Gravitational-Wave Modeling from Binary Neutron Stars on Loewe Cluster

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Introduction

One of the last predictions of Einstein‘s general relativity is the existence of gravitational waves (GWs), which is ripples of spacetime with the speed of light and is produced by the acceleration of mass. In order to confirm this prediction, there is currently a global effort to detect the radiation from astrophysical sources. One of the most likely sources is the inspiral and merger of binary neutron stars (BNSs) because they are the most violent events in the universe.

Although those waves are extremely weak at the Earth, i.e., the typical non-dimensional amplitude is „h~(size of atom) / (distance between Sun and Earth)“, the first signal will be observed by advanced detectors such as LIGO, Virgo, and KAGRA, which will be operational within five years. The expected realistic detection-rate is around 40 events per year.[1] In order to enhance the detectability and to interpret the observational data, it is necessary to prepare theoretically accurate modeling for the dynamics of the sources and for the radiated waveforms, in which we rely on cutting-edge numerical relativity simulations. Such simulations can only be carried out on large scale supercomputers.

Methods

In this project, we statistically studied the merger of BNSs with various masses and equation of states (EOSs). Our calculations were performed by using a large collection of software modules based on the CACTUS computational toolkit,[2] which provides infrastructure for large scale simulations, including MPI parallelization, mesh refinement, memory management, and data storage. The equations of general relativity are integrated using the McLachlan module from the Einstein Toolkit,[3] which is based on high order finite differencing methods. The hydrodynamic equations are evolved using our privately developed code, Whisky, in which it employs modern finite volume methods for conservation laws in conjunction with various approximate Riemann problem solvers and a piecewise parabolic reconstruction algorithm. Initial data for BNSs was generated using the LORENE code,[4] a solver for elliptic PDEs based on spectral methods.

Results

For each model, we extracted the gravitational waveform, and obtained a few peak-frequencies via the corresponding power spectrum contains contributions from the hyper-massive neutron star (HMNS) stage. We studied important and interesting correlations between such characteristic frequencies and physical quantities in the binary such as the averaged mass and radius. Then, for example, we found a new correlation between the low-frequency peak and the total compactness of the stars in the binary is essentially universal, while the high-frequency peak depends on the equation of state. By using these correlations we found, finally we constructed a method to decide the redshift[5] and developed a powerful tool to constrain EOS [6,7] from observed GWs.

Outlook

These results are really important and will help us to extract many physical information of BNSs from observed GWs in near future. Although we consider only the merger of BNSs and the HMNSs in this project, we will focus on the late inspiral phase of BNSs to more robustly extract the physical information in our next project.

Reference

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