Implications of PSR J0737–3039B for the Galactic NS-NS Binary Merger Rate

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ABSTRACT
The Double Pulsar (PSR J0737–3039) is the only neutron star - neutron star (NS-NS) binary in which both NSs have been detectable as radio pulsars. The Double Pulsar has been assumed to dominate the Galactic NS-NS binary merger rate \( R_g \) among all known systems, solely based on the properties of the first-born, recycled pulsar (PSR J0737–3039A, or A) with an assumption for the beaming correction factor of six. In this work, we model the second-born, non-recycled pulsar (PSR J0737–3039B, or B) and estimate the contribution from the Double Pulsar on \( R_g \) based on both A and B.

Observational constraints from the B pulsar favour a small beaming correction factor for A (\( \sim 2 \)), which is consistent with a bipolar model. Considering known NS-NS binaries with the best observational constraints, including both A and B, we obtain \( R_g = 21^{+28}_{-14} \) Myr\(^{-1}\) at 95 per cent confidence from our reference model. We expect the detection rate of gravitational waves from NS-NS inspirals for the advanced ground-based gravitational-wave detectors is to be \( 8^{+10}_{-5} \) yr\(^{-1}\) at 95 per cent confidence. Within several years, gravitational-wave detections relevant to NS-NS inspirals will provide us useful information to improve pulsar population models.

Key words: pulsars: individual binaries: close methods: statistical

1 INTRODUCTION
As of today, there are four confirmed NS-NS binaries in the Galactic plane that will merge within a Hubble time. All known NS-NS binaries contain at least one radio pulsar that is detected by large-scale pulsar surveys: PSRs B1913+16 (Hulse & Taylor 1975), B1534+12 (Wolszczan 1991), the Double Pulsar J0737–3039 (Burgay et al. 2003; Lyne et al. 2004), and J1756–2251 (Faulkner et al. 2005). NS-NS mergers are one of the most promising sources of GWs with ground-based interferometers (e.g., Abadie et al. 2010, and reference therein). By modelling the Galactic disk pulsar population as well as selection effects based on observed properties of known binaries and survey characteristics, one can infer the Galactic merger rate estimates (\( R_g \)) and GW detection rate (\( R_{\text{det}} \)) for NS-NS binaries with ground-based GW detectors (Phinney 1991; Narayan et al. 1991; Curran & Lorimer 1995; Kalogera et al. 2001; Kim, Kalogera, & Lorimer 2003, 2010; O'Shaughnessy & Kim 2010).

The Double Pulsar has been assumed to dominate \( R_g \) based on the properties of the first-born, recycled pulsar PSR J0737–3039A (hereafter A) due to its large assumed beaming correction factor and short estimated lifetime. Kalogera et al. (2004) estimated the most likely value of \( R_g \sim 90 \) Myr\(^{-1}\), considering PSRs B1913+16, B1534+12, and the A pulsar. Without observational constraints, they assumed A’s beaming correction factor to be six. This is an average of the estimated beaming correction factors for PSRs B1913+16 and B1534+12, based on polarization measurements.

O'Shaughnessy & Kim (2010) attempted to calculate the beaming correction factor for each pulsar found in NS-NS and NS-white dwarf (WD) binaries in the Galactic disk making use of the latest observations available then. They estimated A’s beaming correction factor adapting the results from the polarization measurements (Demorest et al. 2004)
and pulse profile analysis (Ferdman et al. 2008). They found that, if A is bipolar and an orthogonal rotator (α ∼ 90°), its beam must be wide leading to a small beaming correction factor (∼ 1.55 based on their reference model). Here, α is the magnetic misalignment angle between the spin and magnetic axes. If A is unipolar, where the magnetic axis is likely to be aligned with the spin axis (α < 4°), its beam size is unconstrained. Although they calculated B pulsar’s beaming correction factor (∼ 14) motivated by the empirical correlation between a pulsar’s beam size and spin period, B was still not included in the rate calculation, due to the lack of information to model this pulsar. Considering PSRs B1913+16, B1534+12, PSR J0737–3039A, J1756–5521, and J1906+0746 with estimated beaming correction factors, they suggested R_b is most likely to be ∼ 60 Myr−1 (the median is ∼ 89 Myr−1).

The latest pulse profile analysis of A is presented by Ferdman et al. (2013). For the pulse widths obtained at 25 – 50 per cent intensity levels, the corresponding beaming correction factor of A ranges between 3 – 5. Low intensity levels show broader pulse widths, and hence, imply smaller beaming correction factors. Fitting a two-pole model to the 25 per cent intensity pulse widths, they obtained α = 90°+5.0−4.7, ρ1 = 21°+0.5−0.3, and ρ2 = 14°+7.9−3.6 at 68 per cent confidence.

The PSR J0737–3039B (hereafter B) was detectable by the Green Bank Telescope (GBT) for almost five years since the discovery (Lyne et al. 2004). The last significant detection made by the GBT was in March 2008 (MJD 54552) as reported by Perera et al. (2010). The non-detection of the B pulsar after 2008 is interpreted as the filled part of B’s beam moving completely out of the line of sight due to geodetic precession (Barker & O’Connell 1973). The predicted and measured precession rates of B are 5.0347±0.0007 and 4.77±0.66 deg yr−1 at the 68 per cent confidence level, respectively (Breton et al. 2008). Based on the estimated geodetic precession time-scale for B, it will be detectable again in the time window 2013–2035 (Perera et al. 2010; Kramer 2010; Perera et al. 2012). The uncertainty in the reappearance time depends on the symmetry of the beam function and the exact details of the flux gradients across the beam.

The main challenges in modelling B are attributed to its strong pulse profile modulations. Pulsar B’s secular pulse profile change is also evidence of the effects of geodetic precession. Moreover, the interaction between A’s wind and B’s magnetosphere affects B’s pulse profiles over a single orbit. Due to the impact of the wind from A (Lyutikov 2003), B was only observable during a fraction of its orbital phase, detected as two bright (BP1 and BP2) and two weak (WP1 and WP2) phases (Lyne et al. 2004; Perera et al. 2010). In contrast, A has an extremely stable pulse profile since its discovery (Ferdman et al. 2008), which is consistent with the interpretation that its spin axis is likely to be aligned with the orbital angular momentum vector (e.g., Stairs et al. 2000). In this work, we model the B pulsar based on the extensive, long-term GBT observations.

In §2 we briefly describe P(R), the PDF of a pulsar binary merger rate estimate based on the empirical modelling. In §3 and §4 we describe our model for the B pulsar and derive P(R) for the Double Pulsar. Considering PSRs B1913+16 and B1534+12, J0737–3039A, and J0737–3039B, we also calculate the PDF of the Galactic NS-NS merger rate (P_g(R_g)). We discuss results in §5.

