An Upper Limit on the Coalescence Rate of Double Neutron-Star Binaries in the Galaxy

Vassiliki Kalogera
Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138; vkalogera@cfa.harvard.edu

Duncan R. Lorimer
Arecibo Observatory, HC3 Box 53995, Arecibo, Puerto Rico, PR 00612; dunc@naic.edu

ABSTRACT

In the context of assessing the detectability of the coalescence of two neutron stars (NS) by currently built gravitational-wave experiments, we present a way of obtaining an upper limit to the coalescence rate in the Galaxy. We consider the NS/NS progenitors just before the second supernova explosion. We combine the theoretical understanding of orbital dynamics at NS formation with methods of empirically estimating pulsar birth rates and derive an upper limit of a few mergers every $10^{5}$ yr. Such a Galactic rate implies a possible detection by the “enhanced” LIGO of up to a few to ten mergers per year.

Subject headings: binaries: close — stars: neutron — pulsars: general

1. Introduction

With the upcoming completion of the first-level functional stage of gravitational-wave detection experiments (LIGO, VIRGO, GEO600) currently under development, a serious effort has been focused on studying possible sources of gravitational radiation and on examining their detectability. The coalescence of two compact objects, neutron stars (NS) and/or black holes (BH), is one of the primary sources expected to be detected out to $\sim 20$ Mpc with the first-generation LIGO and out to $\sim 200$ Mpc with the “enhanced” LIGO (e.g., Abramovici et al. 1992; Thorne 1996). Apart from the strength of the expected signal, a major factor in assessing the detectability of such sources is the frequency of coalescence events in the Galaxy. This Galactic rate provides the basis for estimates of the detection rate depending on the detector sensitivity. For the expected sensitivity of “enhanced” LIGO, a Galactic NS/NS merger rate of $10^{-5}$ yr$^{-1}$ would lead to a detection rate of 2 – 3 events per year (using the extrapolation out to 200 Mpc by Phinney 1991).
So far two ways have been used to estimate the Galactic rate of compact binary mergers. One is purely theoretical and relies on modeling the formation of such systems through a long series of evolutionary stages by means of population synthesis. This method has been used by several different groups to obtain coalescence rate estimates for NS/NS, BH/NS and BH/BH binaries in recent years. However, the calculations involve a number of uncertain factors related to the properties of primordial binaries and to the details of stellar and binary evolution. Detailed parameter studies to examine the robustness of the results is a crucial component of the population synthesis calculations. The results on the binary compact object merger rate in our Galaxy from a number of recent studies (Fryer et al. 1999; Belczynski & Bulik 1999; Bethe & Brown 1998; Portegies-Zwart & Yungelson 1998; Fryer et al. 1998; Lipunov et al. 1997) cover a range of values of $\sim 3 - 4$ orders of magnitude ($< 10^{-7}$ to $> 10^{-4}$ yr$^{-1}$). The major uncertainty turns out to be the average magnitude of kicks imparted to newborn compact objects. For kicks in a range from very low values to several hundreds of km s$^{-1}$, the coalescence rate typically varies by more than two orders of magnitude. Other uncertainties include the physical assumptions made when modeling common envelope evolution (particularly the fate of NS), the mass-ratio distribution in primordial binaries, and the progenitor masses for BH. Overall it appears that the predictive power of population synthesis calculations particularly for the coalescence rate of NS/NS, BH/NS, and BH/BH binaries is rather limited (see Kalogera 1999).

For binaries that are known to exist in our Galaxy, i.e., coalescing NS/NS binaries, there is also an empirical way of estimating their merger rate. It is based on modeling radio pulsar selection effects (for the pulsar surveys conducted so far). The results of such studies (Narayan et al. 1991; Phinney 1991; Curran & Lorimer 1995; Arzoumanian et al. 1998; Evans et al. 1999) appear to cover a much narrower range (about an order of magnitude wide) ranging roughly from $\sim 10^{-7}$ to $\sim 10^{-6}$ yr$^{-1}$. For a more detailed discussion of the uncertainties involved see Arzoumanian et al. (1998) and Kalogera et al. (1999).

