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What can we learn about neutron star binaries from gravity wave observations?

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Abstract. Coalescing neutron star binaries are expected to be among the strongest sources of gravitational radiation to be seen by laser interferometers. We review some recent work on binary neutron stars as sources of gravitational waves. Using the well tested StarTrack binary population synthesis code we show that a significant fraction of the observed binary neutron stars in gravitational waves will have low mass ratios $q \sim 0.6 - 0.7$. These systems contain a star with gravitational mass close to maximum available mass of neutron stars and a neutron star with respectively smaller mass. We show that binary radio pulsars, which are extended systems, are only a few percent of all binary neutron stars observed in gravitational waves. We discuss recent relativistic results on inspiraling binary neutron stars showing how we can impose constraints on equation of state of dense nuclear matter with gravitational wave observations.

Key words. dense matter -equation of state - gravitation -relativity-stars: neutron-stars:binaries -gravitational waves

1. Introduction

One of the most important prediction of Einstein general theory of relativity is gravitational radiation. Coalescing compact object binaries are the strongest and hence most promising sources of gravitational waves (GW) to be detected by the interferometric detectors. Among these binary neutron stars (BNS) have been a subject of extreme interest since the GW signal of a coalescing binary could yield important information about the equation of state at nuclear densities (e.g. Faber et al. 2002). With accurate templates of GW of terminal phases (the hydrodynamical phase or the merger phase) of BNS, it may be possible to extract information about physics of neutron stars from signals observed by the interferometers. It is necessary then to carry out the most realistic studies of BNS (taking into account realistic description of nuclear matter and as-

Send offprint requests to: D. Gondek-Rosińska trophysicaly relevant masses of neutron stars in binary systems) to construct accurate templates of expected GW signal.

All relativistic calculations of the terminal phase of inspiral and merger phase have been done for mass ratio one or close to one (e.g. Limousin, Gondek-Rosińska & Gourgoulhon 2005, Bejger et al. 2005, Shibata, Taniguchi & Uryu 2005, Taniguchi & Gourgoulhon 2003, Faber et al. 2002). The assumption of almost equal masses of neutron stars in binary system was based on the current set of well-measured NS masses in relativistic binary radio pulsars. One has to note that the conclusions based on analysis of properties of radio selected binary pulsars suffer from small number statistics and from several selection effects.

In this paper, we calculate the expected masses of binary neutron stars using well tested StarTrack population synthesis code (Belczyński et al. 2002). We discuss the difference in the mass distribution for binary neutron stars to be observed in gravitational waves and in radio.

Then taking into account both the population synthesis results and properties of the known double neutron star binaries we perform relativistic calculations of the final phase of binary neutron star inspiral using a numerical code based on multidomain spectral methods and constructed upon the Lorene C++ library. We have used several realistic EOS and studied the dependence of gravitational signal on nuclear equations of state. Up to now, all relativistic calculations of the hydrodynamical inspiral phase (except Oechin et al. 2004) or of the merger phase (except Shibata, Taniguchi & Uryu 2005) have been done for binary systems containing NS described by a simplified equation of state (EOS) of dense matter (the polytropic EOS).

2. The expected mass ratio of neutron star binaries observed in radio and in gravitational waves

In order to choose the realistic initial parameters for the calculations of BNS one can follow two leads. The first is to consider the properties of the known double NS binaries. Only seven such systems are known (Thorsett & Chakrabarty 2001, Burgay et al. 2003). The observed sample exhibits a strong peak for the mass ratio close to unity ($M_{\rm NS} \sim 1.35 M_\odot$), and a possible long tail stretching down to smaller values ($q \sim 0.7$). However the radio selected sample includes the long lived pulsars while a significant fraction of the merging binary neutron star population do not satisfy these conditions (Belczyński & Kalogera 2001).There are many evolutionary channels that lead to formation of short lived double NS systems that are hardly observable as radio pulsars.

A second approach is to use the population synthesis method, i.e. to synthesize the population of BNS using the knowledge of their evolution. We calculate the distribution of masses of BNS using the StarTrack population synthesis code (see Belczyński et al. 2002 for detailed description). This method has been already applied to investigate the properties of compact object binaries observed in gravitational waves (Bulik, Gondek-Rosińska & Belczyński 2004, Bulik& Belczynski 2003; Bulik, Belczynski, Rudak 2004). We start with binaries at zero age main sequence, evolve a large number of them, and consider the properties of the resulting population of compact object binaries. For each binary we note the masses of individual objects. Assuming a value for the maximum mass and minimum mass of a neutron star we extract the double neutron star binaries from all compact binary systems. In this paper we assume the $M_{\rm min} = 1.2\ M_\odot$ and the maximum mass of neutron stars $M_{\rm max} = 2.5\ M_\odot$.