2 PROBABILITY DENSITY FUNCTION OF NS-NS MERGER RATE BASED ON A PULSAR BINARY

Following the same empirical method described in Kim, Kalogera, & Lorimer (2003), Kalogera et al. (2004), Kim, Kalogera, & Lorimer (2010), and O’Shaughnessy & Kim (2010), we calculate P(R) for a NS-NS binary population, based on an observed system (e.g., PSR B1913+16), by

\[
P(R) = \frac{\left(\frac{\tau_{\text{life}}}{N_{\text{pop}}}\right)^2 R \exp \left[-\left(\frac{\tau_{\text{life}}}{N_{\text{pop}}}\right) R\right]}{C^2 R \exp[-CR]},
\]

where \(\tau_{\text{life}}\) is an effective lifetime of the binary and \(N_{\text{pop}}\) is the population size, i.e., the total number of pulsars like the observed one in the Galactic disk. Both \(\tau_{\text{life}}\) and \(N_{\text{pop}}\) depend on the observed properties of the known pulsar and the binary. The derivation of Eq. 1 can be found in §5.1 in Kim, Kalogera, & Lorimer (2003).

The population size can be obtained by \(N_{\text{pop}} = N_{\text{par}} \zeta f_{\text{b, eff}}\), where \(N_{\text{par}}\) represents the number of detectable pulsars like the known pulsar (e.g., the B pulsar) among those beaming toward the Earth, given one detection. \(f_{\text{b, eff}}\) is the beaming correction factor to take into account a pulsar’s finite beam size. Unlike other pulsars known in NS-NS binaries, the B pulsar is observable only during certain orbital phases. In this work, we introduce a parameter \(\zeta\) to model B-like pulsars, incorporating the observable orbital phases.

We note that Eq. 1 can be used when a NS-NS binary has only one detectable pulsar. Although both pulsars in the Double Pulsar have been detected, Kalogera et al (2004); Kim, Kalogera, & Lorimer (2010); O’Shaughnessy & Kim (2010) used Eq. 1 as they considered only the A pulsar in their work. In §4 we derive \(P(R)\) for the Double Pulsar, considering two independent observational constraints from the A and B pulsars.

3 MODELING OF THE B PULSAR

We perform Monte Carlo simulations to calculate \(N_{\text{par}}\) for each known pulsar, modelling a Galactic disk pulsar population and pulsar survey sensitivities. Below, we summarize our model assumptions and steps to calculate \(N_{\text{par}}\). More details on the modelling can be found in §3 and §4 in Kim, Kalogera, & Lorimer (2003).

We establish a population of pulsars like one of the known pulsars like the B pulsar), by fixing the intrinsic pulse width (W) and spin period (P_s) of model pulsars to those of the pulsar. Each model pulsar’s sky location and luminosity are randomly sampled from a pulsar luminosity function \(p_L(L)\) and spatial distribution \(p_L(x, y, z)\). All pulsars are assumed to be beam toward the Earth. We assume a Gaussian radial distribution and exponential vertical distribution that are consistent with the observed pulsars in the Galactic disk (see Kim, Kalogera, & Lorimer 2003) for further details and the systematic uncertainties regarding
\( p_r(x, y, z) \) in the rate estimates). As for the luminosity distribution, we choose a lognormal distribution based on the discussion presented in [37]. We emphasize that the empirical rate calculation presented in this work as well as other works such as Kalogera et al. (2004) does not involve with observed radio fluxes or distances of known pulsars. The only literature that used the observed radio flux (of the A pulsar) to infer the Galactic NS-NS merger rate is Burgay et al. (2003).

At a given frequency, the apparent radio flux density of each model pulsar \( k \) is calculated by \( F_L/k = (x_k^2 + y_k^2 + z_k^2) \), where \( F \) (\( 0 < F \leq 1 \)) is a flux degradation factor taken into account the Doppler smearing in an orbit and is fixed for the known pulsar. When there is no degradation \( F = 1 \). The flux degradation factor depends on the known pulsar’s spin period, pulse width, binary orbital period, eccentricity of the orbit, and the integration time of each survey. Fast-spinning pulsars in tight orbit normally have small \( F \). For example, the apparent flux density of a pulsar similar to the A pulsar is only \( \sim 15 \) per cent of its intrinsic ratio flux density for the Parkes multibeam survey (PMB) with 35-min integration time (Manchester et al. 2001). Therefore, we incorporate \( F_{\text{PMB}} = 0.154 \) when simulating the PMB survey for the A-like pulsar population. Due to its longer spin period, however, we can set \( F = 1 \) for all surveys for the B pulsar.

The outcome of the Monte Carlo simulation is \( N_{\text{det}} \), which is the number of pulsars brighter than the survey threshold among a total of \( 10^6 \) realizations. Following §2.1 in O’Shaughnessy & Kim (2010), we calculate \( N_{\text{par}} \) by \( 10^6/N_{\text{det}} \) for each known pulsar. This is based on the linear relation between \( N_{\text{det}} \) and the number of realization \( N \) as described in Kalogera et al. (2003). See Fig. 3 and Eq. (8) in their paper for more details. Using this relation \( N_{\text{det}} = sN \), where \( s \) is the proportionality constant, we can write \( N/N_{\text{det}} = N_{\text{par}} \).

We consider 22 large-scale pulsar surveys in this work, including three more surveys to those listed in Table 1 in Kim, Kalogera, & Lorimer (2003). The two additional surveys, the Parkes multibeam high latitude survey (Burgay et al. 2006) and the mid-latitude drift scan survey with the Arecibo telescope (Champion et al. 2004), are considered in O’Shaughnessy & Kim (2010) as well. The new addition in this work is the latest large-scale pulsar survey with the Arecibo L-band Feed Array (PALFA; Cordes et al. 2006). We adopt the PALFA precursor survey parameters (e.g., 100 MHz bandwidth, \( 40^\circ \leq l \leq 75^\circ \) and \( 168^\circ \leq l \leq 214^\circ \) with \( |b| \leq 1^\circ \)) as described in Lorimer et al. (2006). This is the survey that discovered PSR J1906+0746. See Fig. 2 in Cordes et al. (2007) for the comparison of survey regions between different large-scale L-band pulsar surveys including the PALFA precursor survey. We assume all survey data are completely processed.

We obtain \( N_{\text{pop}} \) by applying correction factors to compensate for observational biases to \( N_{\text{par}} \) for each known pulsar. We discuss details of important ingredients to modelling the B pulsar in the following subsections. In Table 1 we list the properties of A and B pulsars used in this work. For PSRs B1913+16 and B1534+12, we use the same parameters listed in Table 1 in O’Shaughnessy & Kim (2010), but \( N_{\text{par}} \) and \( N_{\text{pop}} \) are recalculated by the latest code including the PALFA survey.

