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

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Motivation: NS-NS binaries as GW sources

- There are four confirmed neutron star - neutron star (NS-NS) binaries in the Galactic disk
- All NS-NS binaries have been discovered by radio pulsar surveys (PSRs B1913+16, B1534+12, J1756−2251, and J0737−3039)
- NS-NS binaries are one of the prime targets for gravitational-wave (GW) detectors
- The detection rate of NS-NS inspirals via GWs can be inferred by the expected merger rate of known NS-NS binaries, accounting for observational biases for pulsar surveys

NS-NS inspiral detection rate = NS-NS merger rate in Milky Way X # density of Milky Way-like galaxies within the detection volume of the second generation interferometers

Our Work

- considers PSRs B1913+16, B1534+12, and J0737-3039A and B
- uses best observational constraints and obtains beaming correction factors ($f_{b,eff}$) for the A and B pulsars
- simulates 22 large-scale pulsar surveys including the PALFA (Arecibo L-band Feed Array) precursor survey (Cordes et al. 2006) and Parkes multibeam high-latitude survey (Burgay et al. 2006)
- adopts the horizon distance for NS-NS inspirals (445 Mpc) from Abadie et al. (2010)

$$\mathcal{R}_{\rm g} = 20^{+26+38}_{-13-16}\ {\rm Myr}^{-1} \qquad \mathcal{R}_{\rm det} = 7^{+10+14}_{-5\ -6}\ {\rm yr}^{-1}$$ at 95, 99% C.L.

Galactic NS-NS merger rate based on pulsar binaries — **GW detection rate for NS-NS inspirals**

The Double Pulsar (PSR J0737−3039)

contains two radio active pulsars

A pulsar (Burgay et al. 2003): first-born, recycled, spin period=22.7 ms
B pulsar (Lyne et al. 2004): second-born, non-recycled, spin period=2.77s

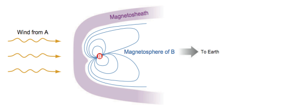
provides the best indirect evidence of gravitaiontal waves (Kramer et al. in prep)

Table 1. Observational and estimated properties of A and B

PSR	P_s (ms)	$\dot{P}_s 10^{-18}$ (ss^{-1})	M_{psr} $(M_\odot)$	spin-down age (Gyr)	merger timescale(Gyr)	radio emission timescale(Gyr)
A	22.7	1.74	1.34	0.14	0.09	>14
B	2770	892	1.25	0.05 – 0.19	0.09	0.04

observable lifetime of the Double Pulsar = spin-down age of A + radio emission timescale of B

Selection effects for the B pulsar

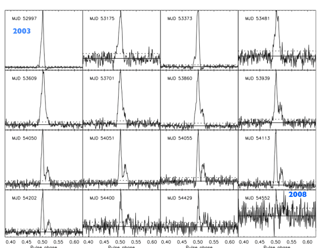


[Schematic plot of the B's magnetosphere with the wind from A]

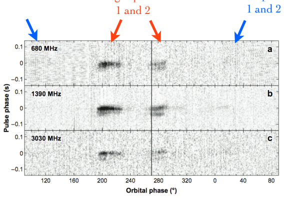
B is observable for only ~50% of orbital phase

fraction of the observable orbital phase for the B pulsar

$$\zeta_{\rm B} = 1.9 \sim \frac{360^\circ}{\sum \text{observable orbital phase}^\circ}$$



[Mean pulse profile change of one of the two bright phases (BP1) of the B pulsar from 5-yr observations with the Green Bank Telescope (Perera et al. 2012)]

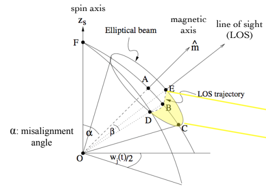


[B's pulse phase vs orbital phase as shown in Lyne et al. (2004) Orbital phases of two bright and weak phases are indicated by red and blue arrows, respectively.]

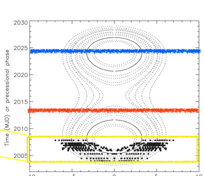
Pulse profile change is mainly attributed to geodetic precession
B pulsar is undetectable since March 2008!
Geodetic precession timescale ~ 71 yrs $\Omega_{\rm prec} = 5^\circ\!.061(2){\rm yr}^{-1}$

Elliptical beam model for the B pulsar

[B's beam geometry (Perera et al. 2012)]



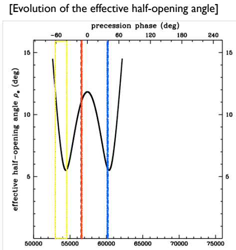
[2-d pulse profile of BP1 (Perera et al. 2012)]



B was observable

- We adopt the model suggested by Perera et al. (2012), based on a partially-filled radio beams (shaded region in the plot above)
- We calculate the **effective half-opening angle ρ$_e$** (black solid curve in the right figure), which is the **apparent beam size** as our LOS cuts the beam. It is almost the same with the intrinsic semi-major axis of the beam ellipse (~15°) when B was discovered (∠AOC) and decreased over time up to the minimum (~5°) predicted by the model (∠AOB).
- We **fix α = 61°** (best-fit value from Perera et al. 2012) and **calculate the effective beaming correction factor $f_{b,eff}$ for B**
- The model cannot explain nondetection of the emission beam
- B's reappearance time will be useful to further constrain the beam geometry: 2013 (red line) or 2024 (blue line)

[Evolution of the effective half-opening angle]



Probability density function (PDF) of NS-NS merger rate $\mathcal{R}$

$$\mathcal{P}(\mathcal{R}) = \left(\frac{\tau_{\rm life}}{N_{\rm pop}}\right)^2 \mathcal{R}\exp\left[-\frac{\tau_{\rm life}}{N_{\rm pop}}\mathcal{R}\right] \equiv C^2\mathcal{R}\exp[-C\mathcal{R}] \qquad (1)$$

