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THE COSMIC COALESCENCE RATES FOR DOUBLE NEUTRON STAR BINARIES

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ABSTRACT

We report on the newly increased event rates due to the recent discovery of the highly relativistic binary pulsar J0737−3039. Using a rigorous statistical method, we present the calculations reported by Burgay et al., which produce a coalescence rate for Galactic double neutron star (DNS) systems that is higher by a factor of 6–7 compared to estimates made prior to the new discovery. Our method takes into account known pulsar survey selection effects and biases due to small-number statistics. This rate increase has dramatic implications for gravitational wave detectors. For the initial Laser Interferometer Gravitational-Wave Observatory (LIGO) detectors, the most probable detection rates for DNS in-spirals are one event per 5–250 yr; at 95% confidence, we obtain rates up to one per 1.5 yr. For the advanced LIGO detectors, the most probable rates are 20–1000 events per year. These predictions, for the first time, bring the expectations for DNS detections by the initial LIGO detectors to the astrophysically relevant regime. We also use our models to predict that the large-scale Parkes Multibeam pulsar survey with acceleration searches could detect an average of three to four binary pulsars similar to those known at present.

Subject headings: binaries: close — gravitational waves — methods: statistical — stars: neutron

1. INTRODUCTION

For almost 30 years, close double neutron star (DNS) binary systems have been known to exist in the Galaxy as a small subset of the observed radio pulsar population (Hulse & Taylor 1975; Wolszczan 1991). These systems lose orbital energy owing to the emission of gravitational waves (Taylor & Weisberg 1989, 2003; Stairs et al. 1998); the associated orbital in-spiral continues until the binary system coalesces, resulting in a burst of gravitational waves. DNS in-spirals are prime targets for gravitational wave detection by the ground-based interferometers Laser Interferometer Gravitational-Wave Observatory (LIGO; Abramovici et al. 1992), GEO (Danzmann et al. 1995), and VIRGO (Caron et al. 1997). Event rate estimates are very important for the development of gravitational wave interferometers (Thorne & Cutler 2002). They are based on estimates of Galactic rates and their extrapolation throughout a survey volume (Finn 2001), given the source strength and instrument sensitivity. For DNS binaries, Galactic rate estimates have been obtained using two very different methods. One is purely theoretical and involves models of binary evolution calibrated usually to the observationally determined supernova rate for the Galaxy. The other, more empirical, approach is based on the physical properties of the close DNS binaries known in the Galactic field and modeling of radio pulsar survey selection effects. For a review and details of both these approaches, see Kalogera et al. (2001, hereafter KNST) and references therein. The empirical method has generally provided us with better constraints on the coalescence rate (KNST), although the uncertainty still exceeds 2 orders of magnitude. This is primarily due to (1) the very small number (only two until recently) of close DNSs known in the Galactic field with merger times shorter than a Hubble time and (2) the implicit assumption that this small sample is a good representation of the total Galactic population (KNST).

Two recent developments make it appropriate to revisit the DNS merger rate calculations. First, the discovery of the 2.4 hr DNS binary PSR J0737−3039 in a large-area survey using the Parkes radio telescope (Burgay et al. 2003) brings the number of known DNS systems to merge in the Galactic field to three. With an orbital period of only 2.4 hr, J0737−3039 will coalesce in only 85 Myr, a factor of 3.5 shorter than the merger time of PSR B1913+16. This immediately hints toward a possible significant increase of the coalescence rate (Burgay et al. 2003). Second, a novel statistical method has been developed by Kim, Kalogera, & Lorimer (2003, hereafter KKL) that automatically takes into account statistical biases inherent in small-number samples, like the relativistic DNS binaries, and in addition allows us to quantify our expectation that the actual DNS binary coalescence rate has a particular value, given the current observations.