### Table 1. Observational and estimated properties of A and B: Pulsar’s spin period (\( P_s \) in ms), time derivative of spin period (\( \dot{P}_s \) in \( 10^{-18} \text{ ms}^{-1} \)), mass (\( M_{\text{PSR}} \) in solar mass), age estimate (\( \tau_{\text{age}} \) in Gyr), binary merger time-scale (\( \tau_{\text{merg}} \) in Gyr), radio-emission time-scale (\( \tau_{\text{eq}} \) in Gyr), and references. See §3.3 for definitions of the time-scales.

| PSR | \( P_s \) (ms) | \( \dot{P}_s \) \( \times 10^{-18} \) | \( M_{\text{PSR}} \) (\( M_\odot \)) | \( \tau_{\text{age}} \) (Gyr) | \( \tau_{\text{merg}} \) (Gyr) | \( \tau_{\text{eq}} \) (Gyr) | Ref. |
|-----|-------------|----------------|----------------|----------------|----------------|----------------|------|
| A   | 22.7        | 1.74          | 1.34           | 0.14           | 0.085          | \( >14 \)       | 1    |
| B   | 2770        | 892           | 1.25           | 0.05 – 0.19    | 0.085          | 0.04           | 2    |

*aReferences: (1) Burgay et al. (2003); (2) Lyne et al. (2004)

*bKramer et al. (2006)

§The range of \( \tau_{\text{eq}} \) for the B pulsar is adapted from Lorimer et al. (2007)

In this work, we incorporate the flux degradation factor taken from Kalogera et al. (2004) first incorporated the flux degradation factor for the A-like population in the survey simulation code. O’Shaughnessy & Kim (2010) and this work use the same code they used, adding more surveys as mentioned in the text.

3.1 Equivalent Pulse Width

We calculate B’s equivalent pulse width \( W_{\text{eq}} \) from observed pulse profiles in two bright phases. We define \( W_{\text{eq}} \) as the area under the integrated pulse profile with zero offset divided by the maximum peak of the profile. We use \( W_{\text{eq}} \) as an approximation of an intrinsic pulse width. Fig. 1 shows the estimated \( W_{\text{eq}} \) from each bright phase (triangles for BP1 and open circles for BP2). We find that \( W_{\text{eq}} \) changes between \([1^9.9^5] \) including 1σ errors. The error bars are larger in later observations when B became significantly fainter by 3 – 4 orders of magnitudes. See Figs. 1 and 2 of Perera et al. (2010) for actual pulse profiles from BP1 and BP2. For a given pulse width, the duty cycle \( \delta \) is estimated by \( W_{\text{eq}} \) (in deg)/360°. We use the average duty cycle \( \delta \approx 0.013 \) (\( W_{\text{eq}} \approx 4^\circ68 \)) as a reference parameter for B in the Monte Carlo simulations.

3.2 Pulsar Luminosity Distribution

Our reference pulsar luminosity function is described by the lognormal distribution with \( \log L = -1.1 \) and \( \sigma_{\log L} = 0.9 \) (Faucher-Giguère & Kaspi 2006), motivated by the fact that it does not require a fiducial minimum luminosity. It is known that both power-law \( (p_s (L) \propto L^{-2}) \) and lognormal luminosity distributions are consistent with the current pulsar observations, regardless of a pulsar’s formation scenario (e.g., binaries or singles), location (e.g., disk or globular clusters), or spin evolution (e.g., recycling).

Faucher-Giguère & Kaspi (2006) studied isolated pulsars in the Galactic disk, and suggested that the lognormal distribution best fits the observed luminosity distribution of the canonical (i.e., non-recycled, young, isolated) pulsar population. Based on 82 isolated and binary pulsars found in several globular clusters, Hessels et al. (2007) argued that there is no significant difference in the luminosity distribution between isolated and binary pulsars. Hessels et al. (2007) also found that the luminosity distribution of globular cluster...
Pulsars can be described by a power-law distribution, which is similar to what is proposed by Cordes & Chernoff (1992) based on 22 millisecond pulsars ($P_s < 20$ ms) found in the Galactic disk. Recently, Bagchi et al. (2011) analysed about a hundred recycled pulsars found in globular clusters and fit the observed pulsar luminosity distribution with power-law and lognormal distributions. They concluded that a lognormal distribution is a slightly better fit to the observed luminosity distribution with power-law and lognormal distributions. They showed that the uncertainty in the peak rate estimate due to the choice of the pulsar luminosity distribution is less than 10 per cent (see their Appendix A for details). The simplest beam model involves only two parameters, the half-opening angle (α) and magnetic misalignment angle (ζ). Assuming all pulsars have two poles with the same beam size (Δζ = 0 for 1.9 kpc), we calculate $\alpha$ follows

$$f_b(\alpha, \rho) = 4\pi \left[\frac{2\pi}{2\rho - \frac{\pi}{2}}\right]^{-1}.$$

The magnetic misalignment angle of B is estimated based on different assumptions and techniques. Perera et al. (2012) obtained $\alpha = 61^\circ 0.7^\circ$ at 68 per cent confidence from the pulse profile analysis. Breton et al. (2008) estimated $N_{\text{pop},B} \sim 1500$. $N_{\text{pop},B}$ obtained from B-like pulsars in the Galactic disk. Considering B’s pulse profile modulation, we expect the number of B-like pulsars in the Galactic disk ranges between ~ 1300 and 1800. This can also be read as the total number of the Double Pulsar-like binaries in the Galactic disk, based on the properties of the B pulsar.

### 3.3 Effective Beaming Correction Factor

A beaming correction factor $f_b$ is defined as the inverse of the pulsar’s beaming fraction, i.e., the solid angle swept out by the pulsar’s radio beam divided by $4\pi$. The simplest beam model involves only two parameters, the half-opening angle of the beam ($\rho$) and magnetic misalignment angle ($\alpha$). Assuming all pulsars have two poles with the same beam size of $\rho$, we calculate $f_b(\alpha, \rho)$ as follows

$$f_b(\alpha, \rho) = 4\pi \left[\frac{2\pi}{2\rho - \frac{\pi}{2}}\right]^{-1}.$$

The magnetic misalignment angle of B is estimated based on different assumptions and techniques. Perera et al. (2012) obtained $\alpha = 61^\circ 0.7^\circ$ at 68 per cent confidence from the pulse profile analysis. Breton et al. (2008) estimated $\sim 1500$. $N_{\text{pop},B}$ obtained from B-like pulsars in the Galactic disk. Considering B’s pulse profile modulation, we expect the number of B-like pulsars in the Galactic disk ranges between ~ 1300 and 1800. This can also be read as the total number of the Double Pulsar-like binaries in the Galactic disk, based on the properties of the B pulsar.
\(\alpha \sim 70^\circ\) by fitting a phenomenological model with the eclipse profile of A. All estimates given in the literature are consistent within the 95 per cent confidence level (see Table 2 in Perera et al. (2010) for a summary). Assuming that other parameters needed to describe the beam geometry to be relatively constant over time (Breton et al. 2008), we adopt the best-fitting value \(\alpha = 61^\circ\) from Perera et al. (2012) as our reference.

