The galactic merger-rate of neutron star binaries: perspectives for gravity-wave detectors

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The galactic merger-rate of (ns, ns) binaries

I. Perspective for gravity-wave detectors

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Abstract. We use a detailed binary-evolution model to predict the rate for merger events of neutron-star/neutron-star binaries, for various extreme assumptions about initial conditions and evolutionary mechanisms. The models in which neutron stars acquire a kick velocity at birth of $\sim$ 450 km/s predict a merger rate in the Galaxy, and consequently a rate for bursts of gravitational waves, of at least $\sim 10^{-5}$ yr^{-1}. This rate is slightly larger than the 'best guess' derived from three observed (ns, ns) binaries (Phinney 1991). Also the galactic population produced with these models is consistent with the result from Narayan et al. (1991). Models without kick velocities produce a galactic population that is two orders of magnitude larger than the models with a high-velocity kick. These models are also incompatible with Bailes'(1995) upper limit for coalescence rates of (ns, ns) binary pulsars. The merger rates for these models are an order of magnitude larger than for the models with a kick.

Key words: stars: binaries – stars: neutron star – gravitation

1. Introduction

The emission of gravitational waves was predicted by Einstein (1916, 1918). The existence of gravitational radiation was confirmed indirectly by tracking the Hulse-Taylor (ns, ns) binary pulsar (Taylor and Weisberg 1982). Energy and angular-momentum loss due to the emission of gravitational waves results in a decrease of the orbital period which finally, within a Hubble time, can lead to a merger. Gravitational waves emitted shortly before the merging of two neutron stars are expected to be measurable up to a distance of $\sim$ 950 Mpc (Chernoff and Finn 1993).

Obtaining a good estimate for the merger rate of (ns, ns) binaries is of considerable importance since several gravitational-wave observatories are currently under development (see Vogt 1991 and Abramovici et al. 1992). Merging neutron stars may also be the cause for the observed gamma-ray bursts (see Narayan et al. 1992).

Population synthesis of binaries give the birthrate and the orbital parameters (period and eccentricity) of newborn binary pulsars. From these, birthrate and period-eccentricity distribution, combined with the general theory of relativity, the present orbital parameters and the merger rate can be derived.

Since binary evolution models include many unknown parameters, parameter space cannot be studied systematically. Seven rather extreme models are considered here.

2. Formation and evolution of (ns, ns) binaries

We model the evolution of a population of neutron-star binaries in three separate steps. First, we use the simple equations given by Eggleton et al. (1989) to describe the various evolutionary stages of a single star. Secondly, we combine these equations with a set of prescriptions to make a model that describes the evolution of any binary (see Portegies Zwart & Verbunt 1995). Finally the prescriptions are combined with the distribution of initial parameters for a population of binaries to determine the orbital parameters at birth and the birthrate of (ns, ns) binaries.

Since the model for the evolution of single stars and binaries is discussed extensively by Portegies Zwart & Verbunt (1995) we discuss these issues only briefly.

2.1. Model description

The results of detailed calculations of the evolution of the stellar radius and luminosity (e.g. Eggleton 1971, 1972) have been summarized in the form of convenient fitting formulae by Eggleton et al. (1989). These are applicable to population I stars in a mass range of $\sim$ 0.1 to 100 $M_\odot$ and with a uniform composition (hydrogen: X = 0.7, helium: Y = 0.28 and metals: Z = 0.02).

The transformation of single stellar- to full binary-evolution is performed in our code by evolving two stars synchronously. The model carefully follows the evolution of both stars while taking account of the effects of mass loss by stellar wind (Judge & Stencel 1991), tidal circularization (Zahn 1977), mass transfer on various time scales (Van den Heuvel 1978) and evolution during the stages of common envelope and spiral-in (Livio & Soker 1988, Iben and Livio 1993).

We assume that stars with initial masses in the range of 8 to 40 $M_\odot$ leave a neutron star with a mass of $M_{ns} = 1.34 M_\odot$ (see Thorsett et al. 1993), and a radius of 10 km. For the kick imparted to the neutron star we use a Maxwellian velocity distribution with a dispersion of 450 km s^{-1} in a random direction (see Lyne & Lorimer 1994).

For a detailed description of the binary-evolution model see Portegies Zwart and Verbunt (1995).

