Binary neutron star mergers with quark matter equations of state

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With recent observations of gravitational wave signals from binary neutron star mergers (BNSM) by LIGO-Virgo-KAGRA (LVK) Collaboration and NICER, the nuclear equation of state (EoS) is becoming increasingly testable by analysis with numerical simulations. Numerous simulations currently exist exploring the EoS at different density regimes for the constituent neutron stars. In this paper we summarize the GR three-dimensional hydrodynamics based simulations of BNSMs for EoSs with a specific emphasis on quark matter EoS at the highest densities.

Keywords: Neutron star binaries; Gravitational waves; Nuclear equation of state.

1. Introduction

Neutron stars are an ideal laboratory in which to probe the properties of matter at very high density. The microphysics of nuclear interactions in a neutron star reflects in its large structural features like its mass and radius. This results in modulation of the evolution of their binaries. This amplification of subatomic physics makes probing the physics at scales 10^{-14} m plausible at neutron star size 10^4 m scales. In particular, neutron star binary systems provide a means to analyze the pressure of nuclear matter at all domains of nuclear densities. Indeed, the first detection of gravitational waves from the binary neutron star merger GW170817 by the LIGO-Virgo Collaboration and the pulsar PSR J0740 by NICER has provided fundamental new insights into the nature of dense neutron-star matter.[1,2] The detected gravitational wave signal depends upon the tidal distortion of the neutron stars as they approach merger. For example, in the LIGO analysis[1,3] the tidal polarizability[4,5] was deduced from post-Newtonian dynamics implying that the radius of the stars of 1.4 $M_\odot$ is in the range 10.5 km $\leq R \leq$ 13.3 km. This has placed tight constrains on the equation of state (EoS) for nuclear matter as the stars approach merger.

Here we summarize the work done in the regime of quantum chromodynamics (QCD) formed during the merged neutron star binaries. The detection of the gravitational radiation during the postmerger could be used as a sensitive probe of both the order of the quark-hadron phase transition and the properties of matter in the non-perturbative regime of QCD.

The prospect of the postmerger evolution being used to explore EoS issues has been proposed for some time.[6] Indeed, there have been several investigations into the effects of the formation of quark matter in the BNSM.[7–10] For the most part these studies have considered effects of a first-order phase transition and the formation of a mixed quark-hadron phase. In this case the first-order transition can soften the EoS and hasten the formation of the black hole.

The neutron star-ringdown occurs in a frequency range 2-5 kHz and thus the strain strength for a binary at 50 Mpc is not easily accessible to aLIGO/aVirgo/KAGRA. However, the third generation GW observatories, the Einstein Telescope and the Cosmic Explorer, will have enhanced sensitivities in this frequency range and will be susceptible to observing postmerger evolution of a BNSM. Further, there is a suggestion in the literature (see Refs. 11, 12) of post merger energy output in gravitational radiation from the GW170817 event that appears to be an extended ringdown (see however Ref. [13].) In Ref. [12] it was hypothesized that such extended emission might result from spin down of a magnetar.

2. Equation of state

To describe the evolution of matter completely, the hydrodynamics equations require an additional constraint that relates the various state variables of the matter, i.e. pressure, density, electron fraction, chemical potentials, etc. in a neutron star.[14,15] Constraints on the equation of state (EoS) have been placed by aLIGO based upon the tidal polarizability deduced from the chirp associated with event GW170817.[1,3] Any realistic description of the equation of state (EoS) of matter formed in the merger of neutron stars must also include the consequences of a transition between hadronic matter and quark matter. As the merged system collapses to a black hole it unavoidably encounters all dense phases of matter, particularly the transition to quark matter.

It is worth noting that as the baryon density and chemical potential increase the QCD strong coupling constant α_s approaches unity and a nonperturbative approach to QCD is imperative. In particular, There is rich physics in this region of the quark-matter phase diagram including the generation of constituent quark masses, due to chiral symmetry breaking,[16] and quark pairing leading to color superconductivity.[17] The evolution of these effects until the asymptotic regime must be described during the collapse.

The transition from hadronic matter to quark matter is not yet fully understood.[18] However, people have proposed many interesting models to describe the transition from hadronic matter to quark matter at densities between 2-5 ρ_{nuc}.[19,20] Considering strongly interacting quark states for the crossover density region, people could have made the EoSs satisfying 2 times solar mass observational bound.[21] Also, many models having the first order phase transition features have been proposed to describe the transition.

3. Power spectral density of the gravitational waves

In addition to f_{max} which could be obtained from the instantaneous change of the phase of h, the power spectral density (PSD) of the strain, h, poses to reveal further features about the star's EoS. Refs. [22, 10] shows the presence of high frequency spectral features in the f_1, f_2 and f_3, as defined in Ref. [22] modes for binaries with different EoS description. The positioning and strength of the frequencies depends on the nature of the EoS. One of the important aspects about the power spectra of the mergers is that the strength of the PSD at 2 kHz to 5 kHz frequencies is weak enough that the current LVK detectors are unable to discern them from the noise. It is also pointed out that the third generation gravitational wave interferometers, the Einstein Telescope and the Cosmic Explorer, would have higher sensitivities at these frequencies making them more likely to resolve the f-modes. Further, Ref. [22] notes the occurrence of 'quasiuniversal' relations relating f-modes with compactness and the maximum frequency of chirp with tidal deformability of a single stable NS for the given EoS. These relations can be explained partially by the stiffness of the equation of state, softer EoSs leading to higher f-modes. Recent studies of the BNSM with the phase transtion have examined whether the features of the phase transition could be imprinted in the f-mode frequencies, for example, the shift of the peak frequencies.[8,23] We are currently investigating the spectral features of the BNSM with a specific crossover EoS and have found some interesting postmerger behaviour showing elongated duration owning to the stiffened EoS.[18,19,24]

4. Conclusion

We have briefly summarized some recent studies on the BNSM with quark matter. An observation of the postmerger and the collapse in a BNSM could be used to determine the nature of the phase transition and the physics at the crossover densities. The next generation GW detectors will probe and unveil the physics of this dense matter physics with their highly improved power of detectabilities at higher GW frequencies.

Finally, noting a caveat that there have been no studies fully considering such as MHD and neutrino transport for the simulations, however, we expect that essential features of the non-perturbative characters of the QCD would be revealed and confirmed without taking these considerations into account.

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