Given on the one hand all the uncertainties of the various rate estimates and on the other the significance of a reasonable detection rate for the gravity wave experiments, attempts to obtain a secure upper limit on the coalescence rate have been made. Specifically for NS/NS binaries, Bailes (1996) derived an empirical upper limit based on the non-detection of a young (non-recycled) pulsar among the observed NS/NS binaries. He used the total number of young radio pulsars detected at the time and their birth rate and concluded that the NS/NS formation rate cannot exceed $10^{-5}$ yr$^{-1}$. More recently, Arzoumanian et al. (1998) revised this upper limit taking into account current pulsar numbers and the reduction in search sensitivity to short orbital period binary systems due to Doppler shifting of the pulse period during an observation. These considerations led Arzoumanian et al. to increase Bailes’ upper limit to $10^{-4}$ yr$^{-1}$.

In this paper we present an alternative way of obtaining an upper limit to the NS/NS coalescence rate in our Galaxy that combines our basic theoretical understanding of the late stages in the evolutionary sequence of NS/NS formation with empirical birth rate estimates of other radio pulsar systems that contain pulsars similar to the ones detected in NS/NS binaries. In the next
section we describe the basic method for deriving the upper limit. In §3 we deal quantitatively with the problem of supernova orbital dynamics and the formation of the second NS in NS/NS binaries. In §4 we obtain an empirical estimate of the birth rate of single pulsars similar to those found in NS/NS binaries and in §5 we calculate the upper limit on the NS/NS coalescence rate in our Galaxy and compare it to the requirements for gravitational-wave detection. Finally, in §6 we discuss in detail some of the uncertainties related to the derived upper limit as well as the prospects of constraining this limit further in the future.

2. Basic Method

We consider the *immediate* progenitors of NS/NS binaries, i.e., the stage just before the second supernova (SN) explosion. Regardless of the details of prior evolution all different formation mechanisms discussed in the literature (e.g., Bhattacharya & van den Heuvel 1991; Brown 1995; Terman & Taam 1995) converge to the same binary configuration prior to the formation of the second NS: a binary consisting of the first-born NS and a helium star (He-star) in a circular orbit. The implicit assumption in these formation channels is that the observed radio pulsar is the first-born NS in the binary and the orbit before the second explosion has been circularized through a mass-accretion phase, during which the NS also got (mildly) recycled.

Depending on its mass ($\gtrsim 2 - 3 M_\odot$ and $\lesssim 10 M_\odot$; Habets 1985; Fryer 1999), the He-star can terminate its life in a supernova explosion and the formation of a NS. During the explosion the binary characteristics change not only because of mass loss but also because of a birth kick imparted to the compact remnant. Although the physical origin of this kick is not well understood, its existence is supported by the characteristics of a number of different NS populations (isolated and in binaries; e.g., van den Heuvel & van Paradijs 1997; see however Iben & Tutukov 1998). There are three possible outcomes after this SN explosion: (i) a NS/NS binary is formed in a tight enough orbit so that the system coalesces due to gravitational radiation within $10^{10}$ yr; coalescing binary (CB), (ii) a NS/NS binary is formed but the orbit is too wide for coalescence to occur within $10^{10}$ yr; wide binary (WB), and (iii) the binary gets disrupted and a single (S), mildly recycled pulsar is freed. The characteristics discriminating between the three results are the post-SN orbital semi-major axis, $a$, and eccentricity, $e$. In Figure 1, the three different types of systems are identified on the $A - e$ plane for coalescence within $10^{10}$ yr.

For specific values of the mass of the He-star, $M_\odot$, the pre-SN orbital separation, $a_0$, and the magnitude, $V_k$, of the kick imparted to the second NS, and under the assumption of isotropic kicks, we can calculate the branching probabilities for each of the above outcomes, $P_{CB}$, $P_{WB}$, and $P_S$. All three subgroups contain pulsars with the same properties as the ones found in the observed coalescing NS/NS binaries, since the pulsar was born and recycled prior to the "immediate-progenitor" stage we consider here. Therefore the ratio of two of the above branching probabilities is equal to the ratio of birth rates for the corresponding two types of systems. In
what follows we choose to consider the coalescing binaries and the disrupted systems:

$$\frac{P_{CB}}{P_S} = \frac{BR_{CB}}{BR_S},$$

(1)

where $BR_{CB}$ and $BR_S$ are the birth rates of coalescing NS/NS and single, mildly recycled pulsars.

