collapse kicks, or an excess of formation of neutron stars via electron capture supernovae or some other process, it seems to be clear that the kicks that operate in close interacting binaries (like for progenitors of DNS) are significantly smaller than the ones inferred for the population of Galactic single pulsars (e.g., Hobbs et al. 2004). It is interesting to note that the supernova hydrodynamical simulations predict increase of asymmetries with rotation (Chris Fryer, private communication). If natal kicks are connected to assymetries in regular (FeNi) core collapse then NS in binaries (fast rotation) are expected to receive larger kicks then single stars, opposite to what seems to be inferred from observations. On the other note, the kick mechanism may be totally different for an exploding $\sim 10-15\,\mathrm{M}_{\odot}$ H-rich star (single NS progenitor) and a $\sim 2-3\,\mathrm{M}_{\odot}$ He-rich star (binary).

ACKNOWLEDGMENTS

We would like to thank T.Bulik, W.Kluzniak and P.Haensel for useful discussions on pulsar populations. This research was partially supported by a WVEPSCoR Research Challenge Grant held by the WVU Center for Astrophysics. KB acknowledges the partial support from the Polish MSHE grants N N203 302835 and N N203 511238 and by LANL under contract No. DE-AC52-06NA25396. The pulsar parameters used in Table 1 were obtained from the ATNF Pulsar Catalogue (Manchester et al. 2005).