The pulse profiles of B has dramatically changed over the five years since its discovery. This is because our line-of-sight cuts through different parts of the pulsar emission beam over time due to geodetic spin precession. We calculate B’s beaming correction factor based on its effective beam size \(\rho_s\), given a misalignment angle. We emphasize that \(\rho_s\) is different from the pulsar’s intrinsic beam size \((\rho = 14^\circ 3)\) that represents the angular radius across the semi-major axis of an elliptical beam (see Fig. 5 in Perera et al. (2012) for the schematic plot of B’s beam geometry). The effective beam size is subject to change over time depending on how the angle between B’s spin axis precesses with respect to our line-of-sight. By definition, \(\rho_s \leq \rho\).

In order to calculate \(\rho_s\) of the B pulsar, we fix the best-fitting values that describe the elliptical beam (including \(\alpha\)), and compute the pulse profile width at 10 percent of the maximum intensity \((W_{10})\) by using Eqs. (9)–(12) in Perera et al. (2012) as a function of time. Then we calculate \(\rho_s\) corresponding to \(W_{10}\) by Eq. (20) in their paper. Fig. 3 shows the obtained \(\rho_s\) over the precession time-scale of 71 years, corresponding to \(\alpha = 61^\circ\). It varies between \(5.5^\circ \leq \rho_s \leq 14.3^\circ\). In early observations, e.g., when our line-of-sight enters within B’s beam, the apparent beam size of the B pulsar is close to the intrinsic beam size of the full ellipse. As our line-of-sight moves upward to the centre of the beam over time, \(\rho_s\) becomes smaller and we obtain \(\rho_s = 5.5^\circ\) from later observations, when our line-of-sight crosses around the centre of the beam.

We calculate B’s effective beaming correction factor \(f_{b,\text{eff}}\) considering the secular change of \(\rho_s\) and the 95 per cent confidence interval for \(\alpha\) based on Perera et al. (2012). We note that the range of \(\rho_s\) remains the same between \(\alpha = [56^\circ, 77^\circ]\) that we consider. For a given value of \(\alpha\), we randomly select \(\rho_s\) between \([5.5^\circ, 14.3^\circ]\), assuming a uniform distribution. We obtain \(f_{b,\text{eff}}\) by averaging \(N = 10^5\) beaming correction factors obtained from Eq. (2).

\[
f_{b,\text{eff}} \equiv \langle f_{b,\text{i}}(\alpha, \rho_{0,i}) \rangle = \frac{1}{N} \sum_{i=1}^{N} f_{b,i}.
\]

We obtain \(f_{b,\text{eff}} = 3.7\), assuming \(\alpha = 61^\circ\).

The beam size of canonical pulsars with spin periods \(P_s > 0.1\) s can be estimated from its spin period by the empirical relation, i.e., \(\rho(P_s) \propto P_s^{-0.5}\) (e.g., Tauris & Manchester 1998, Kramer et al. 1998 and references therein). This is based on a circular beam model where the half-opening angle of the beam \(\rho\) is assumed to be constant over time. This relation is useful to estimate the beam size of pulsars with simple and stable pulse profiles, e.g., typical canonical pulsars, where our line of sight always cuts through the same part of the beam. However, the \(\rho - P_s\) relation can fail to describe the beam function of pulsars like B, when the pulse profile (i.e., the beam size) is time-dependent.

In Fig. 4 we compare the estimated \(f_{b,\text{eff}}\) based on the elliptical beam model considering the plausible range of \(\rho\) and \(\alpha\) (solid), with \(f_s\) obtained by a fixed \(\rho = 3^\circ 2\) obtained from the \(\rho - P_s\) relation (dashed) between \(\alpha = (0.90)\) degrees. The effective beaming correction factor is robust within the 95 per cent interval of \(\alpha\) between \([56^\circ, 77^\circ]\). The beaming correction factor based on the \(\rho - P_s\) relation is overestimated, regardless of the value of \(\alpha\), from what is preferred by the more realistic elliptical beam model.

As for the reference beaming correction factor for A, we follow similar steps described in Ferdman et al. (2013). However, we use pulse profiles at a more conservative 5 per cent intensity level instead of the 25 per cent used by Ferdman et al. (2013) as they allow greater sensitivity to subtle changes in the pulse profiles. By fitting each beam of the two-pole model independently to the observed pulse profiles, we obtain \(\alpha = 88^\circ 2\), \(\rho_1 = 27^\circ 2\) and \(\rho_2 = 32^\circ\). This implies \(f_{b,\text{eff}} \alpha \simeq 2\) and we use this as a reference value for A in this work. The details of the pulse profile analysis for the A pulsar will be presented in a separate paper (Perera et al. in prep.).
3.4 Bright and Weak Orbital Phases

The orbital longitudes of the bright and weak phases given in Table 1 in Perera et al. (2010) imply that each phase is observable for only \( \sim 10 - 15 \) per cent of B’s full orbital phase. The orbital longitudes of BP1, BP2, WP1, and WP2 are 190° - 235°, 260° - 300°, 340° - 30°, and 80° - 130°, respectively. This is consistent with the earlier observations made by the Parkes telescope at 1390 MHz (Burgay et al. 2003).

We introduce a dimensionless factor \( \zeta \) as the inverse of the fraction of the orbital longitudes when B is detectable. Based on the GBT observations, B was observable over only about half of the orbit, i.e., \( \zeta_B \equiv 360°/185° \sim 1.9 \). The GBT observations imply that the combined fraction of bright phases decreased over time. As we use the observable orbital longitudes measured during early observations when B appears brighter than later in time, \( \zeta \) is conservative.

The A pulsar is detectable over all phases of the 2.45 hr orbit except for the 30 s epoch (e.g., Burgay et al. 2003). Therefore, we can safely assume \( \zeta_A = 1 \). All pulsars found in the known NS-NS binaries, such as PSR B1913+16, have \( \zeta = 1 \), except the B pulsar.

3.5 Effective Lifetime

An effective lifetime of a NS-NS binary, \( \tau_{\text{life}} \), is defined

\[
\tau_{\text{life}} \equiv \tau_{\text{age}} + \tau_{\text{obs}} \quad (4)
\]

\[
\equiv \min(\tau_{\text{age}}, \tau_{\text{obs}}[1 - (P_{\text{birth}}/P_0)^{n-1}]) + \min(\tau_{\text{mrg}}, \tau_{d}),
\]

where \( \tau_{\text{age}} \) is the current age of the pulsar, determined by its current spin period and period derivative (with an assumption on its surface magnetic field), and \( \tau_{\text{obs}} \) represents the binary’s remaining observable time-scale from the current epoch.

