Evolution of Close Binaries: Formation and Merger of Neutron Star Binaries

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Abstract. We discuss the formation and evolution of binaries which contain neutron stars or black holes. It is shown that in a stellar system which for $10^{10}$ yr had star formation rate similar to the current one in the Galactic disc, the rate of neutron star mergers is $\sim 2 \times 10^{-5}$ yr$^{-1}$, consistent with the observational estimates. The rate of black hole and neutron star mergers is by an order of magnitude lower. The pairs of black holes form but do not merge because heavy mass loss by their progenitors efficiently moves the binary components apart.

1 Introduction

The wealth of observational features makes the merging of close neutron star (NS) binaries one of the most interesting phenomena in astrophysics. Apart from the expected bursts of gravitational waves (GWR), $\gamma$-ray bursts and production of $r$-process elements are possibly related processes. Some NS binaries are observed as high mass binary pulsars (HMBP, Table 1, see \cite{28} for references), but these are possibly only a fraction of the entire population.

Table 1. Observed population of high-mass binary pulsars

| PSR       | $P$  | $\log \dot{P}$ | $P_{orb}$ | $e$  | age | $\log B$ | $M_1$ | $M_2$ |
|-----------|------|----------------|-----------|------|-----|----------|-------|-------|
| J1518+49  | 40.94| -19.4          | 8.634     | 0.249| 1600| 9.1      | 2.62  |
| B1534+12  | 37.90| -17.6          | 0.420     | 0.274| 250 | 10.0     | 1.34  | 1.34  |
| B1820-11  | 279.83| -14.86         | 357.762   | 0.795| 3.3 | 11.8     | f(m) = 0.7 |
| B1913+16  | 59.03| -17.1          | 0.323     | 0.617| 110 | 10.4     | 1.44  | 1.39  |
| B2127+11C | 30.53| -17.3          | 0.335     | 0.681| 100 | 10.1     | 1.35  | 1.36  |
| B2303+46  | 1066.37| -15.24         | 12.340    | 0.658| 30  | 11.9     | M_t = 2.60 |

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All estimates for the Galactic merger rates of NS binaries based on the observed population arrive at values smaller than $\approx 10^{-5} \text{yr}^{-1}$ (e.g. [24], [33]). Estimates based on simulations of the evolution of close binaries arrive at rates up to $\approx 3 \times 10^{-4} \text{yr}^{-1}$ (e.g. [21], [32]). We will show that the estimated merger rates from observations and model computations may be reconciled.

Figure 1: Scenario of the evolution of massive close binaries.

2 Formation of neutron star binaries

2.1 Population synthesis

“Theoretical” estimates for the birth and merger rates of NS binaries are usually derived from the models which combine the parameterized computations of the evolution of stars with prescriptions for the variation in the binary parameters due to the evolution of its components. By combining the model with distribution functions for the zero-age primary masses, mass-ratios, orbital periods and eccentricities, a complete picture of the population of binary stars is obtained. An example of the evolutionary scenario for a binary, which leads to the
formation of two NS is given in Fig. 1.

Although the concept of the formation of NS binaries is relatively well understood ([10], [31], see however [3]), the models imply some badly understood processes. The most crucial among these are the nonconservative mass exchange (especially the common envelope phase) and the supernova process.

### Table 2. Fraction of surviving systems and relative birthrates of NS binaries

| Event       | No kick | Eq.(1) kick | Maxwellian kick |
|-------------|---------|-------------|-----------------|
| 1st SN      | 38%     | 4%          | 3%              |
| 2nd SN      | 10%     | 5%          | 4%              |
| NS+NS       | 4%      | 0.2%        | 0.1%            |
| MS+MS       |         |             |                 |
| NS+NS       | 5%      | 0.2%        | 0.1%            |
| BH-NS       |         |             |                 |

A common envelope (CE) forms when the accretor in a binary is unable to acquire all matter lost by the donor. The outcome of the CE phase is either the coalescence of stars or the expulsion of the envelope. Models of the CE phase are still in an embryonic state. Therefore, a common envelope parameter $\alpha_{ce}$ is usually introduced. The most common definition of $\alpha_{ce}$ is the ratio of the binding energy of the CE to the orbital energy of the binary (e.g. [16]). Models of the populations of close binary white dwarfs, low- and high-mass binary millisecond pulsars (see below) and some other objects may be fit to observations if $\alpha_{ce} \approx 1 - 2$. Though, formally, $\alpha_{ce} \gtrsim 1$ means that sources other than orbital energy must be invoked in the expulsion of the CE, in fact, in such a parametric approach, this simply suggests that energy deposited into a CE has to be comparable to the orbital energy. Roughly, the ratio of semi-major axes of the orbit of a binary after and prior to the CE stage is $a_f/a_i \propto \alpha_{ce}$, while the timescale for gravitational in-spiral is $\propto a_f^3$. This makes all merger rate estimates highly sensitive to $\alpha_{ce}$. Estimates given below were found by Portegies Zwart & Yungelson [28] for $\alpha_{ce} = 2$.

