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Pulsar Binaries as Gravitational-Wave Sources: Rate predictions

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Abstract

Pulsar binaries are important targets for ground-based and future space-borne gravitational-wave (GW) detectors. In order for improving detector design and assessing detector performances, it is a prerequisite to understand the astrophysics of GW sources such as the population size or merger rates. Here, we summarize recent results for Galactic merger rates of two known types of pulsar binaries: (a) double-neutron star-system (DNS) and (b) neutron star-white dwarf (NS–WD) binaries. Based on the merger rate estimates, we discuss prospects for the ground-based interferometers considering LIGO (Laser Interferometer Gravitational-wave Observatory) and space mission LISA (Laser Interferometer Space Antenna).

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I. INTRODUCTION

Compact binaries in close orbits have drawn attention from the GW community due to their implications for a *direct* measurement of gravitational waves on the ground and in space [1]. All ground-based GW detectors are optimized to detect signals from compact binaries at around 100 − 1000 Hz of frequency band. As of summer 2008, several ground-based detectors based on the interferometry are operational around the world, such as the German-British GEO600 [2] and the French-Italy VIRGO [3], and the Japanese TAMA300 [4], and the LIGO in the United States [5]. The LIGO observatories have been running at the design sensitivity since Fall 2005 [6]. In space, when the planned mission LISA will be launched, it will be possible to detect GWs from compact binaries in our Galaxy as well as in cosmological distances [7]. LISA is a joint programme funded by NASA (National Aeronautics and Space Administration) and ESA (European Space Agency) and scheduled to be launched around 2015. With its low detection frequencies (0.01 mHz - 0.1 Hz), LISA will be complementary with the ground-based detectors.

Pulsar binaries, a subset of compact binaries, provide the indirect evidence of the existence of GWs. The Hulse-Taylor pulsar (PSR B1913+16) is the first DNS system found in our Galaxy [8]. The thirty-year observations of the advance of periastron of PSR B1913+16, i.e. effectively a measure of an orbital decay rate, are in extremely good agreement with the prediction from general relativity within 0.03% accuracy [9]. In this paper, we focus on two types of pulsar binaries in the Galactic disk: (a) DNS systems and (b) NS–WD binaries. In particular, we will consider binaries that have merging timescales shorter than a hubble time. We will define them to be *merging* binaries. As of September 2008, eight DNS systems are known in the Galactic disk including the recently discovered DNS candidate (PSR J1906+0746 [10]). Amongst, five DNS systems are in tight orbits and will merge within a Hubble time. There are more than ~ 40 NS–WD binaries known in our Galaxy and only three of them are merging binaries in the disk. The observed properties of merging pulsar binaries considered in this work are listed in Table 1 (see [11, 12] for comprehensive reviews on currently known pulsar binaries in our Galaxy).

A merger rate of a given pulsar binary can be defined as follows: $\mathcal{R} \equiv N_{\rm pop}/\tau_{\rm life}$, where $N_{\rm pop}$ is the number of binaries in the Galactic disk and $\tau_{\rm life}$ is a representative lifetime of a binary. We consider one pulsar at a time, PSR B1913+16 for example, and calculate a

P($\mathcal{R}$) relevant to only the selected binary. We generate a large number ($\sim 10^5$) of model pulsars that follow spatial and luminosity distributions defined by a pulsar model. All model pulsars are assumed to have different positions and luminosities, but have the same binary characteristics, lifetime, and pulse profile with those of PSR B1913+16. We calculate how many of model pulsars are detectable for a given population size $N_{\rm pop}$, by comparing flux densities of model pulsars and survey thresholds of different large-scale pulsar surveys such as Parkes multibeam survey [13]. We found that the likelihood function of detected pulsars follows Poisson, as expected. We calculate the most likely value of $N_{\rm pop}$, which is a best-fit to the Poisson distribution based on the fact that there is only one known sample (namely, PSR B1913+16). Using a Bayesian analysis method, we calculate a PDF of the $N_{\rm pop}$ of PSR B1913+16-like pulsars. P($N_{\rm pop}$) can then be easily converted to P($\mathcal{R}$) using the definition of merger rate and a chain rule. Obtaining a PDF of the merger rate estimates is a main difference between this work and the rate estimates obtained empirically from previous studies [14–19]. More details including a calculation of P($\mathcal{R}$) are shown in [20, 21].