The characteristic age \( \tau_{\text{age}} \equiv P/(n-1)\dot{P} \) is typically considered as \( \tau_{\text{age}} \) for non-recycled pulsars with spin periods of \( \sim 1 \) s like B, where \( n \) is a magnetic braking index. For recycled pulsars such as the A pulsar, however, we calculate their effective spin-down ages by \( \tau_{\text{age}} = [1 - (P_{\text{birth}}/P_i)^{n-1}] \). This is based on an assumption that current spin periods of recycled pulsars are comparable to their birth periods \( P_{\text{birth}} \) (Arzoumanian et al. 1994). We consider the effective spin-down age as the reference age estimate for all recycled pulsars used in this work. For non-recycled pulsars, we choose their characteristic age. For simplicity, we assume that all pulsars in merging binaries have surface dipole magnetic fields with magnetic braking index \( n = 3 \) and no magnetic field decay.

The Double Pulsar provides us with two age constraints from the A and B pulsars. The characteristic age of the B pulsar is \( \sim 50 \) Myr. However, Lorimer et al. (2007) suggested that the age of the B pulsar is likely to be between 50 - 190 Myr, where the upper limit is favoured by a model involving interactions between A’s wind and B’s magnetosphere (model 4). We use A’s effective spin-down age (\( \sim 140 \) Myr) as the current age of the Double Pulsar, assuming independent spin-down history for A and B for simplicity.

The remaining lifetime of the binary \( \tau_{\text{obs}} \) used in the empirical method concerns the detectability of pulsar(s) in the binary by radio pulsar surveys and is determined by either \( \tau_d \), the radio emission time-scale or the so-called ‘death-time’ (e.g., Chen & Ruderman 1993), or \( \tau_{\text{mrg}} \) is a merging time-scale of the binary due to GW emission (Peters & Mathews 1963). For the Double Pulsar, \( \tau_{\text{obs}} \) is determined by the B’s radio emission time-scale of 40 Myr. Based on what is described above, the effective lifetime of the Double Pulsar is estimated to be \( \tau_{\text{age}} + \tau_{\text{obs}} = 180 \) Myr.

For comparison, we note that Kalogera et al. (2003) used 185 Myr as the lifetime of the Double Pulsar, which is the sum of the effective spin-down age estimate for the A pulsar (\( \sim 100 \) Myr) and the binary merger time-scale (\( \sim 85 \) Myr). Their age estimate for A is based on \( P_i = 2.3 \times 10^{-18} \) ss^{-1} measured by Burgay et al. (2003), when A was discovered, O’Shaughnessy & Kim (2010) and this work adopt \( P_i = 1.74 \times 10^{-18} \) ss^{-1} from the follow-up timing observations (Kramer et al. 2006). Since 2006, there is very little change in \( P_i \) of the A pulsar.

We assume that the epochs of observation as well as the beam directions of any B-like pulsars are random. This implies that there are equal numbers of pulsars beaming toward our line-of-sight at any epoch, and hence, \( \tau_{\text{obs}} \) of B or the Double Pulsar is not affected by its geodetic precession time-scale of 71 years. Applying the same equivalent assumption to the PSR B1913+16-like pulsar population, their lifetime is defined to be \( \tau_{\text{age}} + \tau_{\text{obs}} = 370 \) Myr, even though PSR B1913+16 is expected to move away from our line-of-sight around 2025 and will return in 2220 (e.g., Kramer 1999, 2010).

4 THE GALACTIC NS-NS MERGER RATE ESTIMATES

In this section, we derive \( P(R) \) for the Double Pulsar using both A and B and calculate \( P(R) \) considering PSRs B1913+16, B1534+12, and the Double Pulsar. Table 2 summarizes reference parameters used for each NS-NS binary. We note that all the beaming correction factors are constrained by pulsar observations. For PSRs B1913+16 and B1534+12, we adopt \( \rho \) and \( \alpha \) estimated by polarization measurements (see Kalogera et al. 2001) for further details. For \( N_{\text{pop}} \) and \( C \), we show rounded values to the nearest hundreds and thousands digits. However, we show \( N_{\text{tot}} \) for all pulsars as obtained from the Monte Carlo simulations including the PALFA surveys. In addition to reference values for A and B (indicated as REF), we also show parameters and results for a case with \( f_{\text{off,A}} = 6 \) for comparison.

Kim, Kalogera, & Lorimer (2003) showed that the likelihood of detecting a pulsar like one of the known pulsars follows the Poisson distribution. In this section, we focus on the A and B pulsar-like populations (i.e., \( i = A,B \)), but this
The posterior of detecting a binary like the Double Pulsar (consisting of A and B pulsars) is therefore

$$P(\lambda_{J0737}|D_{J0737};X) \equiv P(\lambda_A, \lambda_B|D_A D_B X) = \lambda_A \lambda_B \varepsilon^{-(\lambda_A+\lambda_B)},$$

where $D_A = D_B = 1$, and therefore, $D_{J0737} = 1$ in this work. We note that it is impossible to directly calculate $P(\lambda_{J0737}|D_{J0737};X)$, as the detection of the Double Pulsar (i.e., counting of $D_{J0737}$) obtained only when both A and B are detected by pulsar observations, independently. Therefore, what we actually can calculate from the pulsar observations is $P(\lambda_A, \lambda_B|D_A D_B X)$.

Due to the different observational biases, $N_{\text{par,A}}$ and $N_{\text{par,B}}$ are not necessarily the same. Based on our results, the A pulsar is more likely to be detected than the B pulsar ($N_{\text{par,B}} < N_{\text{par,A}}$). If we correct the observational biases perfectly, however, the population sizes of the Double Pulsar ($N_{\text{pop},J0737}$) estimated by A and that based on B are to be the same:

$$N_{\text{pop,A}} = N_{\text{pop,B}} \equiv N_{\text{pop,J0737}} .$$

As shown in Table 2, the population sizes of the Double Pulsar estimated by A ($N_{\text{pop,A}} = 1400$) and B ($N_{\text{pop,B}} = 1500$), respectively, from reference parameters are consistent.