A velocity kick may be imparted to the nascent NS. While the mechanism and distribution of natal kicks are still a matter of debate, there is firm observational evidence for their occurrence [34]. Natal kicks may unbind binaries, which otherwise might have remain bound and, vice versa, conserve the binaries which without the kick would have been dissociated. An analysis of the role of kicks may be found e.g. in [18], [36].

In [28] we used the distribution for isotropic kick velocities $v$ which has the functional form suggested in [23] with numerical parameters from [13]:

$$P(u)du = \frac{4}{\pi} \cdot \frac{du}{(1 + u^2)^2}, \quad u = v/\sigma, \quad \sigma = 600 \text{ km s}^{-1}.$$  \hspace{1cm} (1)

Implementation of Eq. (1) provides the best fit to the observed population of single pulsars close to the Sun ([12], [13]). Peculiarity of this distribution is the
combination of a peak at low velocity and of a high-velocity tail. Selection effects in the population of single radio pulsars, however, cause the exact shape of the kick velocity distribution to be ill constrained both at low and high velocities. Alternatives as e.g. a Maxwellian distribution with mean of 250 to 500 km s$^{-1}$ can be found in the recent literature ([17], [19]).

Figure 2: Probability distribution for orbital period and eccentricity for the population of NS binaries at the age $T = 0, 10^8$ and $10^9$ yr. The darkest shades correspond to the birthrate of $3.5 \times 10^{-7}$ yr$^{-1}$ (top panel) and numbers of 110 and 1100 (middle and bottom panels, respectively). Dots and asterisks show known HMBP.

The results of computations without kicks, with a kick taken isotropically from Eq. 1 and with a kick from a Maxwellian distribution with $\sigma = 450$ km s$^{-1}$ are presented in Table 2. Another parameters, like the initial mass-ratio distribution or initial orbital separation, affect the results by a factor of $\sim 2$. 
2.2 Merger rate of NS binaries in the Galactic disc

A model which aims to predict a reliable birth and merger rate for NS binaries should provide also the characteristics of related types of binaries and HMBP. For the HMBP, the most useful observational parameters for comparison with the model are the orbital period $P_{\text{orb}}$ and eccentricity $e$.

In [28], the best fit between the observations of HMBP and the computations is obtained for $\alpha_{\text{ce}}=2$ and the distribution of kick velocities given by Eq. (1). Figure 2 shows probability distributions of the orbital parameters of the NS binaries with $P_{\text{orb}} \leq 10^4$ day at an age of the population of $T = 0$, $10^8$ and $10^9$ yr. As demonstrated in [28], natal kicks “smear” $P_{\text{orb}} - e$ distribution. In the absence of kicks only PSR B1913+16 appears in the region of the $P_{\text{orb}} - e$ diagram with high probability. Figure 2 suggests that the average age of the population of observed HMBP is several hundred Myr. Therefore it suggests that recycled pulsars are born with low magnetic fields.

Table 3 compares the predictions of the preferred model from [28] to the observations of NS binaries and related objects. The model is normalized to the current star formation rate in the Galactic disc of 4 M$_\odot$ yr$^{-1}$ [35]; $M_{\text{min}} = 0.1$ M$_\odot$ and 100% binarity are assumed. The adopted lower mass limit for the formation of a NS is 8 M$_\odot$ for an isolated star and 11.4 M$_\odot$ for stars in close binaries. The model satisfactorily reproduces the occurrence rates of supernovae descending from massive stars, numbers of Be/X-ray and massive X-ray binaries (see also [25]). The model does not contradict observational estimates of the birthrate of single pulsars or the fraction of single recycled pulsars among all pulsars (see also [14]). It is important to notice that our computations do not violate the “Bailes criterion” [6], which limits the fraction of HMBP among the population of radio pulsars.

The birthrate of NS binaries derived from computations is considerably higher than the observational one, which involves highly uncertain estimates of the incompleteness of the sample of observed objects [6] and their lifetimes [33]. Observational estimates are also likely to underestimate the actual birthrate, since a considerable fraction of old NSs in binaries may avoid recycling and after the death of the young pulsar never show up as pulsars.