In this paper, we show how one can calculate P($\mathcal{R}_{\rm gal}$), a probability density function (PDF) of the Galactic merger rate, of pulsar binaries. Based on the merger rate estimates, we infer the GW detection rates of DNS inspirals for LIGO and examine the contribution of NS–WD binaries to the GW background for LISA.

II. GALACTIC DNS MERGER RATE AND THE GW DETECTION ON THE GROUND

When two neutron stars in a DNS system merge, they are expected to emit strong gravitational radiation that can be detected by ground-based interferometers such as LIGO [22]. The GW detection rate relevant to DNS inspirals for a detector can be inferred from Galactic DNS merger rate, assuming a detector's sensitivity. A $P(\mathcal{R})$ obtained for a given pulsar binary can be written as follows:

$$P(\mathcal{R}) = C^2 \; \mathcal{R} \; e^{-C\mathcal{R}} \; , \tag{1}$$

The coefficient C depends on observed properties of the pulsar binary

$$\mathcal{C} \equiv \left(\frac{\tau_{\rm life}}{N_{\rm pop} f_{\rm b}} \right) \; . \tag{2}$$

$\tau_{\rm life}$ can be derived based on observed properties of the pulsar binary (e.g., ~230 Myr for PSR J0737-3039A). We calculate $N_{\rm pop}$ following the steps described in a previous section. In this work, we calculate $N_{\rm pop}$ for the reference pulsar model [23, 24]. $f_{\rm b}$ is a correction factor for the pulsar beaming fraction. We calculate $f_{\rm b}$ for PSRs B1913+16 ($f_{\rm b} = 5.7$) and B1534+12 ($f_{\rm b} = 6.0$) and use an average value of $\simeq$6 (corresponding to a 17% of the beaming fraction) for PSRs J0737-3039A and J1906+0746 as the beaming fraction of these pulsars are not known. Once the individual PDFs for each DNS system are at hand, a PDF for Galactic DNS merger rate can be calculated by the following equation.

$$\begin{aligned}\mathcal{P}(\mathcal{R}_{gal}) &= \int d\mathcal{R}_1 d\mathcal{R}_2 d\mathcal{R}_3 d\mathcal{R}_4 \delta(\mathcal{R}_{gal} - \mathcal{R}_1 - \mathcal{R}_2 - \mathcal{R}_3 - \mathcal{R}_4) \\ &\times \mathcal{P}_1(\mathcal{R}_1)\mathcal{P}_2(\mathcal{R}_2)\mathcal{P}_3(\mathcal{R}_3)\mathcal{P}_4(\mathcal{R}_4)\ . \end{aligned} \tag{3}$$

In this work, we consider four known DNS systems in the Galactic disk, i.e. PSRs B1913+16, B1534+12, J0737-3039A, and J1906+0746. We note that the contribution from a DNS that is not considered in this work, PSR J1756–2251, to the Galactic merger rate is at most a few percent [24]. PSR J1906+0746 was recently discovered in the ALFA (Arecibo L-band Feed Array) pulsar survey [10]. The nature of its companion is not completely confirmed to be a neutron star at the moment, but recent timing observations point toward that PSR J1906+0746 is likely to be another DNS system [25]. If indeed PSR J1906+0746 is the fifth DNS system found in the disk, this is the first discovery of the second-born neutron star in a DNS system. Based on the reference model, we found that the discovery of PSR J1906+0746 increase the estimated Galactic DNS merger to $\mathcal{R}_{\rm peak} = 118^{+258}_{-92}$ Myr^{-1} (Figure 1). The upper and lower limits correspond to a 99% confidence interval. The inferred detection rates for initial and advanced LIGO correspond to a 99% confidence interval are $\mathcal{R}_{\rm det,ini} = 0.05^{+0.1}_{-0.04}$ yr^{-1} and $\mathcal{R}_{\rm det,adv} = 265^{+580}_{-208}$yr^{-1}, respectively. Therefore, we expect that the detection rate of DNS inspirals for the advanced LIGO is most likely to be a few per month. Importantly, even for the most pessimistic model, we found that the advanced LIGO will detect a few DNS inspiral events per year at a 99% confidence level. In order to calculate the detection rates for LIGO, we assume a constant DNS merger rate and a homogeneous distribution of galaxies within a detection volume of LIGO. We assume maximum detection distances of initial and advanced LIGO to be $\simeq$ 20Mpc and 350Mpc, respectively [26].