REFERENCES

Abbott B., Abbott R., Adhikari R., Ageev A., Agresti J., Ajith P., Allen B., Allen J., Amin R., Anderson S. B., Anderson W. G., Araya M., Armandula H., Ashley M., Asiri F., Aufmuth P., Aulbert C., 2006, Phys. Rev. D, 73, 102002
Arzoumanian, Z., Cordes, J. M., Wasserman, I., 1999, ApJ, 520, 696
Archibald, A. M., Stairs, I. H., Ransom, S. M., Kaspi, V. M., Kondratiev, V. I., Lorimer, D. R., McLaughlin, M. A., Boyles, J., Hessels, J. W. T., Lynch, R., van Leeuwen, J., Roberts, M. S. E., Jenet, F., Champion, D. J., Rosen, R., Barlow, B. N., Dunlap, B. H., Remillard, R. A. 2009, Science, 324, 1411
Bailes, M. 1989, ApJ, 342, 917
Barziv, O., Kaper, L., Van Kerkwijk, M. H., Telting, J. H., & Van Paradijs, J. 2001, A&A, 377, 925
Belczynski, K., Kalogera, V., & Bulik, T. 2002a, ApJ, 572, 407
Belczynski, K., Bulik, T., & Rudak, B. 2002b, ApJ, 571, 394
Belczynski, K., Kalogera, V., Zezas, A., & Fabbiano, G. 2004, ApJ, 601, L147
Belczynski, K., & Taam, R. 2004, ApJ, 616, 1159
Belczynski, K., Bulik, T., & Ruiter, A. 2005, ApJ, 629, 915
Belczynski, K., Perna, R., Bulik, T., Kalogera, V., Ivanova, N., & Lamb, D.Q. 2006, ApJ, 648, 1110
Belczynski, K., Taam, R., Kalogera, V., Rasio, F., & Bulik, T. 2007, ApJ, 662, 504
Belczynski, K., Kalogera, V., Rasio, F., Taam, R., Zezas, A., Bulik, T., Maccarone, T., & Ivanova, N. 2008a, ApJ Sup., 174, 223
Belczynski, K., O'Shaughnessy, R., Kalogera, V., Rasio, F., Taam, R., & Bulik, T. 2008b, ApJ, 680, L129
Bethe, H., & Brown, G. 1998, ApJ, 506, 780
Brown, G. 1995, ApJ, 440, 270
Burgay M., D'Amico N., Possenti A., Manchester R. N., Lyne A. G., Joshi B. C., McLaughlin M. A., Kramer M., Sarkissian J. M., Camilo F., Kalogera V., Kim C., Lorimer D. R., 2003, Nature, 426, 531
Burgay M., Joshi B. C., D'Amico N., Possenti A., Lyne A. G., Manchester R. N., McLaughlin M. A., Kramer M., Camilo F., Freire P. C. C., 2006, MNRAS, 368, 283
Camilo F., Nice D. J., Taylor J. H., 1993, ApJ, 412, L37
Champion D. J., Lorimer D. R., McLaughlin M. A., Cordes J. M., Arzoumanian Z., Weisberg J. M., Taylor J. H., 2004, MNRAS, 350, L61
Chaurasia H. K., Bailes M., 2005, ApJ, 632, 1054
Chen, K., Ruderman, M., 1993, ApJ, 402, 264
David, J. G., Large, M. I., Pickwick, A. C., Nature, 227, 1123
Dessart, L., Burrows, A., Ott, C.D., Livne, E., Yoon, S.Y., & Langer, N. 2006, ApJ, 644, 1063
Dewi, J., & Pols, O. 2003, MNRAS, 344, 629
Dewi, J., Podsiadlowski, P. & Pols, O. 2005, MNRAS, 363, L71
Dewi, J., Podsiadlowski, P. & Sena, A. 2006, MNRAS, 368, 1742
Druckier, G. A. 1996, MNRAS, 280, 498
Eldridge, J., & Tout, C. 2004a, MNRAS, 348, 201
Eldridge, J., & Tout, C. 2004a, MNRAS, 353, 87
Faulkner, A. J., Stairs, I. H., Kramer, M., Lyne, A. G., Hobbs, G., Possenti, A., Lorimer, D. R., Manchester, R. N., McLaughlin, M. A., D'Amico, N., Camilo, F., Burgay, M., 2004, MNRAS, 355, 147
Faulkner A. J., Kramer M., Lyne A. G., Manchester R. N., McLaughlin M. A., Stairs I. H., Hobbs G., Possenti A., Lorimer D. R., D'Amico N., Camilo F., Burgay M., 2005, ApJ, 618, L119
Fryer, C., & Kalogera, V. 2001, ApJ, 554, 548
Faucher-Giguere, C.-A., & Kaspi, V. 2006, ApJ, 643, 332
Hamann, W., & Koesterke, L. 1998, A&A, 335, 1003
Hulse R. A., Taylor J. H., 1975, ApJ, 195, L51
Ihm C. M., Kalogera V., Belczynski K., 2006, ApJ, 652, 540
Ivanova, N., Belczynski, K., Kalogera, V., Rasio, F., & Taam, R. E. 2003, ApJ, 592, 475
Jacoby, B.A., Hotan, A., Bailes, M., Ord, S., & Kulkarni, S. 2005, ApJ, 629, L113
Jacoby, B. A., Bailes, M., Ord, S. M., Knight, H. S., Hotan, A. W., 2007, ApJ, 656, 408
Johnston H. M., Kulkarni S. R., 1991, ApJ, 368, 504
Kalogera V., Lorimer D. R., 2000, ApJ, 530, 890
Keith, M. J., Kramer, M., Lyne, A. G., Eatough, R. P., Stairs, I. H., Possenti, A., Camilo, F., Manchester, R. N., 2009, MNRAS, 393, 623
Kim C., Kalogera V., Lorimer D. R., 2003, ApJ, 584, 985
Kitaura, F., Janka, T., Hillebrandt, W., 2006, A&A, 450, 345
Kiziltan, B., Thorsett, S. E., 2009, arXiv:0909.1562v1
Kramer, M., Bell, J. F., Manchester, R. N., Lyne, A. G., Camilo, F., Stairs, I. H., D'Amico, N., Kaspi, V., Hobbs, G. B., Morris, D. J., Crawford, F., Possenti, A., Joshi, B. C., McLaughlin, M. A., Lorimer, D. R., Faulkner, A. J., 2003, MNRAS, 342, 1299
Linden, T., Sepinsky, J. F., Kalogera, V., Belczynski, K., 2009, ApJ, 699, 1573
Lorimer D. R., Bailes M., Dewey R. J., Harrison P. A., 1993, MNRAS, 263, 403
Lorimer D. R., Faulkner A. J., Lyne A. G., Manchester