In this Letter, we use this statistical method and investigate in detail the effect of this new DNS discovery on the estimates of Galactic DNS in-spiral rates and its implications for gravitational wave detection in this decade. We summarize the method in § 2 and discuss the resulting Galactic in-spiral rate in § 3. In § 4, we use our models to make predictions for the expected number of DNS binaries that the Parkes Multibeam (PMB) survey (e.g., Manchester et al. 2001) could detect when acceleration searches are completed, and in § 5 we discuss the

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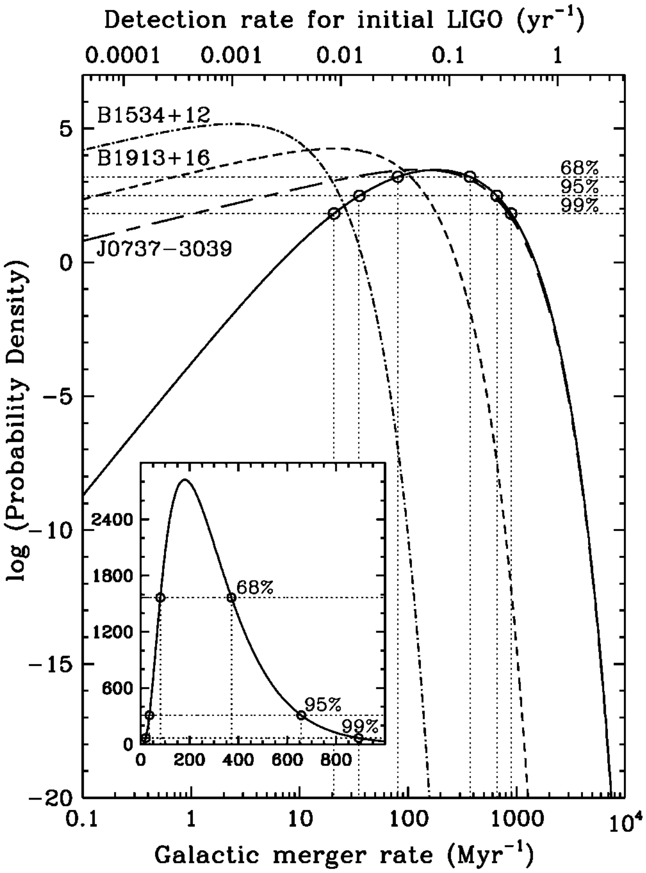

FIG. 1.—Probability density function that represents our expectation that the actual DNS binary merger rate in the Galaxy (*bottom axis*) and the predicted initial LIGO detector rate (*top axis*) take on particular values, given the observations. The curves shown are calculated assuming our reference model parameters (see text). The solid line shows the total probability density along with those obtained for each of the three binary systems (*dashed lines*). *Inset*: Total probability density, and corresponding 68%, 95%, and 99% confidence limits, shown in a linear scale.

implications of our results for the detection rates of upcoming gravitational wave detectors.

2. METHOD FOR RATE CALCULATION

Until recently, estimates of DNS coalescence rates provided a range of possible values without any information on the likelihood of these values. KKL presented a newly developed statistical analysis that allows the calculation of a *probability distribution* for rate estimates and the determination of confidence intervals associated with the rate estimates. The method can be applied to any radio pulsar population (see KKL for the two close DNS systems known at the time and Kim et al. 2004 for close binaries with a pulsar and a massive white dwarf companion). Here we update the results of KKL, taking into account the recent discovery of the new DNS binary PSR J0737−3039 (Burgay et al. 2003).

The method is described in detail in KKL, but we briefly summarize the main elements here. The method involves the simulation of selection effects inherent in all relevant radio pulsar surveys and a Bayesian statistical analysis for the probability distribution of the in-spiral rate estimates. The small-number bias and the effect of the faint end of the pulsar luminosity function, previously identified as the main sources of

TABLE 1

ESTIMATES FOR GALACTIC IN-SPIRAL RATES AND PREDICTED LIGO DETECTION RATES (AT 95% CONFIDENCE) FOR DIFFERENT POPULATION MODELS