The results of computations agree with observations for the stages preceding formation of NS binaries, give a reasonable estimate of their birthrate and reproduces their distribution in the $P_{\text{orb}} - e$ diagram. We therefore expect that computations also correctly predict the merger rate of NS binaries: $2.3 \times 10^{-5}$ yr$^{-1}$ in the Galaxy. This estimate exceeds the most optimistic “observational” values by a factor of a few. However, about 10% to 20% of all NS binaries merge only

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6. These estimates strongly depends on the assumptions on the evolution of the magnetic field, the distribution of the interstellar material and the beaming fraction. For the latter $f = 0.3$ was adopted.

7. Lipunov et al. [20] suggest that recycled pulsars constitute only several per cent of the total population of NS binaries; this estimate, however, weights heavily on the details of the accretion process on highly magnetized neutron stars.
after the recycled pulsar has died in 0.5 – 1 Gyr (Fig. 3). Another ∼ 10% merge within ∼ 10 Myr, while the young pulsar is still visible. And we note that possibly only a fraction of old NS are recycled and show up in HMBP. This suggests a revision of the “observational” merger rate upward.

Table 3. Descendants of massive binaries

| Object                  | Model          | Observational estimate | Ref. |
|-------------------------|----------------|------------------------|------|
| SNII+SNIb/c             | 15 × 10⁻³ yr⁻¹ | (7 ± 21) × 10⁻³ yr⁻¹   | 3   |
| Be/X-ray bin.           | 10³ – 10⁴     | ∼ 2000                  | 22  |
| MXRB                    | ~ 50           | 30 ÷ 80                 | 7   |
| BH+MS/NS+MS             | 8/60           | 4/30                   | 7   |
| Single PSR              | 15 × 10⁻³ yr⁻¹ | (9 ± 3) × 10⁻³ yr⁻¹     | 3   |
| Single recycled NS/all NS | ~ 1/100     | ∼ 8/800                | 7   |
| Young NS+Old NS/all NS  | ~ 1/430        | ∼ (1 ÷ 2)/800          | 7   |
| NS+BH/Single NS         | ~ 1/2000       | < 1/800                | 7   |
| Birthrate of NS binaries| 3.4 × 10⁻⁵ yr⁻¹| 2.7 × 10⁻⁵ yr⁻¹       | 3   |
| Merger rate NS+NS       | 2 × 10⁻⁵ yr⁻¹  | 0.8 × 10⁻⁵ yr⁻¹        | 3   |
| Merger rate BH+NS       | 0.1 × 10⁻⁵ yr⁻¹ | ?                     |     |

Figure 3: Relative distribution of zero-age NS binaries over merger age.

In [28] it is demonstrated that a higher average kick velocity in the supernova decreases the merger rate. In the most unfavored case of a Maxwellian kick combined with a mass ratio distribution peaked to 0 and small αce the merger rate may drop by an order of magnitude.

The lifetime for a NS binary before it merges is typically below 1 to 2 Gyr (Fig. 3). The merger rate is therefore dominated by the star formation rate in the last few Gyr. In massive (∼ 10¹¹ M☉) spiral (like the Milky Way) and irregular galaxies the star formation rate in the far past was probably significantly higher than at present [29]. However, past bursts of star formation contribute only little to the current merger rate of NS binaries. The same point has to be made.
with respect to elliptical galaxies, as most of their stars were formed in a short (\(< 1 \text{ Gyr}\)) burst; the overwhelming majority of NS binary mergers happened long ago. If we have two 10 Gyr old, equal mass galaxies with the same average star formation rate but in one case all stars are formed in a single initial burst and in the other the star formation was constant, the merger rate of NS binaries in the first galaxy is \(\sim 10\) to \(15\%\) of that in the latter.

Extrapolating our merger rates for NS binaries to the local Universe, using the blue luminosity of the Universe \(\text{[24]}\) and assuming \(h = 0.5\), we obtain for the detection rate by the first generation of GWR detectors sensitive to distances of \(\lesssim 25 \text{ Mpc} \text{[2]}\) only \(\sim 1\) in 200 yr! For advanced detectors (sensitive to a distance of 250 Mpc) the detection rate increases to \(\sim 5 \text{ yr}^{-1}\).

The merger rate for black hole + neutron star binaries (BH+NS) is expected to be about 20 times smaller than for NS binaries \(\text{[28]}\) and the rate of BH+BH mergers is virtually zero. The reason behind this is twofold. First, massive stars suffer heavy mass loss especially when they become Wolf-Rayet stars. E.g., evolutionary computations for solar composition stars with \textit{observationally inferred mass loss rates} \(\text{[30]}\) suggest that stars with an initial mass larger than \(\sim 25 \text{ M}_\odot\) have mass about \(10 \text{ M}_\odot\) prior to supernova. The stellar wind is expected to be isotropic and to carry away the specific angular momentum of the donor. Therefore mass loss in a stellar wind increases the orbital separation. Secondly, BH are not expected to receive sizable kicks which may, if “properly” directed, decrease the binary separation.