R. N., Kramer M., McLaughlin M. A., Hobbs G., Possenti A., Stairs I. H., Camilo F., Burgay M., D'Amico N., Corongiu A., Crawford F., 2006, MNRAS, 372, 777
Lorimer D. R., McLaughlin M. A., Arzoumanian Z., Xilouris K. M., Cordes J. M., Lommen A. N., Fruchter A. S., Chandler A. M., Backer D. C., 2004, MNRAS, 347, L21
Lorimer D. R., Stairs I. H., Freire P. C., Cordes J. M., Camilo F., Faulkner A. J., Lyne A. G., Nice D. J., Ransom S. M., Arzoumanian Z., Manchester R. N., Champion D. J., van Leeuwen J., Mclaughlin M. A., Ramachandran R., Hessels J. W., 2006, ApJ, 640, 428
Lorimer D. R., 2008, Living Rev. Relativity 11, 8
Lyne A. G., Camilo F., Manchester R. N., Bell J. F., Kaspi V. M., D'Amico N., McKay N. P. F., Crawford F., Morris D. J., Sheppard D. C., Stairs I. H., 2000, MNRAS, 312, 698
Manchester, R. N., Hobbs, G.B., Teoh, A., Hobbs, M., 2005, AJ, 129, 1993
Manchester, R. N., Lyne, A. G., Camilo, F., Bell, J. F., Kaspi, V. M., D'Amico, N., McKay, N. P. F., Crawford, F., Stairs, I. H., Possenti, A., Kramer, M., Sheppard, D. C., 2001, MNRAS, 328, 17
Manchester, R. N., Lyne, A. G., D'Amico, N., Bailes, M., Johnston, S., Lorimer, D. R., Harrison, P. A., Nicastro, L., Bell, J. F., 1996, MNRAS, 279, 1235
Nice D. J., Sayer R. W., Taylor J. H., 1996, ApJ, 466, L87
Nomoto, K., 1987, ApJ, 322, 206
Pfahl, E., Rappaport, S., Podsiadlowski, P., Spruit, H., 2002a, ApJ, 574, 364
Pfahl, E., Rappaport, S., Podsiadlowski, P., 2002b, ApJ, 573, 283
Phinney E. S., 1992, Philos. Trans. Roy. Soc. London A, 341, 39
Piran, T., & Shaviv, N. 2005, Physical Review Letters, 94, 051102
Podsiadlowski, P., Langer, N., Poelarends, A.J.T., Rappaport, S., Heger, A., & Pfahl, E.D. 2004, ApJ, 612, 1044
Portegies Zwart S. F., Yungelson L. R., 1998, A&A, 332, 173
Ransom, S., et al. 2005, Science, 307, 892
Ridley, J.P., & Lorimer, D.R. 2010, MNRAS, in press
Stairs, I., Thorsett, S., Dewey, R., Kramer, M., & McPhee, C. 2006, MNRAS, 373, L50
Timmes, F.X., Woosley, S.E., & Weaver, T.A. 1996, ApJ, 457, 834
van den Heuvel, E.P.J., & Lorimer, D.R. 1996 MNRAS, 283, 37
Webbink, R. F. 1984, ApJ, 277, 355
Willems, B., Kaplan, J., Fragos, T., Kalogera, V., & Belczynski, K. 2006, Physical Review D, 74, 043003
Wolszczan A., 1991, Nature, 350, 688
Zdunik, L., Haensel, P., & Gourgoulhon, E. 2002, A&A, 381, 933