To obtain an exact value of the ratio of branching probabilities, $P_{CB}/P_S$, the distribution functions of the three input parameters, $M_o$, $A_o$, and $V_k$, are needed. This however requires modeling of the complete binary evolution prior to the stage we consider here, which brings us back to the problem of all the uncertainties that affect the population synthesis calculations of NS/NS binaries, because of which the calculated probability ratio would be uncertain by several orders of magnitude. We can avoid all these uncertainties by calculating an upper bound to the ratio rather than its actual value. This upper bound, which requires knowledge of the allowed ranges of values for $M_o$, $A_o$, and $V_k$ but not their distribution functions, can then be used to derive an upper limit to $BR_{CB}$. The missing link then is $BR_S$, an estimate of which we obtain empirically (as is usually done for coalescing NS/NS binaries) based on the observed pulsar sample. Using the two components, $(P_{CB}/P_S)_{max}$ and $BR_S$, we can derive an upper limit to the NS/NS coalescence rate in our Galaxy. In the next two sections we describe our assumptions and the derivation in detail.

3. Supernova Orbital Dynamics

We consider the immediate progenitors of NS/NS binaries consisting of the first NS (pulsar) of mass $M_{NS} = 1.4M_\odot$ and a He-star (the progenitor of the second NS) of mass $M_o$ in an orbit of semi-major axis $A_o$. We assume that the pre-SN orbit is circular because of an earlier mass transfer phase, during which the first NS got mildly recycled. At the SN explosion we assume that the newborn NS is also of $M_{NS} = 1.4M_\odot$ and it receives an isotropic kick of given magnitude, $V_k$. Our assumption about the NS masses is well justified by the measured masses (or sum of two masses) in all the observed NS/NS binaries (Thorsett & Chakrabarty 1999).

For a given set of values for the input parameters, $M_o$, $A_o$, and $V_k$, we can use conservation laws of energy and angular momentum for the system and derive expressions for the post-SN orbital semi-major axis, $A$, and eccentricity, $e$ (see also Hills 1983):

$$A = \frac{\beta A_o}{2\beta - u_k^2 \sin^2 \theta - (u_k \cos \theta + 1)^2}$$

(2)

$$1 - e^2 = \frac{1}{\beta^2} \left[ u_k^2 \sin^2 \theta \cos^2 \phi + (u_k \cos \theta + 1)^2 \right] \left[ 2\beta - u_k^2 \sin^2 \theta - (u_k \cos \theta + 1)^2 \right].$$

(3)

In the above equation $u_k$ is the kick magnitude in units of the pre-SN relative orbital velocity, $V_{orb} = [G(M_{NS} + M_o)/A_o]^{1/2}$, $\beta \equiv (M_{NS} + M_{NS})/(M_{NS} + M_o)$, and angles $\theta$ and $\phi$ describe the direction of the kick: $\theta$ is the polar angle from the pre-SN orbital velocity vector of the exploding
He-star and ranges from $0 - \pi$ (at $\theta = 0$, $\vec{V}_k$ and $V_{\text{orb}}$ are aligned); $\phi$ is the azimuthal angle in the plane perpendicular to $V_{\text{orb}}$ and ranges from $0 - 2\pi$ (at $\phi = 0$, the kick component in that plane points towards the first NS).

### 3.1. Constraints

Considerations of the complete set of constraints imposed on the angles $\theta$ and $\phi$ lead to a few interesting constraints on $u_k$ and the ratio $A/A_o$. We confirm two limits on $u_k$ found earlier by Brandt & Podsiadlowski (1995) and discuss two more limits imposed on $A/A_o$. Given an amount of mass loss during the SN, i.e., given a value of $\beta$, the binary gets disrupted unless

$$u_k < 1 + \sqrt{2}\beta.$$  \hspace{1cm} (4)

If more than half of the total binary mass is lost ($\beta < 0.5$) then there is a minimum kick magnitude that is required to keep the system bound

$$u_k > 1 - \sqrt{2}\beta.$$ \hspace{1cm} (5)

For a given amount of mass loss and kick magnitude there is a lower limit to the degree of orbital contraction (or expansion) that can be achieved after the explosion

$$\frac{A}{A_o} > \left[2 - \left(\frac{u_k - 1}{\beta}\right)^2\right]^{-1}. \hspace{1cm} (6)$$