We define the mass ratio of a binary as the ratio of less to more massive component, so it is always less than unity. In Figure 1 we present the distributions of the mass ratio q obtained with the population synthesis calculations with the standard model of stellar evolution (denoted as model A in Belczyński et al. 2002). This model can be considered as the "best bet" and contains all values of the stellar evolution parameters that are generally considered to be in best agreement with observations. In order to assess the robustness of the results we investigate 20 extra different models of stellar evolution, where we vary the parameters describing various stages of stellar and binary evolutions

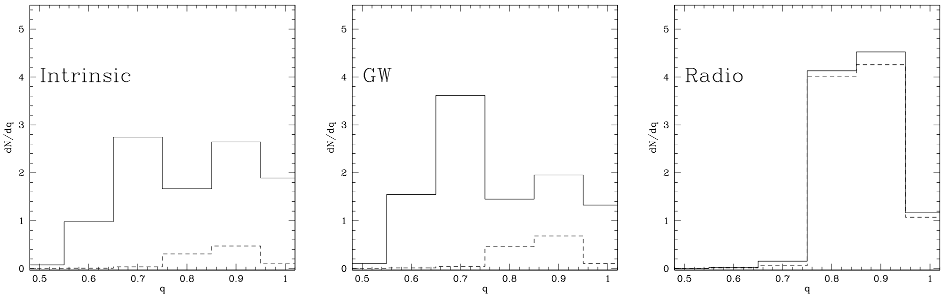

Fig. 1. The results of the population synthesis calculations obtained with the standard model of stellar evolution under assumption of maximum gravitational mass of neutron stars $M_{max} = 2.5\,M_\odot$. The expected mass ratio distributions in the volume limited sample; in the gravitational waves observations (flux limited) selected sample and in the radio observations selected sample from left to right respectively. Solid lines corresponds to all binary neutron stars while the dashed lines show the contribution of the population of systems with the lifetime $t_{grav} > 100$ Myrs (binary radio pulsars)

(see Bulik, Gondek-Rosińska & Belczyński 2004). Figure 1 contains the distributions of the entire population of binary neutron stars(solid line), and these with the lifetimes longer than 100 Myrs (dashed line). All the observed binary radio pulsars lifetimes (from formation till merger) are longer than 100 Myrs. The left panel of Figure 1 corresponds to the intrinsic distribution of expected mass ratios of neutron stars in binary systems, which is the one obtained in a simulation without taking into account observability. In other words this is the distribution of mass ratios in double neutron star systems formed in a short star-burst, when we count all the systems that appear in the simulation. The middle panel of Figure 2 corresponds to the distribution of mass ratios of binaries selected by observability in gravitational waves. It is skewed toward the heavier ones since the volume in which they are detectable is $\propto \mathcal{M}^{5/2}$, where $\mathcal{M} = (m_1 m_2)^{3/5}(m_1 + m_2)^{-1/5}$ is the chirp mass being a function of individual masses m_i. The low mass ratio binaries are usually the ones containing a neutron stars with the typical mass and a one with the mass near to the maximal value allowed by the equation of state (see also Fig. 2). The right panel corresponds to the expected ratios of neutron stars seen in radio. Here we assume that all the binary neutron stars contain millisecond (recycled) pulsars with very long lifetimes as pulsars. They are observable as pulsars for the entire lifetime of the binary. In practice this overestimated the observability of the short orbit systems. The short orbit systems are difficult to detect as pulsars because the pulse frequency is blurred by the orbital motion in the power spectrum. In this distribution each pulsar is weighted by its lifetime due to the gravitational wave emission t_{grav}. The binary pulsars observed in the radio tend to have similar masses. The long lived systems (with $t_{grav} > 100$ Myrs, dashed line in Figure 1) have evolved without the possibility of significant accretion onto a neutron star while the short lived systems (with $t_{grav} < 100$ Myrs) did undergo common envelope episodes when hypercritical accretion onto the neutron star was possible. This common envelope episodes have two consequences: they tightened the orbits and lead to decrease of the mass ratio of the final double neutron star system, as one of the neutron stars accreted some matter.