This is $\mathcal{P}(\mathcal{R})$ based on **one pulsar in the binary** (e.g., Kim et al. 2003)

The rate coefficient C contains the information on binary and pulsar properties

$N_{\rm pop} \equiv N_{\rm psr}\zeta f_{\rm b,eff}$	population size of the binary in the Milkey Way corrected for selection biases of an individual pulsar (e.g., A only or B only)
$N_{\rm psr}$	number of pulsars brighter than telescope thresholds among those beaming toward us
$f_{\rm b,eff}$	effective beaming correction factor
$\tau_{\rm life}$	observable lifetime of the binary (by pulsar surveys)

N_{psr} is obtained by pulsar survey simulations for each known pulsar, assuming a pulsar population model

For the Double Pulsar we derive $\mathcal{P}(\mathcal{R}_{J0737})$ constrained by both A and B where $C_{\rm J0737} \equiv C_{\rm A} + C_{\rm B}$

$$\mathcal{P}(\mathcal{R}_{\rm J0737}) = \frac{C^3_{\rm J0737}}{2}\,\mathcal{R}^2_{\rm J0737}\,{\rm e}^{-C_{\rm J0737}\mathcal{R}_{\rm J0737}} \qquad (2)$$

$f_{b,eff,A} = 1.55$ O'Shaughnessy & Kim (2010)
$f_{b,eff,B} = 3.6$ This work
and we fix τ_{life}=180 Myr for the Double Pulsar

The PDF of the Galactic NS-NS merger rate is obtained from Eq. (3). We use Eq. (1) for binaries containing pulsars like PSRs B1913+16 and B1534+12, and use Eq. (2) for the Double Pulsar-like binaries

$$\mathcal{P}(\mathcal{R}_{\rm g}) = \int \prod_{\rm i=1}^{\rm N=3} d\mathcal{R}_{\rm i}\mathcal{P}_{\rm i}(\mathcal{R}_{\rm i})\,\delta\left(\mathcal{R}_{\rm g} - \sum_{\rm i=1}^{\rm N=3}\mathcal{R}_{\rm i}\right) \qquad (3)$$

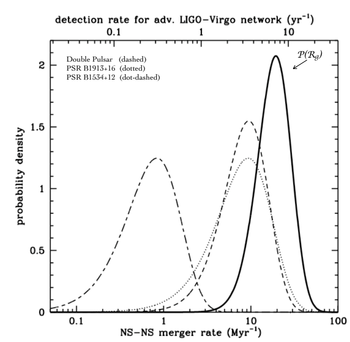


Table 2. Reference parameters and N_{psr} from Monte-Carlo simulations used to calculate the rate coefficient for each pulsar.

PSR name	$f_{\rm b,eff}$	ζ	$N_{\rm psr}$	$N_{\rm pop}$	$\tau_{\rm life}$ (Gyr)	C (kyr)
A pular	1.55	1	907	1400	0.18	130
B pulsar	3.6	1.9	213	1500	0.18	120
B1913+16	5.72	1	392	2200	0.37	170
B1534+12	6.04	1	253	1500	2.93	1900

Note: Although the A pulsar is easier to detect than the B pulsar, the population sizes (N_{pop}) of the Double Pulsar based on A and B, corrected for the observational biases respectively, are consistent

Summary

- Observational constraints favor $f_{b,eff}$ ~2 (A pulsar) and ~4 (B pulsar)
- No single binary (or pulsar) dominates the Galactic NS-NS merger rate estimates
- Beam functions of individual pulsars can be diverse
- We expect NS-NS inspiral detection would likely be on a **monthly basis** with advanced detectors
- Feedback from GW detection will be invaluable to constrain pulsar population models as well as beam functions of pulsars used in the rate estimates

Appendix: $\mathcal{P}(\mathcal{R}_{J0737})$ calculation

We require all Double Pulsar-like binaries have A-like and B-like pulsars and calculate the likelihood for the Double Pulsar (likelihood$_{J0737}$)

$$\text{likelihood}_{\rm J0737} \propto \text{likelihood}_{\rm A} \times \text{likelihood}_{\rm B}\,, \qquad \mathcal{L}(\bar{N}_{\rm J0737}) \propto \bar{N}_{\rm A}e^{-\bar{N}_{\rm A}} \times \bar{N}_{\rm B}e^{-\bar{N}_{\rm B}} \qquad (4)$$

individual pulsar's likelihood follows the Poisson distribution; we have $\bar{N}_{\rm A} = \bar{N}_{\rm B} = \bar{N}_{\rm J0737} = 1$ from pulsar observations.

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

$$N_{\rm pop,i} \propto \bar{N}_{\rm i}\ ({\rm i = A, B})\ \text{and}\ N_{\rm pop,J0737} \propto \bar{N}_{\rm J0737}$$

population size of the Double Pulsar based on A only ($N_{pop,A}$) and B only ($N_{pop,B}$) should be consistent; we define # of binaries like Double Pulsar in the Milky Way to be $N_{pop,J0737}$

N_{pop} is linearly proportional to the average number of detected pulsars ($\bar{N}$) like ecah known pulsar (Kim et al. 2003)

Using the above relations, we can express Eq. (4) based on parameters related to individual pulsars (A and B) and convert $\mathcal{L}(\bar{N}_{J0737})$ to $\mathcal{P}(N_{pop,J0737})$ and $\mathcal{P}(\mathcal{R}_{J0737})$ (Eq. 2) by the chain rule

References

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