Finally, if a kick is not necessary to keep the system bound ($\beta > 0.5$) but it still imparted and its magnitude is moderate, $u_k < \sqrt{2}\beta - 1$, then there is also an upper limit to the degree of orbital contraction (or expansion) that can be achieved after the explosion

$$\frac{A}{A_o} < \left[2 - \left(\frac{u_k + 1}{\beta}\right)^2\right]^{-1}. \hspace{1cm} (7)$$

It can be easily shown that the right part of equation (6) is smaller than that of equation (7) for any $\beta$ and $u_k$. We note that these limits on $A/A_o$ are imposed in addition to the two long-known limits (Flannery & van den Heuvel)

$$\frac{1}{1+\epsilon} < \frac{A}{A_o} < \frac{1}{1-\epsilon}. \hspace{1cm} (8)$$

### 3.2. Distribution Functions

To calculate the branching probabilities for each of the three post-SN outcomes described in §2 we use a semi-analytical method based on Jacobian transformations of distribution functions that describe the characteristics of the populations after the explosion.
For isotropic kicks, the distribution function of their direction, is given by:

\[ G(\theta, \phi) = \frac{\sin \theta}{2\pi} \]  

We can obtain the distribution function of \( A \) and \( e \) using the Jacobian transformation of the phase space \((\theta, \phi)\) to that of \((A, e)\). The necessary derivatives are calculated analytically from equations (2) and (3). It is:

\[ F(A, e) = G(\theta, \phi) \sqrt{J(\theta, \phi, A, e)} \]  

and the final outcome:

\[ F(A, e) = \frac{\beta^2 e}{2\pi u_k A} \left[ \frac{\beta (1 - e^2) A / A_o - \left( 2\beta - \beta A_o / A - u_k^2 - 1 \right)}{2\beta - \beta A_o / A} \right]^{-1/2} \times \left[ 2\beta - \beta A_o / A - \beta (1 - e^2) A / A_o \right]^{-1/2}. \]

The branching probabilities, \( P_{CB} \), \( P_{WB} \), \( P_S \), are then calculated by numerically integrating the above function over the appropriate ranges of values of \( A \) and \( e \) (see Fig. 1) with \( M_o, A_o, \) and \( V_k \) as input parameters.

The ranges of values for \( M_o \) and \( A_o \) are in principle unconstrained unless one models the full binary evolution prior to the stage of immediate NS/NS progenitors. However, here we are interested in obtaining a conservative upper limit to the NS/NS coalescence rate and therefore to the ratio \((P_{CB}/P_S)_{\text{max}}\), so we choose the most conservative (widest) limits to these ranges that would still lead to the formation of coalescing NS/NS. The lower limit to \( M_o \) is set by the requirement that the He-star is massive enough to form a NS. It has been estimated to lie between \( 2 - 3 \, M_\odot \) (e.g., Habets 1985) and we adopt \( M_{o,\text{min}} = 2 \, M_\odot \). The upper limit so that BH formation is avoided is not well known but simulations of the collapse of He-stars place it at \( \sim 10 \, M_\odot \) (Fryer 1999). To be conservative we adopt \( M_{o,\text{max}} = 20 \, M_\odot \). For a given value of \( M_o \), the range of \( A_o \) is limited by the requirement that \( P_{CB} \) is non-zero. It is interesting to note that the possible worrisome case of non-zero values of both \( P_{CB} \) and \( P_S \) does not occur for any values of the input parameters.

For a given kick magnitude we scan the complete range of \( M_o \) and \( A_o \) and calculate \((P_{CB}/P_S)_{\text{max}}\). We note that the maxima occur at \( M_o \sim 4 - 5 \, M_\odot \) and \( A_o \sim 4 - 5 \, R_\odot \) both of which are reasonably expected values for He-star masses and orbital sizes after common envelope evolution. Our results for the maximum probability ratio as a function of kick magnitude are shown in Figure 2 for a wide range of \( V_k \) from 0 to \( 2500 \, \text{km s}^{-1} \). It is evident that there is a pronounced peak at \( \sim 400 \, \text{km s}^{-1} \) that gives us a unique upper limit of \((P_{CB}/P_S)_{\text{max}} \approx 0.27\).
4. Empirical Coalescence Rates

The basic method for obtaining empirical birth rates of pulsar populations has been described in detail in Narayan (1987) and other papers (e.g., Lorimer et al. 1993). In short, for each observed pulsar a scale factor is calculated based on the inverse of the ratio of the Galactic volume throughout which the pulsar could have been detected (given the radio pulsar surveys) over the total Galactic volume (modulo an assumed Galactic spatial distribution of radio pulsars). This scale factor essentially measures how many more pulsars like the one observed exist in the Galaxy. Combined with an estimate of the lifetime of the pulsar and summed over all observed pulsars of interest an estimate for their Galactic birth rate can be obtained.