3. The expected masses of neutron stars observed in gravitational waves

In Figure 2 we present the distribution of the mass ratio q and masses to be seen by GW de-

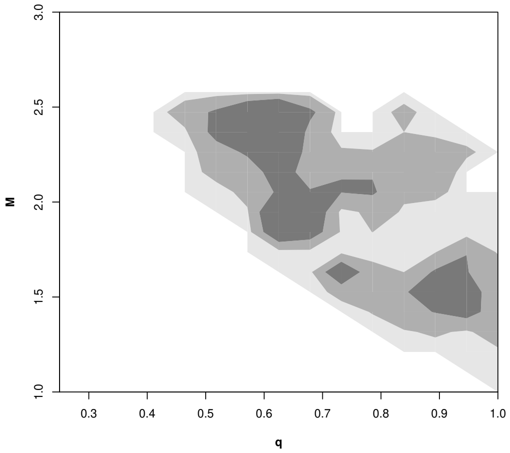

Fig. 2. Distribution of masses (in $M_\odot$) and mass ratios observed in graviational waves: results of population synthesis. The darkest shading represents the region containing 68% of the systems, the medium gray shading represents the region containing 95% of the systems, and all the systems are enclosed within the light gray shading.

tectors. The main result of our calculation is that a significant fraction of the observed BNS in GW will have equal masses close to 1.4 $M_\odot$ or will contain NS with a mass close to the maximum mass allowed by the EOS and NS with respectively smaller mass: $q \sim 0.6 - 0.7$. The second case has so far been overlooked in relativistic calculations of hydrodynamical inspiral or the merger phase. We can determine the individual masses of the two neutron stars in the system taking into account the frequency evolution of the gravitational signal at the inspiral phase and high-order PN effects on the phase evolution of the signal. With the information about maximum mass of a neutron star one can impose constraints on equation of state of neutron stars in supranuclear densities.

4. The last orbits of binary neutron star inspiral

The evolution of a binary system can be separated into three phases : *point-like inspiral* where orbital separation is much larger than the NS radius, *hydrodynamical inspiral* where orbital separation is just a few times larger than the radius of the NS so that hydrodynamics play an important role, and *the merger* in which the two stars coalesce dynamically. Detection of gravitational waves emitted by an inspiraling binary leads to determination of the individual masses of the neutron stars. In addition we can get the compactness parameter M/R of neutron stars based on the observed deviation of the gravitational energy spectrum from point-mass behavior at the end of inspiral (hydrodynamical inspiral). Having both M and R from GW observations we can impose strong constraints on EOS.

In the hydrodynamical phase, one may consider a binary NS system to be in a quasiequilibrium state. For a given EOS, we construct so called an *evolutionary sequence* by calculating a sequence of quasiequilibrium irrotational configurations with constant baryon mass and decreasing orbital separation. Computations of quasiequilibrium sequences are performed within the Isenberg-Wilson-Mathews approximation to general relativity (Baumgarte & Shapiro 2003). In order to calculate the last orbits of inspiral phase (the hydrodynamical phase) of binary NS we use a highly accurate numerical code based on the LORENE library (http://www.lorene.obspm.fr) which solves the five elliptic equations for the gravitational field supplemented by an elliptic equation for the velocity potential of irrotational flow. The complete description of the resulting general relativistic equations, the whole algorithm, as well numerous tests of the code can be found in Taniguchi et al. (2001).

We perform calculations of the final phase of inspiral of equal mass ($M_1 = M_2 = 1.35\,M_\odot$) irrotational neutron star binaries and strange quark star binaries. We use six different types of equations of state at zero temperature - three realistic nuclear equations of state of various softness (*BPAL12* - Bombaci95, Prakash et al. 1997, *AkmalPR* - Akmal et al. 1998, *GlendNH3* - Glendenning 1985) and three different MIT bag models of strange quark matter. We calculate the energy emitted in GW vs frequency of GW for each realistic EOS ((Gondek-Rosińska et al. 2004a,b, Bejger et al. 2005, Limousin, Gondek-Rosińska & Gourgoulhon 2004, 2005). The physical inspiral of binary compact stars terminates by either the orbital instability (turning point of the binding energy) or the mass-shedding limit. In both cases, this defines the innermost stable circular orbit (ISCO). The orbital frequency at the ISCO (depending strongly on M/R for equal mass binaries) is a potentially observable parameter by the gravitational wave detectors.

We find that the ISCO is given by an orbital instability for binary strange quark stars (Limousin, Gondek-Rosińska & Gourgoulhon, 2004, 2005, Gondek-Rosińska & Limousin 2005) and by the mass-shedding limit for neutron star binaries (Bejger et al. 2005). The gravitational wave frequency at the ISCO is found to be $\sim 1100-1460$ Hz for two $1.35\ M_{\odot}$ irrotational strange stars described by the MIT bag model and between 800 Hz and 1230 Hz for neutron stars.

We have extended current equal mass binary neutron star models to include the most realistic masses of components. We show that for neutron star binaries described by the AkmalPR EOS the merger will take place for high frequencies of gravitational waves > 1.1 kHz regardless of the mass ratios 0.675; 0.9; 1 (Gondek-Rosińska et al. 2004b).The smaller mass ratio is (in our case the BNS with lower mass ratio have higher masses) the higher amount of energy emitted in GW.

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