2.2. Initial conditions

The zero-age parameters of the simulated binary population were taken with a Monte-Carlo technique from independent distribution-functions for primary mass, mass ratio, period and eccentricity. The birthrate and initial conditions of binaries are assumed to be constant in time. The mass of the primary stars is chosen in the range of 4 $M_\odot$ up to 100 $M_\odot$. The lower limit of 4 $M_\odot$ was adopted in order to be able to normalize the result to the total number of supernovae, which makes a comparison with the observations possible.

For the determination of the initial primary mass we used the power-law analogon of the initial mass function derived by Miller & Scalo (1979) and Scalo (1986) with the exponent α = 2.7. For the mass-ratio distribution we used $\Psi(q_0) \propto 2(1+q_0)^{-2}$ (Kuiper 1935).

The semi-major axis distribution was taken flat in $\log a$ (Kraicheva et al. 1978) ranging from $a \sim 10$ $R_\odot$ up to 10^6 $R_\odot$ (Abt & Levy 1978).

The initial eccentricity-distribution for a binary system is assumed to be independent of the other orbital parameters, and is $\Xi(e) = 2e$ (Heggie 1975, Duquennoy & Mayor 1991).

2.3. The evolution of (ns, ns) binaries

The birthrate of (ns, ns) binaries combined with their distribution over orbital period and eccentricity uniquely determines the present-day galactic population. The evolution of the systems is given by the equations of Peters (1964). These describe the orbital decay of binaries due to the emission of gravitational radiation in terms of the time derivatives of the semi-major axis and the eccentricity. Peters used linearized general relativity to derive these equations. These indicate that orbits shrink and become less eccentric on time-scales strongly dependent on both orbital period and eccentricity. Also wide systems can merge within a Hubble time if their eccentricities are large enough. For example: an (ns, ns) binary system with an orbital period of 100 days merges within 15 Gyr if its eccentricity is as high as 0.99. Peters also derived a formula for the coalescence times of binary systems. The merger rate is given by the product of the birthrate of newborn (ns, ns) binaries and the fraction of these systems that merge within the age of the universe.

3. Results

We compute a total of seven rather extreme models with a total of $2 \cdot 10^5$ binaries each. The models make different assumptions about the presence of an asymmetric supernova (addition 'K' to model name), the amount of angular-momentum loss during non-conservative mass transfer (Models B and BK) and the effect of a more dramatic effect of the common-envelope evolutionary phase (Models C and CK) on the binary orbit.

3.1. The different computations

The results of the computations for model A (standard model) are displayed in the top row of Table 1. In the standard model (A), the total binding energy of the binary is available to remove the common envelope during the stage of spiral-in ($\lambda\alpha$ = 0.5, see Portegies Zwart & Verbunt 1995).

Model B was computed with enhanced loss of angular momentum during non-conservative mass transfer. Mass lost from the binary (in model B) is assumed to leave the system with six times the amount of angular momentum of the orbit per unit-mass; this is similar to mass loss through the second Lagrangian point for small mass ratios (see Portegies Zwart 1995 or Portegies Zwart & Verbunt 1995 for details).

For the computations of model C we used the standard model A but with a more severe spiral-in during the common-envelope phase ($\lambda\alpha$ = 0.25); only half the orbital energy of the binary is available to remove the common envelope.

Model E was calculated with similar parameters as the standard model A but all binaries are circularized with conservation of angular momentum at birth. Also after the induction of an eccentricity due to the first supernova the binary is circularized instantaneously. Finally we computed the models A, B and C with the presence of a kick velocity at the moment of the supernova (models AK, BK and CK respectively). An asymmetric 'kick-velocity' during the formation of a neutron star or black hole in a supernova (Woosley 1987) gives the possibility of disrupting a large fraction of binaries that would have remained bound otherwise.

3.2. Birthrates of (ns, ns) binaries

Fig. 1 shows the period-eccentricity distribution at birth of the (ns, ns) binaries computed with model AK; systems with large orbital periods tend to have larger eccentricities. The supernova fraction $\mathscr{F}_{sn}$ (see Table 1, second column) gives the total number of supernovae that occurred during the computations (with binaries only) divided by the theoretically expected number of single stars massive enough to experience a supernova. Note that in a population of binaries the fraction of stars that experience a supernova is larger than in a population of single stars only. This effect is the result of the presence of secondary stars massive enough to explode. A secondary star can initially be massive enough to form a neutron star or its mass can be increased by mass transfer from its Roche-lobe filling companion.