We apply this method (following Lorimer et al. 1993) to the subset of single radio pulsars that appear to be “similar” to the ones detected in NS/NS binaries. A crucial issue is how one defines this subset. Our limited theoretical understanding of the details of the evolution of pulsar properties (spin period $P$ and magnetic field strength $B$) does not allow a clear definition of these “NS/NS-like” isolated pulsars in terms of their observed or inferred characteristics. Instead we adopt here a different, rather empirical way of separating this subset which however appears to be quite promising.

A contour map of the estimated total number of pulsars in the Galaxy for each observed pulsar in the $P$–$B$ plane presented by Deshpande, Ramachandran, & Srinivasan (1995) shows quite clearly separate concentrations of pulsars in the plane. Most of them follow a double peaked distribution with a valley (of low pulsar number) separating the two peaks. The appearance of this valley is found to be statistically significant at 98.37% confidence level. At the low-field end of the lower peak island contours include the pulsars found in NS/NS binaries as well as a few isolated pulsars. We choose these few isolated pulsars (excluding the ones in globular clusters) with an inferred magnetic field strength lower than $10^{11}$ G to estimate $B_{S}$. Their scale factors and lifetimes are given in Table 1. We note that for their lifetimes we have simply used their characteristic ages defined as $\tau_{c} \equiv P/2\dot{P}$. Of the five pulsars only one (PSR J2235+1506) has a position on the $P$–$B$ plane that would naturally identify it as a member of the subgroup of interest to us. The rest are chosen as described above. To acknowledge this uncertainty related to identifying the pulsars that originated from NS/NS progenitors we calculate our upper limit using the estimated rate from only PSR J2235+1506 and from all pulsars in Table 1. The range of their birth rate is $8.3 \times 10^{-7} - 1.8 \times 10^{-5}$ yr$^{-1}$.

So far we have ignored the possibility that a pulsar could remain undetected if its beam does not intercept our line of sight. Estimations of the mean beaming fraction (the fraction of $4\pi$ steradians covered covered by the radio beam in one rotation) have fluctuated significantly over the years (c.f. Narayan & Vivekanand 1983; Lyne & Manchester 1988; Biggs 1990). Although recent work by Tauris & Manchester (1998) suggest that the mean beaming fraction may be as low as 10%, it is generally agreed that the beaming fraction is period-dependent, with shorter period pulsars beaming to larger fractions of sky. In this work, where we are dealing with pulsar
periods in the range $\sim 60 - 400$ ms, we shall adopt a mean beaming fraction of $\sim 30\%$, presently the most conservative estimate for this period interval (Lyne & Manchester 1988).

5. Upper Limit

We can now combine our results on the maximum ratio of branching probabilities and the birth rate of “NS/NS-like” isolated pulsars to obtain an upper limit to the NS/NS coalescence rate in the Galactic disk. From equation (1) we have

$$BR_{\text{CB}} \leq \left( \frac{P_{\text{CB}}}{P_{\text{S}}} \right)_{\text{max}} BR_{\text{S}} \leq 7 \times 10^{-7} - 1.5 \times 10^{-5} \text{yr}^{-1}.$$  

(12)