The signal-to-noise ratio for gravitational waves detectors is given by \(\text{[5]}:\)

\[
S/N \propto (M_1 M_2)^{1/2} (M_1 + M_2)^{-1/6} D^{-1},
\]

where \(M_1, M_2\) are the masses of coalescing objects and \(D\) is the distance to them. For \(M_{BH} = 4 \div 17 \text{ M}_\odot\) suggested by observed BH candidates, one would expect that a BH+NS merger is detectable to about 1.5 to 2.5 times as far as NS+NS merger. Hence, the rates of detections of NS+NS and BH+NS mergers may be comparable.

### 2.3 Merger rate of NS binaries in globular clusters

Also in the dense cores of globular clusters (GC) mergers between NS may occur. The fraction of primordial binaries which evolve to the stage where GWR drives the components into coalescence is, however, small. The majority of them are ejected from the cluster or dissociated by the encounter with another star. Some of the ejected binaries still result in a NS binary and finally merge. Single NS in the cores of high-density GC may find another star and be captured by it either in a two- or three body encounter. If two NS are able to form a binary in such a way this may increase the NS binary merger rate for post-collapse clusters considerably.

A reliable estimate for the occurrence rate of such mergers is not trivial as the evolution of the binaries and the stars are coupled in a complex fashion.
For solving this problem direct N-body simulations with a realistic number of stars are required, for which the hardware simply does not exist at present. Recently, however, Portegies Zwart et al. \cite{26,27} developed a simplified model for simulating the interaction between evolving stars and binaries while taking dynamical encounters into account. The microscopic dynamics of close encounters between single stars and binaries are solved using semi-analytic and 3-body techniques, while the macroscopic evolution of the stellar system is assumed to be unaffected by its slowly changing stellar population.

The results of these computations concerning the merging of NS binaries may be summarized as follows: In the model for a core-collapsed cluster, the fraction of merging primordial binaries is $\sim 60\%$. The fraction of NS binaries among these is $\sim 0.004$. The time interval between core collapse and Hubble time is $\sim 5 \text{ Gyr}$. If one takes a globular star cluster with $10^6$ stars of which $10\%$ are in the region with a high density and $25\%$ primordial binaries, one obtains a rate for NS binary mergers of $\sim 1.2 \times 10^{-8} \text{ yr}^{-1}$.

Of the binaries which are formed by tidal capture, which occurs once every $10^7$ years, the merger rate for NS binaries is only $4 \times 10^{-10} \text{ yr}^{-1}$ (almost all tidally formed binaries coalesce, but only a fraction of 0.004 contains two NS).

For a total of $\sim 250$ GC in our Galaxy merger rate for NS binaries becomes $\sim 10^{-7} \text{ yr}^{-1}$. The detection rate for the early GWR detectors is therefore only $\lesssim 1/1000$ years (depending on the fraction of dense star clusters). Thus, the rate of NS mergers in the field under any circumstances is much higher than the rate of mergers in GC.

### 3 Conclusion

“Theoretical” and “observational” merger rates of NS binaries produce similar results if the ejection of CE is highly efficient and nascent neutron stars receive, on average, velocity kicks of the order of $\left(200 \div 300\right) \text{ km s}^{-1}$.

The rate of NS mergers is $\sim 2 \times 10^{-5} \text{ yr}^{-1}$ for a galaxy with constant astration rate of $4 \ \text{M}_\odot \text{ yr}^{-1}$ (and $M_{\text{min}} = 0.1 \text{M}_\odot$ and 100% binarity). This rate is uncertain by a factor of a few mainly due to uncertainties in the kicks velocity distribution and the efficiency of energy deposition into the CE.

Merger rate is mainly determined by the current star formation rate and much less by the star formation history of the Galaxy. The time to coalesce two NS stars is typically a few times $10^8$ years.

Extrapolating the Galactic merger rate of NS binaries, we arrive at a detection rate of once every $\sim 200 \text{ yr}$ for the first generation GWR detectors (which are expected to be sensitive up to $\sim 25$ Mpc). BH+NS mergers may be registered at the rate comparable with binary NS mergers.

Mergers of BH+BH binaries are not to be expected because the severe mass loss in the stellar winds of their very massive progenitors results in too large for merger orbital separations.
Only $\sim 1\%$ of the GWR bursts are expected to originate from GC.

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