The third column ($\mathscr{S}$) in Table 1 gives the percentage of all supernovae that occurred during the runs that left an (ns, ns)

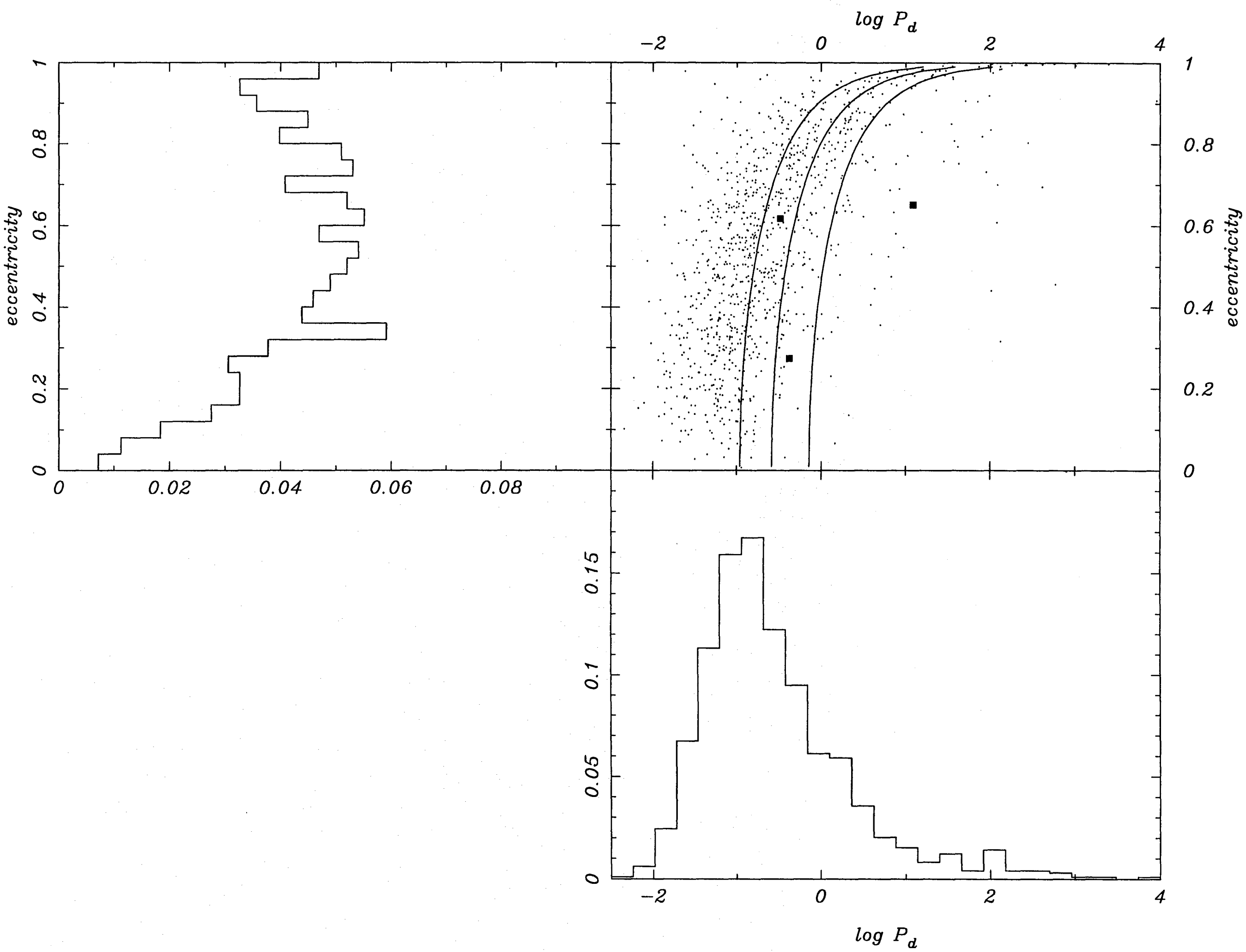

Fig. 1. Period-eccentricity distribution of binary neutron stars (dots) upon birth (from model AK). The lines represent the merger boundaries for the (ns, ns) binaries that merge within 0.1, 1 and 15 Gyr. Observed systems (from left to right: PSR 1913+16, 1534+12, 2303+46) are indicated by a square. 2127+11C is not included in the figure: its evolutionary scenario might differ from the other systems.

