Gravitational waves from binary compact star mergers in the context of strange matter

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Abstract. In this article we will focus on the appearance of the hadron-quark phase transition and the formation of strange matter in the interior region of the hypermassive neutron star and its conjunction with the spectral properties of the emitted gravitational waves (GWs). A strong hadron-quark phase transition might give rise to a mass-radius relation with a twin star shape and we will show in this article that a twin star collapse followed by a twin star oscillation is feasible. If such a twin star collapse would happen during the postmerger phase it will be imprinted in the GW-signal.

1 Introduction

The four confirmed detections of the gravitational waves (GWs) emanated from the inward spiral and merger of pairs of black holes marked the beginning of a new era in observational astrophysics. The new field of gravitational-wave astronomy will uncover violent, highly energetic astrophysical events that could not be explored before by humankind. Without doubt, GWs from a binary compact star merger will soon be announced by the LIGO-VIRGO collaboration including an electromagnetic counterpart.[1] By analysing the power spectral density profile of the post-merger emission, the GW signal can set tight constraints on the high density regime of the equation of state (EOS) of elementary matter. The modification of the EOS due to a potential influence of a hadron-quark phase transition (HQPT) and the impact of strange quark matter on the EOS, which is currently solely probed in relativistic heavy ion collisions, might be imprinted in the post-merger phase of the emitted GW of a merging compact star binary. Hybrid star mergers represent optimal astrophysical laboratories to investigate the QCD phase structure and in addition with the observations from heavy ion collisions will possibly provide a conclusive picture on the QCD phase structure at high density and temperature [1].

2 Gravitational waves from binary compact star mergers

Numerical simulations of merging neutron star binaries in full general relativity show that the maximum (central) value of the rest-mass density $\rho_{\max}$ of the produced hypermassive neutron star (HMNS)

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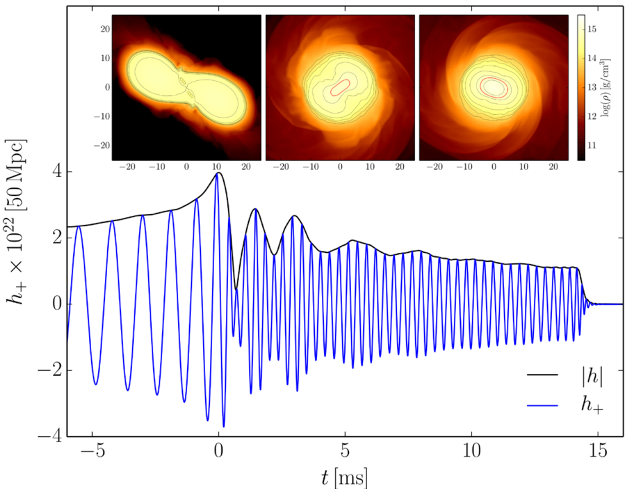

Figure 1. Logarithm of the rest-mass density profile (time snap-shots at $t = -0.17, 4.05, 13.16$ ms) and gravitational wave amplitude $|h|$ and h_+ at a distance of 50 Mpc for the ALF2-EOS with $M_{\rm tot} = 2.7 M_\odot$. Soon after the merger ($t := 0$) the density reaches values above $\rho_{\rm trans} = 3\,\rho_{\rm nuc}$, forming a mixed phase inner region of deconfined quark matter. At $t_{\rm BH} = 14.16$ ms the HMNS collapses and the free quark matter will be macroscopically deconfined by the event horizon of the formed rotating black hole.

increases with time until it either collapses to a black hole or reaches a quasi-stationary hydrostatic equilibrium [2]. The emitted GWs of the merger and post-merger phases are strongly determined by the high density region of the EOS reaching values $\rho_{\rm max}/\rho_{\rm nuc} \approx 2-6$ ($\rho_{\rm nuc} := 2.705 \times 10^{14}$ g/cm^3). Fig.1 shows the GW-amplitude of an equal-mass neutron star binary merger simulation, wherein the used EOS (ALF2) has incorporated a slight phase transition to color-flavor-locked quark matter [2]. The upper panel of Fig.1 depicts the logarithm of the rest mass density profiles and the boundary of the HQPT is marked with a red curve. Although the ALF2-EOS comprises a HQPT, the properties of the resulting hybrid stars are hardly distinguishable from purely hadronic stars as the transition to the deconfined phase is very weak. So far, no simulation of a binary compact star merger containing a strong HQPT has been performed. However, the effects of a strong HQPT have been investigated in the context of static [4] and uniformly rotating hybrid stars [5] and the results show that tremendous changes in the star properties might occur including the existence of a third family of compact stars - the so called "twin stars" [6].