Recalling $s = 1/N_{\text{par}}$ from the linear relation $N_{\text{tot}} = s N_{\text{par}}$ and using Eq. (5), we can express $\lambda_i$ ($i = A, B$) as a function of $N_{\text{pop,J0737}}$ and the correction factors we discussed earlier.

$$\lambda_i = \frac{s_i N_{\text{pop,J0737}}}{f_{b,\text{eff}} \zeta_i} = \frac{N_{\text{pop,J0737}}}{N_{\text{par,psr}}} \equiv \frac{N_{\text{pop,J0737}}}{c_i} ,$$

where the constant $c_i$ is introduced for simplicity. Note $c_i = C_i / \tau_{\text{life,psr}}$ ($i = A, B$) and the uncertainty in $N_{\text{pop}}$ is attributed to the pulse profile change (of B) and the details of beam functions (of both A and B). The PDF for the population size of the Double Pulsar $P(N_{\text{pop,J0737}})$ can then be obtained by changing of variables from Eq. (7).

$$P(N_{\text{pop,J0737}}) = \left(\frac{(c_A + c_B)^3}{2}\right) N_{\text{pop}} \varepsilon^{-(c_A + c_B) N_{\text{pop,J0737}}} .$$

It is straightforward to calculate $P(R_{J0737})$ applying a chain rule.

$$P(R_{J0737}) = P(N_{\text{pop,J0737}}) \left| \frac{dN_{\text{pop,J0737}}}{dR_{J0737}} \right| = \left(\frac{(c_A + c_B)^3}{2}\right) R_{J0737}^2 \varepsilon^{-(c_A + c_B) R_{J0737}} \equiv P_1(R_1) .$$

### Table 2. Reference parameters and results of the NS-NS binaries considered in this work. The correction factor taking into account detectable orbital phase $\zeta$ is assumed to be unity, except the B pulsar ($\zeta = 19$). See text for the definition of all parameters.

| PSR name | $f_{b,\text{eff}}$ | $F_{\text{PMH}}$ | $\delta$ | $N_{\text{par}}$ | $N_{\text{pop}}$ | $\tau_{\text{life}}$ (Gyr) | $C$ (kyr) |
|----------|-------------------|----------------|--------|----------------|----------------|-----------------------|----------|
| A (REF)  | 2                 | 0.154          | 0.27   | 907            | 1800           | 0.18                  | 100      |
| A        | 6                 | 0.154          | 0.27   | 907            | 5400           | 0.18                  | 120      |
| B (REF)  | 3.7               | 1.0            | 0.013  | 213            | 1500           | 0.18                  | 130      |
| B1913+16 | 5.72              | 0.7            | 0.169  | 392            | 2200           | 0.37                  | 170      |
| B1534+12 | 6.04              | 0.3            | 0.04   | 253            | 1500           | 2.93                  | 1900     |

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5 Kim, Kalogera, & Lorimer (2003) used $N_{\text{obs}}$ and $N_{\text{tot}}$ instead of $D$ and $N_{\text{par}}$. Eq. (5) is the same with Eq. (7) in their paper.
We emphasize that Eqs. (10) – (11) can be used only when both NSs in the binary are detected as radio pulsars and their observational biases are reasonably well understood. (i.e., the rate coefficients of both pulsars should be well constrained and comparable). When there is only one detectable pulsar in the binary available for the rate calculation, one can follow the steps described in Kim, Kalogera, & Lorimer (2003) that result in Eq. (1). Even though the B pulsar has been known since 2004, due to the lack of information to model this pulsar, previous works used only the A pulsar’s properties that are better understood.

If all selection effects are properly accounted for, the joint PDF \( P(R_{\text{det}}) \) (based on both A and B) should have the same peak rate estimate \( R_{\text{peak}} \) predicted by the original rate equation based on the single pulsar (either A or B). In other words, the peak rate estimates of Eqs. (1) and (11) occur at \( R_{\text{peak}} = 1/C \), i.e., \( dP(R)/dR = 0 \) at \( R_{\text{peak}} = 1/C \) where \( C = C_A = C_B \). The equality in rate coefficients is satisfied when selection effects for A and B pulsars are correctly applied. As shown in Table 2, our results reasonably satisfy this condition. Based on the consistency in model assumptions and derived rate equations, our results can be directly compared with previous works based on only the A pulsar (e.g., Kalogera et al. 2004).

In Fig. 5, we plot individual PDFs for \( N_{\text{pop}} \) based on A (\( P(N_{\text{pop},A}) \)) (dotted) and B (\( P(N_{\text{pop},B}) \)) (dashed), overlaid with \( P(N_{\text{pop},\text{det}}) \) (solid). For our reference model, \( P(N_{\text{pop},A}) \) and \( P(N_{\text{pop},B}) \) are consistent. Note that \( P(N_{\text{pop},\text{det}}) \) has narrower width than those of individual PDFs, as expected. Based on the combined \( P(N_{\text{pop},\text{det}}) \), we expect there are \( \sim 1500 +4000 \) systems like the Double Pulsar in the Galactic disk at 95 per cent confidence. If we assume \( f_{\text{det}, A} = 6, N_{\text{pop},\text{det}} \sim 2000-5000 \).

Following what described in §5.2 in Kim, Kalogera, & Lorimer (2003), we can calculate the PDF of Galactic NS-NS merger rate estimates \( P_\delta(R_\delta) \). In order to do this, we need a combined PDF based on PSRs B1913+16 and B1534+12 \( P_\delta(R_\delta) \), which is derived by Kim, Kalogera, & Lorimer (2003) as follows:

\[
P_\delta(R_\delta) = \left( \frac{C_{1913} C_{1534}}{C_{1534} - C_{1913}} \right)^2 \left[ R_\delta (e^{-C_{1913} R_\delta} + e^{-C_{1534} R_\delta}) - \left( \frac{2}{C_{1534} - C_{1913}} \right) (e^{-C_{1913} R_\delta} - e^{-C_{1534} R_\delta}) \right] \quad (12)
\]

Following what described in §5.2 in Kim, Kalogera, & Lorimer (2003), we can calculate the PDF of Galactic NS-NS merger rate estimates from Eqs. (11) and (12).

\[
P_\delta(R_+^+ R_-^-) = \int_{R_-^+ R_-^-} dR_-^+ dR_-^- \frac{1}{2} P_1(R_1) P_2(R_2) = \left( \frac{C_{1913} C_{1534}}{C_{1534} - C_{1913}} \right)^3 \int_{R_-^+ R_-^-} dR_-^+ dR_-^- e^{-\left( C_A + C_B \right) R_*} \left[ R_+^+ e^{-C_{1913} R_+^+} + e^{-C_{1534} R_+^-} \right] - \left( \frac{2}{C_{1534} - C_{1913}} \right) \left( e^{-C_{1913} R_+^+} - e^{-C_{1534} R_+^-} \right),
\]

where \( R_+^+ R_-^- \equiv R_+ - R_-^{-}, R_-^+ R_-^- \equiv R_+ + R_-^{-} \), and \( R_+^+ R_-^+ \equiv R_+ + R_-^+ \). Based on the results given in Table 2, \( C_{1913} < C_A + C_B < C_{1534} \).