Table 1. Birth- and merger rate of (ns, ns) binaries (assuming 40% binaries and a supernova rate of 1/40 yr). Uncertainties in the first two columns are smaller than 0.01.

model	$\mathscr{F}_{sn}$	$\mathscr{S}$	$\mathscr{B}$ [yr^{-1}]	$\mathscr{M}$ [yr^{-1}]
A	1.27	3.35	$3.84 \cdot 10^{-4}$	$2.31 \cdot 10^{-4}$
B	1.29	2.70	$3.12 \cdot 10^{-4}$	$1.89 \cdot 10^{-4}$
C	1.31	2.49	$2.90 \cdot 10^{-4}$	$1.74 \cdot 10^{-4}$
E	1.29	2.59	$2.99 \cdot 10^{-4}$	$2.39 \cdot 10^{-4}$
AK	1.28	0.18	$2.08 \cdot 10^{-5}$	$1.90 \cdot 10^{-5}$
BK	1.28	0.17	$1.96 \cdot 10^{-5}$	$1.82 \cdot 10^{-5}$
CK	1.31	0.08	$9.33 \cdot 10^{-6}$	$8.45 \cdot 10^{-6}$

binary. In the fourth column, the birthrate $\mathscr{B}$ (assuming 40% binaries and a supernova rate of once every 40 years; Tamman et al. 1994, Strom 1994) is presented. The last column gives the merger rate $\mathscr{M}$ of (ns, ns) binaries in the galaxy assuming an age of the universe of 15 Gyr.

3.3. The galactic population and merger rate of neutron-star binaries

An estimate of the number of (ns, ns) binaries in the galactic disk, based on three observed systems, was made by Narayan et al. (1991). Taking into account a lower luminosity cutoff similar to that found for single pulsars, they arrive at a total number of $10^{4.5} z_0$ of such systems, z_0 being the scale height. Using a supernova rate of once every 40 years and a Hubble time of 15 Gyr, we arrive at a birthrate of $2.08 \cdot 10^{-5}$ yr^{-1} for the standard model with kicks (model AK). 91.5% of the (ns, ns) binaries formed with this model merge within a Hubble time (15 Gyr); consequently the merger rate is not much less than the birthrate ($1.90 \cdot 10^{-5}$ yr^{-1}).

The average merger time of the systems that coalesce within a Hubble time is $7.2 \cdot 10^8$ years. This results in a galactic population of $4.0 \cdot 10^4$ (ns, ns) binaries. The uncertainty in this number is dominated by the errors in the Hubble time (7.3 ± 0.6 Gyr according to Pierce et al. (1994) and 16 ± 2 Gyr according to Peebles 1993) and the supernova rate (25% according to Tam-

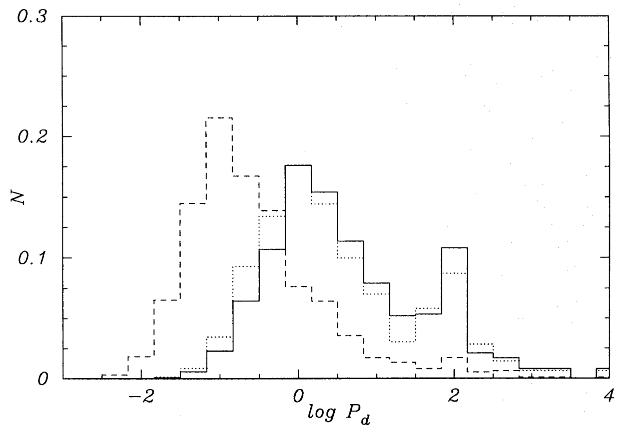

Fig. 2. Period-distribution of (ns, ns) binaries at birth (dashed line) after 7.3 Gyr (dotted line) and after 15 Gyr (full line) as a function of orbital period for model AK. The number densities are normalized to unity.