Comparison of the above range with the requirements ($10^{-5} \text{yr}^{-1}$) for a detection rate of 2–3 per year with “enhanced” LIGO shows that only its upper end could lead to marginally optimistic detection prospects. One possibility for an upward revision of these numbers is a correction for a population of pulsars fainter than the lowest sensitivity limits of pulsar surveys. As pointed out by a number of authors (e.g. Narayan 1987; Lorimer et al. 1993), the scale factor analyses apply only to the population of pulsars with luminosities above that of the faintest source in the sample. When this luminosity limit is significantly larger than the lower limit of the underlying population, presently thought to be around 1 mJy kpc$^2$ (Lyne et al. 1998), a correction factor must be included to account for fainter sources (see e.g. Curran & Lorimer 1995). For the sample we consider here, however, this correction factor is expected to be quite small since the faintest pulsar (B1952+29) has a luminosity of only 1 mJy kpc$^2$ — i.e. very close to the lower cut-off of the pulsar luminosity function. Alternatively, Kalogera et al. (1999) point out a related bias of underestimating the total number of pulsars in the case of small samples of objects. Based on detailed Monte Carlo simulations Kalogera et al. estimate that the likely correction factor for samples of 5 objects (i.e. the same size as the sample in Table 1) lies between 2 and 6.

6. Discussion

In the derivation of the upper limit on the NS/NS coalescence rate the choice of the sample of isolated pulsars similar to those found in observed NS/NS binaries is a crucial step. At present it is not obvious how such pulsars can be identified accurately in a way other than their position on the P–B plane. The upper end of the range covered by the upper limit derived here is quite conservative in this respect (corresponds to a sample of 5 single pulsars). It is plausible that we have included one or more pulsars that actually belong to the group of usual young, non-recycled pulsars or even that they have been recycled but in a type of binary system that could not lead to the formation of NS/NS binaries. In either case the upper limit derived here overestimates the true value. Note that the ratios of branching probabilities calculated here (with a maximum value
\begin{align*}
\lesssim 0.3\% & \text{ indicate that the number of single “NS/NS-like” pulsars should exceed that of } \\
\text{coalescing binaries by at least a factor of } \sim 3. \text{ Hence, a sample bigger than 5–6 single pulsars would be} \\
\text{favored and there may even be a serious deficit of such single pulsars in the observed population (Kalogera 1999).}
\end{align*}

Another issue of concern could be the validity of equation (1), that is the equality of the ratio of birth rates to the ratio of branching probabilities. Given that all three subgroups (of the three post-SN outcomes) have common progenitors, the two ratios could be different if the evolution after the recycling of the first NS is different for each of the subgroups. The only possibility relevant to these late evolutionary stages is related to the characteristic velocities of the different types. However, a quick estimate of the typical center-of-mass velocities of NS/NS binaries and of the corresponding isolated pulsars (based on the results of Kalogera 1996 and Tauris & Takens 1998) shows that their velocities are within factors of 2–3 of the pre-SN orbital velocities and hence of each other. Such differences are probably too small to make any difference in the estimated birth rates, a conclusion also supported by the recent results of Evans et al. (1999) who find that the dependence of the empirical pulsar birth rate estimates are very weakly dependent on the details of the velocity and spatial distribution of the population.

Recently, an uncertainty in empirical rate estimates related to small-number samples and the faint end of the pulsar luminosity function has been pointed out and studied quantitatively in the context of NS/NS coalescence rates (Kalogera et al. 1999). This uncertainty is relevant to our empirical estimate of \( BR_S \) although it is much less significant for the upper end of the derived range. According to Kalogera et al. (1999) for an observed sample of five objects the upward correction is probably \( \sim 2 \).

In determining the low edge of the allowed range of \( A_o \) for a given \( M_o \) we have used the constraint that the He-star lies within its Roche lobe even at its maximum radial extent. In this way we exclude the possibility of the NS going into a common-envelope phase with the He-star, which we expect will lead to the collapse of the NS to a black hole (see e.g., Fryer et al. 1996; Fryer & Kalogera 1997). The lower value of \( A_o \) then depends on the radius-mass relation of evolved He-stars which for stars less massive than \( \approx 3–3.5 \, M_\odot \) is uncertain within factors of a few. To explore the effect of this uncertainty on our results we have repeated the calculation of \( (P_{CB}/P_3)^{\text{max}} \) reducing the He-star radii by a (relatively high) factor of 4 in the above mass range. In this case our estimates for the limit on the coalescence rate increases by \( \approx 2.5 \) \( (P_{CB}/P_3)^{\text{max}} \) increased to 0.7.