Based on our merger rate estimates, we calculate the GW detection rate for NS-NS inspirals with ground-based interferometers by

\[
R_{\text{det}} = R_\delta \times N_\text{G},
\]

where \( N_\text{G} \equiv (4/3) (d_{h,\text{Mpc}}^2 / 2.26)^3 (0.0116) \) is the number of Milky Way equivalent galaxies that would contain NS-NS binaries within the detection volume of the advanced ground-based GW detectors and \( d_{h,\text{Mpc}} = 445 \) Mpc is the horizon distance for NS-NS inspirals with the advanced LIGO-Virgo network (Abadie et al. 2010). See Eq. (5) and Table 5 in their paper for more details.

Fig. 5 shows \( P_\delta(R_\delta) \) (solid) along with the individual PDFs of rate estimates for PSRs B1913+16 (dotted) and the Double Pulsar (short dashed). Although we consider PSR B1534+12 in the rate calculation, we do not show the PDF for PSR B1534+12 in Fig. 6 for clarity. Throughout this paper, we use Eq. (11) to calculate \( P(R) \) for PSRs B1913+16 and B1534+12 as there is only one known pulsar component in these binaries. The PDF for the Double Pulsar is obtained from Eq. (11) constrained by both \( C_A \) and \( C_B \).

We note that, although we assume \( N_{\text{pop},A} = N_{\text{pop},B} = N_{\text{pop,\text{det}}} \) to calculate Eqs. (10) and (11), we incorporate individually estimated \( C_{\text{pop,}A} = 100 \) kyr and \( C_{\text{pop,}B} = 120 \) kyr to plot Figs. 5 and 6 (see Table 2). The lifetime of the Double Pulsar is estimated to be 180 Myr as described in §4.5.

Our reference model implies \( R_\delta = 21^{+26}_{-14} \) Myr\(^{-1}\), and (13) \( R_{\text{det}} = 8^{+10}_{-5} \) yr\(^{-1}\). If we assume \( f_{\text{det}, A} = 6 \), as used in some of the previous work, we obtain \( R_\delta = 26^{+33}_{-17} \) Myr\(^{-1}\), and \( R_{\text{det}} = 10^{+12}_{-6} \) yr\(^{-1}\). All results in this section are given at the 95 per cent confidence interval.
5 DISCUSSION

In this work, we model four pulsars (PSRs 1913+16, 1534+12, J0737−3039A and J0737−3039B) that represent three NS-NS binaries in the Galactic disk, following similar steps described by [Kim, Kalogera, & Lorimer (2003)] (see §2-4 in their paper for details). For the first time, we model the non-recycled B pulsar in the Double Pulsar using the 5-yr GBT observations and derive $P(R_{\text{J0737}})$ for the Double Pulsar based on both A and B (Eq. (16)). Assuming the three pulsar binaries fully represent the Galactic NS-NS population, we calculate $P_\text{g}(R_g)$ as well as the corresponding GW detection rates for advanced ground-based GW detectors.

Based on our reference model, we obtain $R_g = 21^{+14}_{-14} - 17$ Myr at 95 and 99 per cent confidence intervals. The peak rate estimate is smaller than what previously known (e.g., Kalogera et al. 2004). This is mainly due to the smaller beaming correction factors estimated for A and B. In addition, the single discovery of a NS-NS binary from the PALFA precursor survey that has a large field of view and better sensitivity than previous surveys is attributed to the estimated $N_{\text{psr}}$ of each pulsar being smaller by a factor $1.5 - 1.7$ from those given in O'Shaughnessy & Kim (2010). We note that the contributions from the Double Pulsar and PSR B1913+16 are comparable and no single binary dominates the Galactic NS-NS merger rate.

Motivated by the independent constraints from the B pulsar such as $P(N_{\text{pop}})$, we believe that A’s beam is likely to be wider than those of PSRs B1913+16 ($\rho = 12^\circ 4$) and B1534+12 ($\rho = 4^\circ 87$). Furthermore, the long-term observations of PSRs B1913+16, J1141−6545 and the Double Pulsar (through A and B) imply that individual pulsar beam patterns can be quite different. In this work, we consider the three pulsar binaries with the best observational constraints.

Systematic uncertainties related to the pulsar population modelling (e.g., distribution of pulsars in the Galactic disk, radio pulsar luminosity distribution, current age of the Double Pulsar) are studied by [Kim, Kalogera, & Lorimer (2003), Kim, Kalogera, & Lorimer (2010), and O'Shaughnessy & Kim (2010)]. Here, we examine systematic uncertainties in the rate estimates, focusing on the two relatively least constrained parameters for the Double Pulsar, $t_{\text{life}}$ and $N_{\text{par, b}}$ within the plausible range. The lifetime for the Double Pulsar ranges between $t_{\text{life}} \sim 90 - 230$ Myr, and $N_{\text{par, b}} \sim 190 - 270$ (or $N_{\text{pop, b}} \sim 1300 - 1900$) attributed to uncertainties in B’s radio emission time-scale and different duty cycles due to geodetic precession. We consider two extreme cases: (a) B-like pulsars with broad pulse profile ($\delta = 0.03$, $N_{\text{pop}} \sim 1900$) and longest plausible lifetime of $t_{\text{life}, \text{J0737}} = 230$ Myr, and (b) those with narrow pulse profile ($\delta = 0.005$, $N_{\text{pop}} \sim 1300$) and the reference binary lifetime $t_{\text{life}, \text{J0737}} = 180$ Myr. All other parameters are fixed to our reference model. For the parameters we explore, the peak values of $R_g$ range between $\sim 17 - 27$ Myr$^{-1}$. The lower and upper limits at 95 per cent confidence are obtained to be $R_g \sim 5$ and $\sim 60$ Myr$^{-1}$, respectively. Although it is not very likely, if the lifetime of the Double Pulsar is as short as 90 Myr motivated by B’s characteristic age, $R_g = 36_{-26}^{+39}$ Myr$^{-1}$ at 95 per cent confidence.

Although we do not include PSR J1906+0746 in the rate calculation, we consider its contribution to the Galactic NS-NS merger rate, based on the detected non-recycled pulsar. If we take $N_{\text{psr}} \sim 200$ and $f_{\text{b}, \text{J1906}} \sim 3 - 5$ (based on the empirical $\rho - P_s$ relation) given by O'Shaughnessy & Kim (2010), we obtain $N_{\text{pop}} \sim 600 - 1000$ for the PSR J1906+0746-like pulsar population. As PSR J1906+0746 is detectable at all orbital phases (Kasian 2012), we can assume $\zeta = 1.0$. The rate coefficient of this pulsar is $\sim 80 - 130$ kyr based on the estimated $N_{\text{pop}}$ and its lifetime of $\sim 80$ Myr. The lifetime of PSR J1906+0746 is determined by its characteristic age and radio emission time-scale with no magnetic field decay. As of 2008, PSR J1906+0746 shows only mild pulse profile changes compared with those of B (Desvignes et al. 2008). Therefore, it is difficult to constrain the beaming correction factor of this pulsar based on the pulse profile analysis.