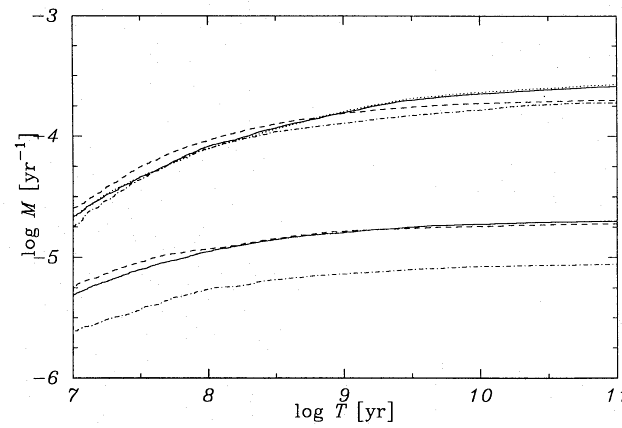

Fig. 3. Galactic merger rates of (ns, ns) binaries as a function of the age of the universe (in log yr) for the different models. Models A and AK : full line, model B and BK: dashes, model C and CK: dash-dot and model E: dots. The upper lines (high merger rates) represent the data without a kick velocity.

mann et al. 1994). Considering the uncertainty in the supernova rate, the results of our computations are in agreement with the estimate of Narayan et al. (1991) for $0.9 \lesssim z_0 \lesssim 1.6$ kpc.

A large fraction of the systems formed with models A, B and C does not merge within a Hubble time (39.8%, 39.3% and 40.0%, respectively). For models AK, BK and CK these fractions are significantly smaller (8.5%, 7.1% and 9.4%, respectively); these models produce relatively more systems with short orbital periods ($\log P \lesssim -1$). It is worthwhile to check how this effects the theoretically predicted present-day distributions. The expected distribution for model AK after 15 Gyr (see Fig. 2) shows that a substantial number of wide binaries ($P \sim 100$ days) should be present. The wider a system, the longer it takes to merge and the more it will dominate the total number of (ns, ns) binaries in the galaxy.

Systems with short orbital periods are depleted in the present-day period distribution; their orbits shrink rapidly and they merge on a short timescale. For all models we find that the peak in the period distribution of (ns, ns) binaries in the galactic disk is at about one day. Fig. 2 shows the period distribution of the standard model with a kick at birth (dashed line), after 7.3 Gyr (dotted line) and 15.0 Gyr (full line). Note that our period distributions (see fig. 2) deviate from the distributions found by Tutukov and Yungelson (1993); we find a higher number density for systems like PSR 2303+46 ($\log P = 1.1$) and a lower number density for systems like PSR 1534+12 and PSR 1913+16.

4. Conclusions

The presence of a kick of order 450 km/s in a random direction turned out to have a much larger effect (order of magnitude) on the birth- and merger rates than adjusting other model parameters (see Table 1). Enhanced loss of angular momentum or a more dramatic spiral-in reduces the birthrates (and consequently the merger rates) of (ns, ns) binaries only moderately.

Enhanced loss of angular momentum for non-conservatively evolving binaries has the strongest effect on binaries with a small initial mass-ratio. These binaries are not the most likely progenitors for binary pulsars (see Portegies Zwart 1995).

In the absence of a high-velocity kick the galactic population of (ns, ns) binaries is larger by two orders of magnitude, which is inconsistent with the estimate of Narayan et al. (1991). These models (A, B and C) result in merger rates which are irreconcilable with Bailes' upper limit for coalescence rates (Bailes 1995) and they produce (ns, ns) binaries in very wide orbits ($P \gtrsim 10^5$ days) which have not been observed. The galactic populations computed using models *with* a high-velocity kick, however, are in good agreement with the estimate of Narayan et al. (1991). These models satisfy Bailes' condition and they give birthrates for (ns, ns) systems close to what Narayan et al. (1991; $10^{-5} z_o$ yr^{-1}) estimates. Phinney's (1991) best guess for the merger rate ($6 \cdot 10^{-6}$ yr^{-1}) agrees best with the result of our model CK ($8.45 \cdot 10^{-6}$ yr^{-1}).

Since we assume that the initial conditions (see Sect. 2) are time independent, the birthrate of (ns, ns) binaries is constant. As a consequence of the formation of binary pulsars that do not merge (due to the radiation of gravitational waves) within the age of the universe, the period distribution of (ns, ns) binaries is not in equilibrium (see Fig. 2); the mean of this distribution moves to longer periods. Consequently, the galactic population of (ns, ns) binaries as well as the merger rate are still increasing (see Fig. 3)!

The computations suggest that the occurrence rate of gravitational-wave bursts for the galaxy is about once every 10^5 yr. This corresponds to a detection-rate for LIGO [1] of ~ 3 events per year within 200 Mpc. In the absence of an asymmetric 'kick' during the formation of a neutron-star in a supernova,

[1] Laser Interferometric Gravitational Observatory

this detection-rate would be larger by an order of magnitude (see also Tutukov & Yungelson 1993).

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