The method proposed here to obtain upper bounds on the coalescence rate can also be used with wide NS/NS binaries instead of the isolated “NS/NS-like” pulsars. The part related to the analysis of the orbital dynamics at the second SN can easily be modified to calculate \( (P_{CB}/P_{WB})^{\text{max}} \). We performed this calculation following the basic procedure outlined in \( \S \ 3 \), scanning the complete allowed ranges of \( M_o \) and \( A_o \). Our results as a function of kick magnitude are shown in Figure 3 and again the ratio of branching probabilities shows a clear maximum. The
second step of the derivation would involve an empirical estimate of the birth rate of WB based on
the observed sample. At present, this sample\footnote{An former member of this subgroup, PSR B2303+46, has been recently shown to be a NS/WD binary (van Kerkwijk & Kulkarni 1999).} consists of only a few objects: the mildly relativistic binary system J1518+4904 (Nice, Sayer & Taylor 1996); PSR J1811–1736, a 104 ms pulsar in a highly eccentric 18.8 day orbit, discovered by the Parkes Multibeam survey (Lyne et al. 1999); and possibly the enigmatic binary pulsar B1820–11 (Lyne & McKenna 1989). The method described here could be used in the future when more WB are discovered and the details pertaining to the selection effects in the most recent surveys become available. This would then provide us with an additional constraint on the NS/NS coalescence rate.

We would like to thank R. Narayan, D. Psaltis and T. Prince for useful discussions and I. Stairs and R. Manchester for sharing with us information about pulsars recently discovered by the Parkes Multibeam Pulsar Survey ahead of publication. Support by the Smithsonian Institute via a Harvard-Smithsonian Center for Astrophysics Post-doctoral Fellowship is also acknowledged. Arecibo Observatory is operated by Cornell University under cooperative agreement with the National Science Foundation.

REFERENCES

Abramovici, A. et al. 1992, Science, 256, 325

Evans, T. et al. 1999, to appear in the proceedings of the XXXIVth Rencontres de Moriond on "Gravitational Waves and Experimental Gravity", Les Arcs, France


Fryer, C. L. 1999, private communication


Kalogera, V. 1999, to appear in the proceedings of the XXXIVth Rencontres de Moriond on "Gravitational Waves and Experimental Gravity", Les Arcs, France

Kalogera, V. 1999, in preparation


This preprint was prepared with the AAS LATEX macros v4.0.
Fig. 1.— Boundaries on the plane of post-SN orbital semi-major axis, $A$ and post-SN eccentricity, $e$, separating (i) NS/NS binaries coalescing within $10^{10}$ yr (CB), (ii) NS/NS binaries too wide to coalesce within $10^{10}$ yr, and (iii) isolated NS freed with the disruption of binaries when $e > 1$ (S).
Fig. 2.— Maximum values of the ratio of branching probabilities, $P_{CB}/P_{S}$, calculated for the complete ranges of He-star masses, $M_o$, and pre-SN orbital separations, $A_o$, plotted as a function of the magnitude, $V_k$, of an isotropic kick imparted to the newborn NS. For the definition of the subgroups CB and S we used the boundaries shown in Figure 1.
Fig. 3.— Maximum values of the ratio of branching probabilities, $P_{CB}/P_{WB}$, calculated for the complete ranges of He-star masses, $M_o$, and pre-SN orbital separations, $A_o$, plotted as a function of the magnitude, $V_k$, of an isotropic kick imparted to the newborn NS. For the definition of the subgroups CB and WB we used the boundaries shown in Figure 1.
Table 1. Sample of Possible “NS/NS-like” Isolated Pulsars

<table>
<thead>
<tr>
<th>PSR Name</th>
<th>Scale Factor</th>
<th>Log(τ_c/yr)</th>
<th>BR (yr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J2235+1506</td>
<td>5000</td>
<td>9.78</td>
<td>8.3×10⁻⁷</td>
</tr>
<tr>
<td>B1848+04</td>
<td>1000</td>
<td>9.45</td>
<td>3.55×10⁻⁷</td>
</tr>
<tr>
<td>B1952+29</td>
<td>15000</td>
<td>9.62</td>
<td>3.6×10⁻⁶</td>
</tr>
<tr>
<td>B0331+45</td>
<td>1000</td>
<td>8.76</td>
<td>1.74×10⁻⁶</td>
</tr>
<tr>
<td>B1804-08</td>
<td>1000</td>
<td>7.96</td>
<td>1.1×10⁻⁵</td>
</tr>
</tbody>
</table>