PSR J1756−5521 is also not included in this work. Kim, Kalogera, & Lorimer (2010) and O'Shaughnessy & Kim (2010) calculated $P(R)$ for this pulsar. It is arguably the most uncertain among the known NS-NS binaries, because the selection effects for acceleration search that discovered this pulsar are only approximated in modelling. The contribution from PSR J1756−5521 is expected to be roughly a few per cent in $R_g$ (Kim, Kalogera, & Lorimer 2010) and is comparable to that of PSR B1534+12 (see fig. 7 in O'Shaughnessy & Kim 2010), if its beam function follows the empirical $\rho - P_s$ relation.

In order to calculate the true contribution of the known pulsar binaries to the Galactic NS-NS merger rate estimates, we call for a more realistic surface magnetic field and/or ra-

![Figure 6. $P_\text{g}(R_g)$ (solid) is overlaid with individual $P(R)$ obtained from PSR B1916+13 (dotted) and the Double Pulsar (short dashed). Based on our reference model, the Galactic NS-NS merger rate is most likely to be 21 Myr$^{-1}$. The corresponding GW detection rate for the advanced ground-based GW detectors is $\sim 8$ yr$^{-1}$.](image-url)
More discoveries of relativistic NS-NS binaries is also important. Large-scale pulsar surveys with unprecedented sensitivity such as the LOFAR (LOw Frequency ARray, van Leeuwen & Stappers 2010) and the planned Square Kilometer Array (Smits et al. 2009) are expected to find more NS-NS binaries. In addition to electromagnetic wave surveys, GW detection will provide a completely new, independent probe for relativistic NS-NS binaries. When the ground-based GW detectors start detecting NS-NS binaries or pulsar-black hole binaries, those observed GW detection rate will be useful to further constrain the pulsar population models.

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REFERENCES

Abadie, J. et al., LIGO Scientific Collaboration, Virgo Collaboration, 2010, Class. & Quantum Grav., 27, 173001
Arzoumanian, Z., Cordes, J. M. & Wasserman, I., 1999, ApJ, 520, 696
Bagchi, M., Lorimer, D. R., Chennamangalam, J., 2011, MNRAS, 418, 477
Barker, B. M., & O’Connell, R. F., 1975, Phys. Rev. D., 12, 329
Breton, R. P., et al., 2008, Science, 321, 104
Burgay, M. et al., 2003, Nature, 426, 531
Burgay, M. et al., 2005, ApJ, 624, L113
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 (Erratum: 2011, MNRAS, 412, 2816)
Champion, D. J., Lorimer, D. R., McLaughlin, M. A., Cordes, J. M., Arzoumanian, Z., Weisberg, J. M., Taylor, J. H., 2004, MNRAS, 350, L61
Chen, K. & Ruderman, M., 1993, ApJ, 402, 264
Contopoulos, I. & Spitkovsky, A., 2006, ApJ, 643, 1139
Cordes, J. M. & Chernoff, D. F., 1997, ApJ, 482, 971
Cordes, J. M. et al., 2006, ApJ, 637, 446
Curran, S. J. & Lorimer, D. R., 1995, MNRAS, 276, 347
Demorest, P., Ramachandran, R., Backer, D. C., Ransom, S. M., Kaspi, V., Arons, J., Spitkovsky, A., 2004, ApJ, 615, L137
Desvignes, G., Cognard, I., Kramer, M., Lyne, A., Stappers, B., Theureau, G., 2008, AIP Conf. Proc. eds. C. Bassa, Z. Wang, A. Cumming, & V. M. Kaspi, 983, 482
Faucher-Giguère, C.-A. & Kaspi, V. M., 2006, ApJ, 643, 332
Faulkner, A. J. et al., 2005, ApJ, 618, L119
Ferdman, R. D. et al., 2008, in AIP Conf. Proc., eds. C. Bassa, Z. Wang, A. Cumming, & V. M. Kaspi, 983, 474
Ferdman, R. D. et al., 2013, ApJ, 767, 85
Hessels, J. W. T., Ransom, S. M., Stairs, I. H., Kaspi, V. M., Freire, P. C. C., 2007, ApJ, 670, 363
Hulse, R. A. & Taylor, J. H., 1975, ApJ, 195, L51
Kalogera, V., Narayan, R., Spergel, D. N., Taylor, J. H., 2001, ApJ, 556, 340
Kalogera, V., et al., 2004, ApJ, 601, L179
Kasian, L., PhD thesis, 2012
Kim, C., Kalogera, V., Lorimer, D. R., 2003, ApJ, 584, 985
Kim, C., Kalogera, V., Lorimer, D. R., 2010, New Astro. Rev., 54, 148
Kramer, M., Xilouris, K. M., Lorimer, D. R., Doroshenko, O., Jessner, A., Wielebinski, R., Wolszczan, A., Camilo, F., 1998, ApJ, 501, 270
Kramer, M., 1998, ApJ, 509, 856
Kramer, M., et al., 2006, Science, 314, 97
Kramer, M., 2010, to be published in proceedings of the 12th Marcel Grossmann meeting (eprint arXiv:1008.5032)
Lorimer, D. R., et al., 2006, ApJ, 640, 428
Lorimer, D. R., et al., 2007, MNRAS, 379, 1217
Lyne, A. G., et al., 2004, Science, 303, 1153
Lyutikov, M., 2005, MNRAS, 362, 1078
Manchester, R. N., et al., 2001, MNRAS, 328, 17
Narayan, R., Piran, T., Shemi, A., 1991, ApJ, 379, L17
O’Shaughnessy, R. & Kim, C., 2010, ApJ, 715, 230
Peters, P. C. & Mathews, J., 1963, Phys. Rev. D., 131, 435
Perera, B. B. P., Lorimer, D. R., Lyutikov, M., 2010, ApJ, 721, 1193
Perera, B. B. P., et al., 2012, ApJ, 750, 130
Perera, B. B. P., Kim, C., McLaughlin, M. A., Fordman, R. D., Kramer, M., Stairs, I. H., Freire, P. C. C., Possenti, A., 2013, in prep.
Phinney, E. S., 1991, ApJ, 380, L17
Smits, R., Kramer, M., Stappers, B., Lorimer, D. R., Cordes, J., Faulkner, A., 2009, A&A, 493, 1161
Stairs, I. H., Thorsett, S. E., Dewey, R. J., Kramer, M., & McPhee, C. A., 2006, MNRAS, 373, L50
Tauris, T. M. & Manchester R. N., 1998, MNRAS, 298, 625
van Leeuwen, J. & Stappers, B. W., 2010, MNRAS, 402, 1254
Wolszczan, A., 1991, Nature, 350, 688