			$\mathcal{R}_{\rm det}$ OF LIGO	
MODEL[a]	$\mathcal{R}_{\rm tot}$ (Myr^{-1})	IRF[b]	Initial (kyr^{-1})	Advanced (yr^{-1})
1	56^{+148}_{-45}	7.0	23^{+62}_{-19}	125^{+334}_{-100}
6	180^{+477}_{-144}	6.7	75^{+200}_{-60}	405^{+1073}_{-325}
9	20^{+53}_{-16}	6.9	8^{+22}_{-7}	45^{+120}_{-36}
10	63^{+167}_{-51}	6.7	27^{+70}_{-21}	143^{+377}_{-114}
12	24^{+64}_{-19}	6.7	10^{+27}_{-8}	54^{+144}_{-43}
14	10^{+27}_{-8}	6.3	4^{+11}_{-3}	23^{+61}_{-18}
15	449^{+1183}_{-361}	7.3	188^{+495}_{-151}	1010^{+2661}_{-813}
17	102^{+268}_{-82}	6.8	43^{+112}_{-34}	229^{+602}_{-184}
19	32^{+85}_{-26}	6.8	13^{+36}_{-11}	72^{+191}_{-58}
20	195^{+506}_{-157}	6.9	82^{+212}_{-66}	439^{+1138}_{-352}

[a] Model numbers correspond to KKL. Model 1 was used as a reference model in KKL. Model 6 is our reference model in this study (see text).

[b] Increase rate factor compared to previous rates reported in KKL; IRF $\equiv \mathcal{R}_{\rm peak,\,new}/\mathcal{R}_{\rm peak,\,KKL}$.

uncertainty in rate estimates (KNST), are *implicitly included* in this analysis.

For a model Galactic pulsar population with an assumed spatial and luminosity distribution, we determine the fraction of the total population that is actually *detectable* by current large-scale pulsar surveys. In order to do this, we calculate the effective signal-to-noise ratio for each model pulsar in each survey and compare this with the corresponding detection threshold. Only those pulsars that are nominally above the

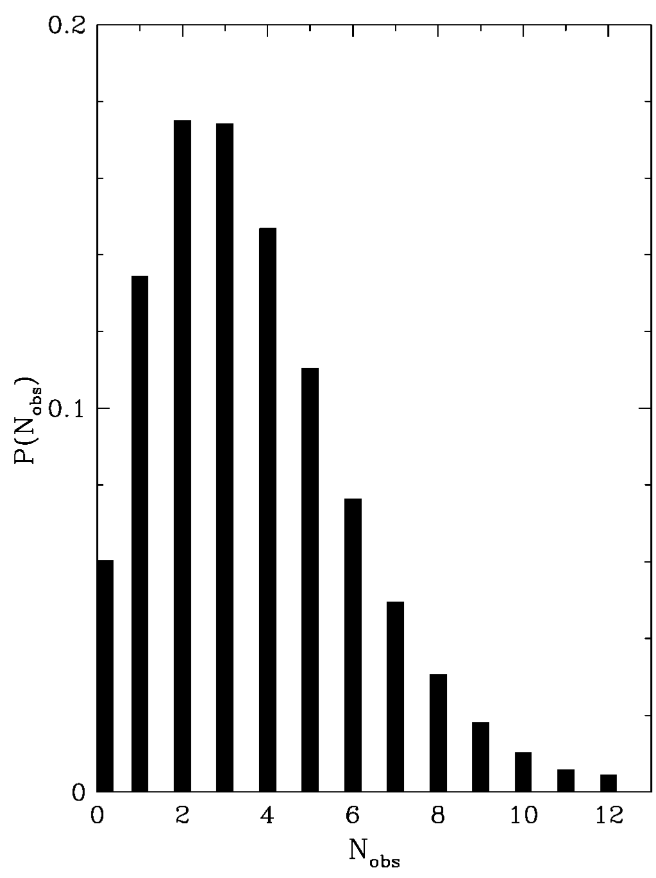

FIG. 2.—Probability density function of the predicted number of observed DNS binary systems $N_{\rm obs}$ for the PMB survey, for our reference model (model 6 in KKL). The mean value is estimated to be $\langle N_{\rm obs}\rangle = 3.6$.

threshold count as detectable. After performing this process on the entire model pulsar population of size N_{tot}, we are left with a sample of N_{obs} pulsars that are nominally detectable by the surveys. By repeating this process many times, we can determine the probability distribution of N_{obs}, which we then use to constrain the population and with a Bayesian analysis derive the probability expectation that the actual Galactic DNS in-spiral rate takes on a particular value, given the observations. More details are given in § 2 of Lorimer et al. (1993) and in KKL.