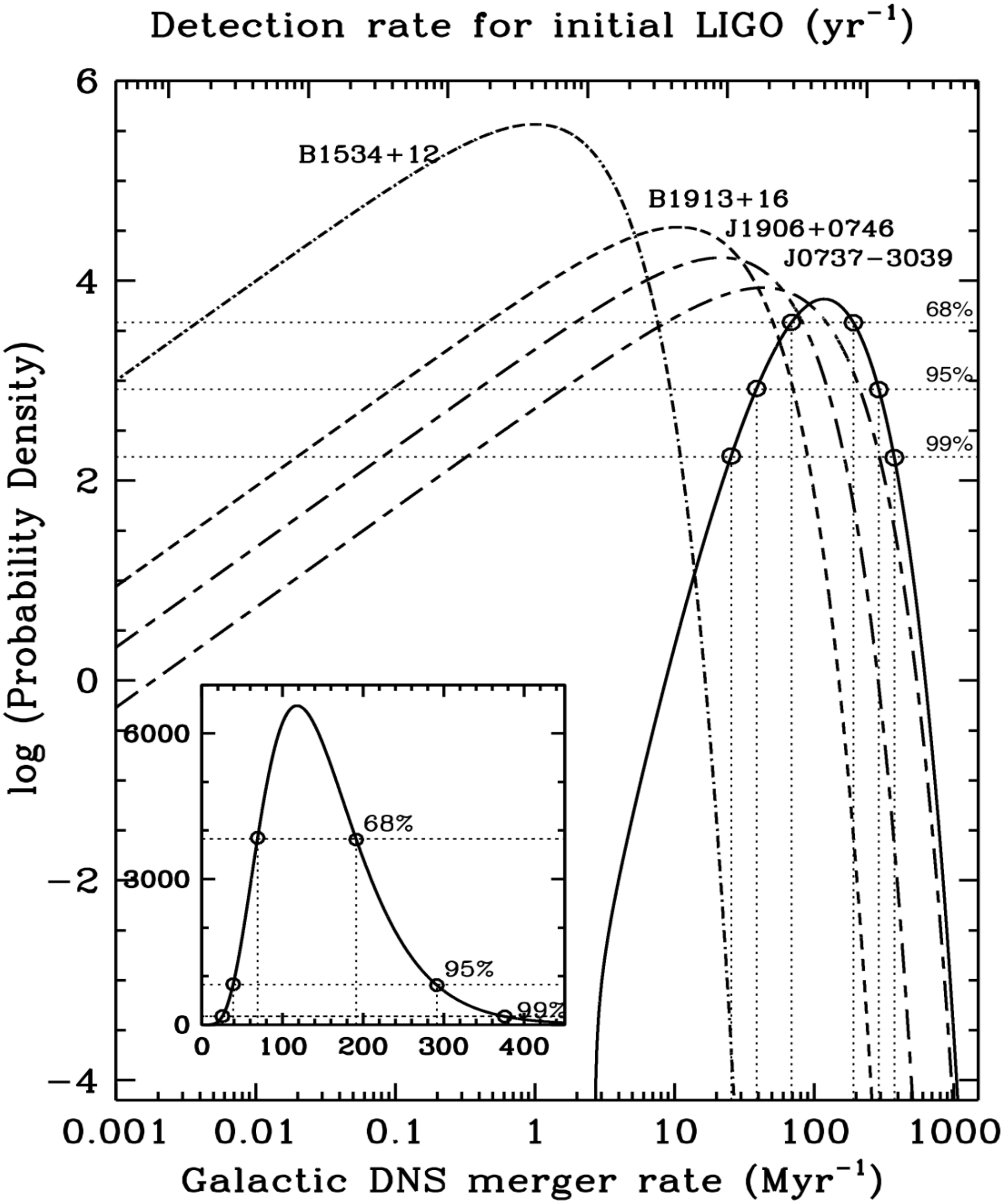

FIG. 1: The PDFs of the DNS merger rate estimates are shown in a log scale. An inset is shown the P($\mathcal{R}_{\rm gal}$) in a linear scale. The solid curve represent the P($\mathcal{R}_{\rm gal}$) and dashed curves correspond to P($\mathcal{R}$) for individual binaries. The logarithmic curves show that PSRs J0737-3039A and J1906+0746 dominate the Galactic DNS rate estimates. As shown in a linear scale, P($\mathcal{R}_{\rm gal}$) is highly peaked. The most likely rate estimate is found at around 120 Myr^{-1}. The results shown here are obtained from our reference pulsar model. The beaming correction factor (=1/beaming fraction) is assumed to be roughly 6 for all four pulsars considered in this work.