3 The Twin Star Collapse

The possibility of neutron star twins has been discussed in the context of different types of phase transitions including pion condensation, HQPTs and phase transitions to hypermatter [3]. A twin star behaviour is present, if the third stable sequence of compact stars is separated from the second one by an unstable region. Fig. 2 shows a typical twin star behaviour for static hybrid stars calculated using the Tolman-Oppenheimer-Volkoff equation. For the hadronic part of the EOS a DD2-RMF parametrization has been used, while the HQPT was modelled using a soft piecewise polytrope mixed phase region ($\Gamma_{\rm MP} = 1.07 \in \rho/\rho_{\rm nuc} = [3, 4.5]$) followed by a stiff deconfined quark phase ($\Gamma_{\rm QP} = 5.7 \in \rho/\rho_{\rm nuc} =]4.5, \infty[$). In [4] it was argued that the unstable region (dotted curves in Fig. 2) opens the possibility of a catastrophic rearrangement of the twin star from one configuration to the other with a prompt burst of neutrinos (with energies of about 100 MeV) followed by a gamma ray burst (with photon energies of about 1 MeV) and a total release of energy of about 10^{52} erg. However, dynamical simulations of such a twin star collapse have not yet been performed. In the following we will present for the first time the results of numerical simulations of a twin star collapse performed

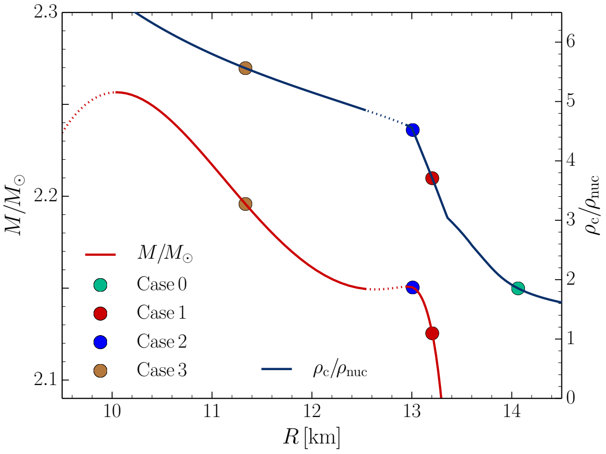

Figure 2. Mass-radius and (central rest-mass)-radius relations for a hybrid star. The underlying EOS has a strong hadron-quark phase transition implemented, where the mixed-matter phase exists in the rest-mass density range $3\,\rho_{\rm nuc} \leq \rho \leq 4.5\,\rho_{\rm nuc}$). The two stable "twin star" solutions are separated by a small unstable region which is visualized using dotted curves. The coloured circles display the initial configurations of the four different stars used in the underlying dynamical simulations (see Fig. 3).

in full general relativity using the `Einstein Toolkit` and the `WhiskyTHC` code. The four different initial configurations of the compact stars (coloured circles in Fig. 2) were perturbed by a radially inward directed initial velocity kick. Fig. 3 shows the time dependence of the maximum value of the rest-mass density and the minimum of the lapse function. With the exception of *Case 0* the unstable twin star region is reached during the evolution and the compact objects oscillate between their two twin star configurations. To illustrate these twin star oscillations, the evolution of the rest-mass density profile for several time snap-shots is displayed in Fig. 4. The black curve shows the profile of the initial star of *Case 2*, which is placed in the stable part of the mass-radius relation in the vicinity of the maximum mass star of the second sequence (see Fig.2). This initial star is radially perturbed using an inward directed velocity kick and as a result its density increases and the star shrinks (see solid blue curve in Fig. 4). During the collapse the density in the core reaches values $\rho/\rho_{\rm nuc} > 4.5$ where