When this method was first developed (KKL), it was shown that, although the shape of the probability distribution of rate estimates is very robust, the rate value at peak probability systematically depends primarily on the characteristics of the radio pulsar luminosity function: its slope and the physical minimum luminosity of pulsars. Both of these are constrained by the general pulsar population (see Cordes & Chernoff 1997), but we explore the dependence of our results on the assumed values.

Here we consider the same set of pulsar population models as in KKL, but we choose model 6 as our reference model in view of the recent discovery of very faint pulsars (for a review, see Camilo 2003). With the addition of the new DNS binary PSR J0737−3039, our calculations differ from those in KKL in two main ways: (1) the latest Parkes survey that led to the discovery of the new system (Burgay et al. 2003) is included, and (2) we calculate and account for the effects of Doppler smearing for DNS binaries akin to J0737−3039 by creating fake time series for a variety of orbital phases (see KKL for details). Even for an ≃4.5 minute integration (Burgay et al. 2003), this effect alone reduces the average signal-to-noise ratio of a 2.4 hr DNS binary by 35%.

The statistical analysis presented in KKL has been extended to account for three systems (see Kim et al. 2004). In our calculations, we adopt a total lifetime for J0737−3039, defined as the sum of the current age and the remaining lifetime until the final coalescence, equal to 100 + 85 = 185 Myr (Burgay et al. 2003). In the absence of detailed beam observations for the new binary, we adopt a beaming factor of ≃6, equal to the average of the two observationally constrained beams of the previously known DNS binaries (KNST; see also Burgay et al. 2003). We do note, however, that studies of other known recycled pulsars (the majority of them strongly recycled, spinning faster compared to the DNSs by about an order of magnitude) have shown that beaming fractions can vary significantly (Kramer et al. 1998). It is important to keep in mind that any uncertainties in the beaming factor proportionally affect the rate estimates but not the rate increase factors derived here.

3. GALACTIC IN-SPIRAL RATE

For our reference pulsar model (with a radio luminosity function consistent with current pulsar observations; Cordes & Chernoff 1997; Camilo 2003), we find the most likely value of the total coalescence rate to be $\mathcal{R} = 180\ \mathrm{Myr}^{-1}$. The ranges of values at 68% and 95% confidence intervals are 80–370 and 40–660 Myr^{-1}, respectively. The width of these ranges are somewhat smaller than previous estimates (the ratio between upper and lower limits at 68% confidence interval is 4.6 compared with 5.4 found by KKL), confirming the expectation that a bigger observed sample would reduce the uncertainty in the rate estimates (KNST). The new value for $\mathcal{R}$ is a factor of 6.7 higher than found by KKL. From the resulting probability distribution shown in Figure 1, it is clear that J0737−3039 dominates the total rate over the other two systems. This is due to two separate factors: (1) The estimated total number of DNS binaries similar to J0737−3039 (3800) is far higher than those of each of the other two systems (1300 for B1913+16 and 1100 for B1534+12). This is mainly due to the shorter pulsar spin and binary orbital period of J0737−3039, which results in a significant Doppler smearing and efficiently "hides" them in the Galaxy. (2) The total lifetime of J0737−3039 (185 Myr) is significantly shorter than those of the other two (365 Myr for B1913+16 and 2.9 Gyr for B1534+12).

We now explore our results for all other models considered in KKL. Our main results are shown in Table 1, where we have included a subset of models that reflect the widest variations of the rates (as shown in KKL, variations in the space distribution of pulsars are not important). The main conclusions that can be easily drawn are: (1) The increase factor on the in-spiral rate is highly *robust* against all systematic variations of the assumed pulsar models and is strongly constrained in the range 6–7; this is consistent with but somewhat lower than the simple estimate presented in Burgay et al. (2003). (2) The shape of the rate probability distribution also remains robust, but the rate value at peak probability depends on the model assumptions in the same way as described in detail in KKL (see Figs. 5–7 in KKL).

4. PREDICTIONS FOR FUTURE DISCOVERIES

As already mentioned, long integration times combined with very short binary orbital periods strongly select against the discovery of new binary pulsars. Specifically, in the large-scale PMB survey (e.g., Manchester et al. 2001) with an integration time of 35 minutes, the signal-to-noise ratio is severely reduced by Doppler smearing due to the pulsars' orbital motion. Acceleration searches in the current reanalysis of the PMB survey (Faulkner et al. 2003) should significantly improve the detection efficiency to DNS binaries.