III. NS–WD BINARIES AND LISA

Close binaries consisting of compact objects including NS–WD binaries are suggested to be important GW sources in a frequency range below 1 mHz. Due to a large number of sources, however, LISA would not be able to resolve each source within a given frequency band. Hence the Galactic binaries are expected to establish a confusion noise level dominated by WD-WD binaries [27–30]. Motivated by this Galactic background, we estimate the contribution of NS–WD binaries to the GW background. We compare the GW amplitude inferred by the number of NS–WD binaries in the nearby Universe with the LISA sensitivity curve (http://www.srl.caltech.edu/ shane/sensitivity/MakeCurve.html). The GW background generated by NS–WD binaries is proportional to their population size within a given volume. Following similar calculations described in I. Introduction, we calculate $\mathrm{P}(N_{\mathrm{pop}})$ and $\mathrm{P}(\mathcal{R}_{\mathrm{gal}})$ for NS–WD binaries considering three known binaries (see Table 1). With no correction for pulsar beaming, the peak merger rate of Galactic NS–WD binaries is estimated to be a few Myr^{-1} based on the reference pulsar population model. Then we extrapolate the population size by integrating a number density of NS–WD binary up to red shift 5, which corresponds an onset of the first Galaxy. We note that no beaming correction is applied for NS–WD binaries, as the beaming fraction for these pulsars are not poorly constrained. As we shown in Figure 2, the inferred contribution from NS–WD binaries to the predicted LISA confusion level is not significant, unless the pulsars in NS–WD binaries are highly beamed. The results shown in Figure 2 obtained with no beaming correction. Details on this work can be found in [31].

IV. CONCLUSIONS

We summarize recent results on the Galactic merger rate of DNS and NS–WD binaries and discuss their implications for the GW detection. Assuming PSR J1906+0746 is a DNS system, we expect that the advanced LIGO will definitely be able to detect gravitational waves relevant to DNS inspirals, more than a few events per year up to a few events per day with the most optimistic model at a 99% confidence level. The expected contribution from NS–WD binaries to the LISA noise level is found to be negligible, but the results are subject to the pulsar beaming fraction. GW astronomy is still in the early stages of development,