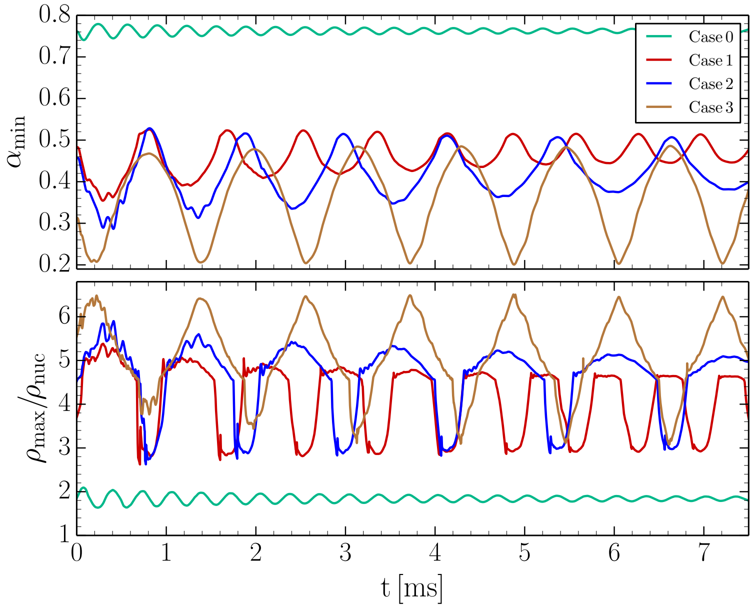

Figure 3. Minimum value of the lapse function $\alpha_{\rm min}$ (upper panel) and maximum of the rest-mass density $\rho_{\rm max}$ (lower panel) versus time in milliseconds. The initial stars configuration has been radially perturbed in the same way for all of the different cases. Due to the low value of the initial rest-mass in *Case 0* (green curve), the interior composition of neutron star never reaches the values where the HQPT starts and as a consequence the oscillations show a regular property.

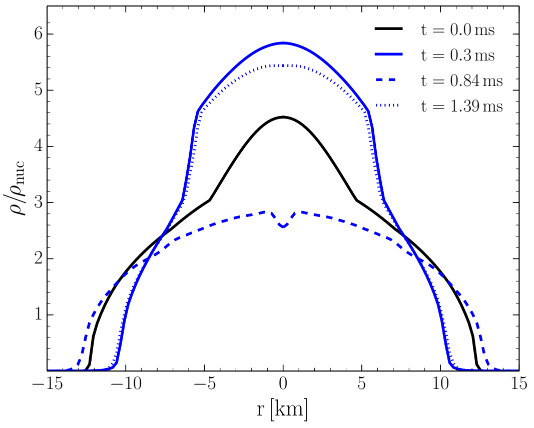

Figure 4. Rest-mass density profiles $\rho(r)/\rho_{\rm nuc}$ for four different time snap-shots calculated using the initial condition of *Case 2*. The black curve shows the initial profile which contains a mixed phase region but no pure quark phase in its inner core ($r \leq 4.5$ km). The solid blue curve depicts the profile of the first maximum of the twin star oscillation and shows the structure of a hybrid star with a large pure quark phase. The dashed curve depicts the profile near the first minimum of the twin star oscillation, while the dotted curve shows the profile in the second maximum.

the stiff part of the pure quark phase generates a high pressure which counteracts against the strong gravitational attraction. As a result, the large deconfined pure quark core pushes the fluid outward, causing the first twin oscillation. The dashed curve depicts the end point of the first oscillation at $t \approx 0.84$ ms. The shape of the profile clearly shows that this star is solely composed of hadronic matter. It should be mentioned that the expected emission of neutrinos and high energetic photons or viscosity effects, which are not included in the simulations, will damp the oscillations.

4 Summary

Neutron star mergers represent optimal astrophysical laboratories to investigate the QCD phase structure using a spectrogram of the post-merger phase of the emitted gravitational waves. As gravitational waves emitted from merging neutron star binaries are on the verge of their first detection, it is important to understand the main characteristics of the underlying merging system in order to predict the expected GW signal. Numerical-relativity simulations of merging neutron star binaries show that the emitted GW and the interior structure of the generated hypermassive neutron stars depends strongly on the equation of state. The appearance of the hadron-quark phase transition in the interior region of the HMNS will change the spectral properties of the emitted GW if it is strong enough. If the unstable twin star region is reached during the "post-transient" phase, the f_2-frequency peak of the GW signal will change rapidly due to the sudden speed up of the differentially rotating HMNS.

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