Following Kalogera, Kim, & Lorimer (2003), we calculate the probability distribution that represents our expectation that the actual number of *DNS pulsars with merger times shorter than a Hubble time* (N_{obs}) that could be detected with the PMB survey takes on a particular value, given the current observations and assuming that the reduction in flux due to Doppler smearing is corrected perfectly. To illuminate the effect of the Doppler smearing, we calculate the average number of expected new discoveries akin to each of the three known DNS binaries.

We have shown before (Kalogera et al. 2003) that the probability distribution of the expected observed number N^i_{obs} for each DNS pulsar subpopulation i (B1913+16, B1534+12, and J0737−3039) is given by

$$P_i(N_{obs}) = \frac{\beta_i^2}{(1+\beta_i)^2}\frac{(N_{obs}+1)}{(1+\beta_i)^{N_{obs}}}, \quad (1)$$

where the constants β_i are a measure of how less likely it is to detect pulsars without acceleration searches relative to with acceleration searches. For each subpopulation, the mean values of N_{obs} can be calculated, and we find them to be

$$\langle N_{obs}\rangle_{1913} = 0.9, \quad \langle N_{obs}\rangle_{1534} = 1.1, \quad \langle N_{obs}\rangle_{0737} = 1.6. \quad (2)$$

As expected, it is evident that the discovery of DNS pulsars in tight binaries like J0737−3039 would be most favored with acceleration searches.

Following Kalogera et al. (2003), we can also calculate the combined probability distribution of the expected number of

DNS pulsars that can be detected with PMB acceleration searches in the future. The result is shown for our reference model in Figure 2. The average combined number is 3.6, and the discovery of up to two (or four) DNS systems has a probability equal to ≃20% (≃55%). We conclude that, if the acceleration search can correct the Doppler smearing effect perfectly, then the PMB survey could be expected to detect an average of three to four DNS pulsars with pulse profile and orbital properties similar to any of the three already known systems.

5. IN-SPIRAL EVENT RATES AND CONCLUSIONS

Estimates of DNS in-spiral rates have suffered from the small number of relativistic binaries known in our Galaxy, mainly because of the implicit assumption in all methods used so far that the observed sample represents the Galactic DNS population. Here we show that the recent discovery of the third relativistic binary in the Galactic field with binary properties (pulse profile and orbital characteristics) significantly different from those of systems previously known reveals a new subpopulation in the Galaxy. Consequently, it leads to a significant (by factors of 6–7) increase of the in-spiral rate estimates.

We now consider the implications of our revised rate estimates for the detection of these events by LIGO and the other upcoming gravitational wave interferometers. Since these instruments can detect DNS in-spirals out to ≃20 Mpc for the initial LIGO detectors (≃350 Mpc for the advanced LIGO detectors; Finn 2001), it is necessary to extrapolate our Galactic event rate out to the Local Group. Using the standard extrapolation of our reference model out to extragalactic distances (Phinney 1991; KNST), we find the most probable event rates for our reference model are one per 13 yr and one per day, for the initial and advanced LIGO detectors, respectively. At the 95% confidence interval, the most optimistic predictions for the reference model are one event per 4 yr and four events per day for the initial and advanced LIGO detectors, respectively. However, considering the full set of 27 models at 95% confidence interval indicates that the respective rates can reach up to one event per 1.5 yr and 10 events per day, respectively. These results are quite encouraging, since, for the initial LIGO detectors in particular, this is the first time that DNS coalescence rate estimates are within an astrophysically relevant regime. Within a few years of LIGO operations, it should be possible to directly test these predictions and, in turn, place better constraints on the properties of binary radio pulsars and the cosmic population and evolution of DNS binaries.

We also find that there is a significant probability (in excess of ≃80%) that when acceleration searches of the PMB survey are completed more than two binary pulsars could be detected. The increase of the observed sample is very important for the reduction of the uncertainties associated with the in-spiral rate estimates. We note, however, that the discovery of new systems that are *similar* to the three already known does not necessarily imply a significant increase in the rate estimates. Significant changes are expected in the case that new systems with pulse profiles or binary properties significantly different are discovered, as it is such systems that will reveal a new DNS subpopulation in the Galaxy.

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