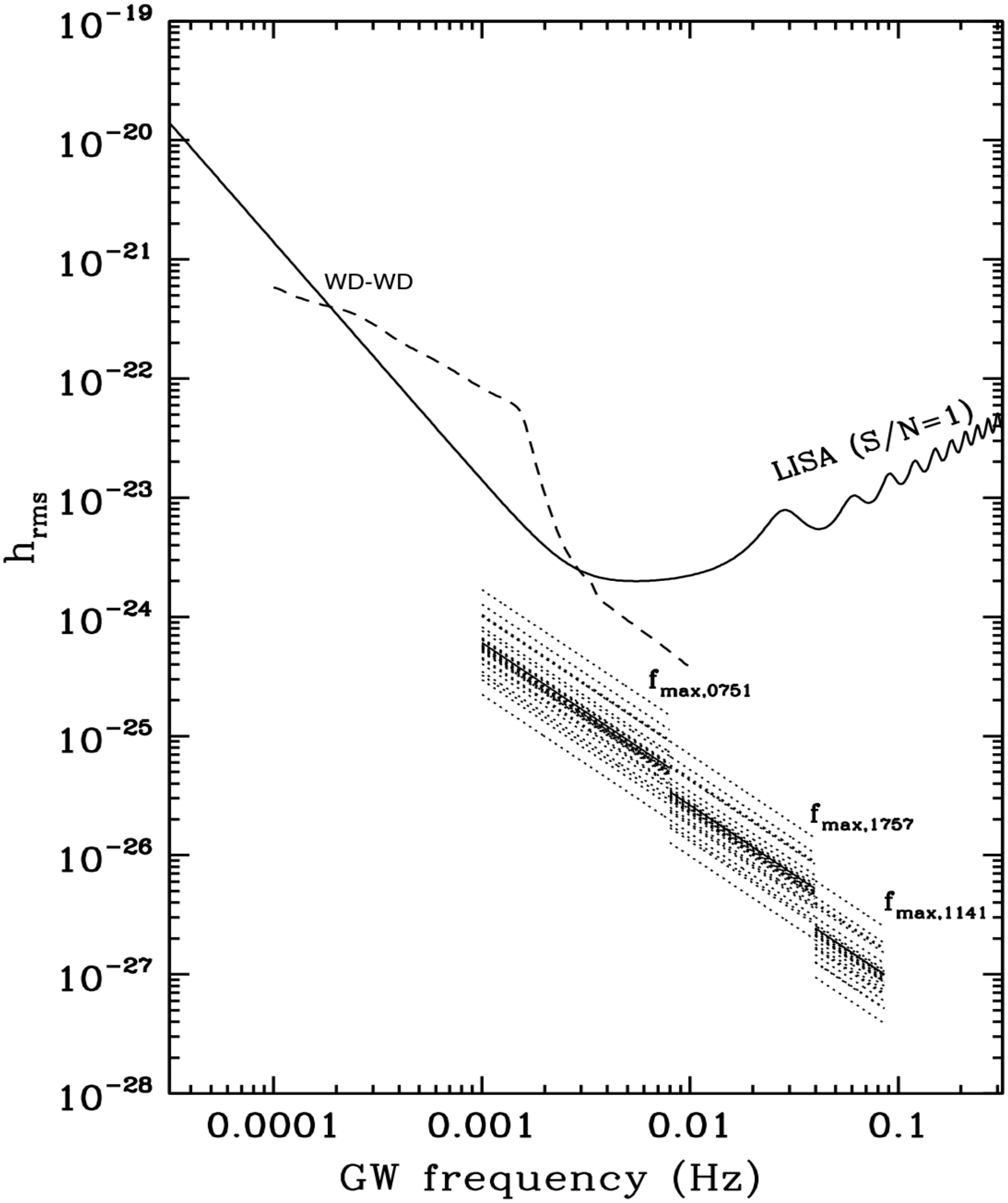

FIG. 2: The effective GW amplitude $h_{\rm rms}$ for merging NS–WD binaries overlapped with the LISA sensitivity curve. The curve is produced with the assumption of S/N=1 for 1 year of integration. Dotted lines are results from all models we consider except the reference model, which is shown as a solid line (see [31] for details). We also show the expected confusion noise from Galactic WD–WD binaries for comparison in a dashed curve. We note that no beaming correction is applied here.

TABLE I: *MERGING* PULSAR BINARIES CONSIDERED IN THIS WORK. We list selected properties and the estimated population size of pulsar binaries considered in this work. $P_{\rm s}$ is a pulsar spin period, $P_{\rm b}$ is an orbital period, e is an eccentricity, $\tau_{\rm life} = \tau_{\rm c}+\min[\tau_{\rm mrg},\tau_{\rm d}]$ is the lifetime of a binary. $\tau_{\rm c}$ is a characteristic pulsar age that sets a current age of the binary. $\tau_{\rm mrg}$ is a merging time scale of the binary due to the emission of GWs. $\tau_{\rm d}$ is a 'death time scale' that determines how long a neutron star would be seen as a radio pulsar. $N_{\rm pop}$ is a population size for a given binary. $N_{\rm pop}$ values shown in the Table 1 are obtained from the *reference* model. The first four pulsars shown from the top are in DNS systems and the bottom three pulsars are found in NS–WD binaries. We note that we consider PSR J0737-3039A in this work, which is a recycled pulsar in the double-pulsar system [33].

PSR name	$P_{\rm s}$ (ms)	$P_{\rm b}$ (hr)	e	$\tau_{\rm life}$ (Gyr)	$N_{\rm pop}$	Reference
B1913+16	59.03	7.75	0.617	0.37	680	[8]
B1534+12	37.90	10.10	0.274	2.93	480	[32]
J0737-3039A	22.70	2.45	0.088	0.23	1680	[33]
J1906+0746	144.14	3.98	0.085	0.082	300	[10]
J0751+1807	3.48	6.31	3×10^{-6}	10.95	2900	[34, 35]
J1757-5322	8.87	10.88	10^{-6}	12.78	1500	[36]
J1141-6545	393.90	4.74	0.172	0.105	370	[37]

but the global network of GW detector is already well established. For the next decade in GW astronomy, it is important to investigate different roles and implications of different pulsar binaries for the GW detection. This work will provide more reliable estimates on detectable number of GW sources for the current and future detectors as well as a test tool to predict the detector performance.

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