国立天文台天文シミュレーションプロジェクト 成果報告書

研究課題名Gravitational Wave from Binary neutron star mergers

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利用カテゴリ XC-MD

以下に成果の概要を記入してください。ページ数に上限はありませんが、最終的に提出される PDF のファイルサイズの上限は 2 MB です。

What are the new states of matter at exceedingly high density and temperature is one of the most attractive questions in the century. Since the first principle is not yet able to describe the interaction among neutrons at several times of the saturation density, and the laboratory experiment can only constrain the related parameters within nearly two saturation density, the neutron stars, whose central density could up to 5~10 times of nuclear saturation density, are ideal astronomical objects. With the gravitational wave (GW) era in progress, data analyzing from the inspiral phase bring the information about neutron star properties such as chirp mass, mass ratio, and tidal deformability. Also, we can detect the signal from the post-merger phase after optimizing high-frequency noise in the full sensitivity era. In one year using the XC-MD, We finish several simulations based on WhiskyTHC, an enhanced version of Whisky code, which contains some new algorithms in solving hydrodynamic equations, and it could be used to do simulation based on the finite-temperature equation of state(EOS). We mainly analyze the influence on post-merger dynamics from thermal pressure, and the difference between finite temperature EOS and the cold EOS in zero-temperature with an additional thermal part in "ideal-gas" approximation. The result shows the delay time in collapse, and peak frequency in gravitational wave spectra is strongly affected by thermal pressure, and finite temperature EOSs are necessary when we need further discuss the frequency peaks shift from pure hadronic models and phase-transition models.

Codes

In the binary neutron star(BNS) simulation, we use LORENE to solve the Tolman–Oppenheimer–Volkoff (TOV) equation, and generate the initial data for binary stars. Lorene is a set of C++ classes to solve various problems arising in numerical relativity, and more generally, in computational astrophysics. It provides tools to solve partial differential equations by means of multi-domain spectral methods and calculates various quantities of neutron stars like mass, radius, the moment of inertia. The simulations for binary stars based on WhiskyTHC, an enhanced version of the Whisky code. It is also constructed on the "Cactus-thorns" format, the same as the Einstein toolkit, so that with the list of thorns, many functions could be achieved, such as HDF5 parallel file I/O, adaptive mesh refinement. For solving the hydro evolution, we use the WhiskyTHC, which evolves the equations of general relativistic hydrodynamics (GRHD) in 3D Cartesian coordinates on a curved dynamical background. It was initially developed by and for members of the EU Network on Sources of Gravitational Radiation, and the new generation code has higher-order methods for solving both of the spacetime and hydrodynamic evolution.

Simulations for BNS mergers

The simulations were based on tabulated EOS LS220, with initial data generated in symmetric configuration with 1.35 M_{sun} for each star. Since the neutron stars' temperature could increase up to 50 MeV, one crucial thing is to know how thermal pressure affected the hydro evolution in the post-merger phase. For analyzing this influence, we used two different treatments for the thermal part in simulations. One is using the cold EOS in zero-temperature and additional thermal part. In this formula, pressure in EOS table is only the function of density and internal energy and the temperature given from thermodynamics equations, which based on "ideal-gas" assumption. The other one is the finite-temperature EOS, in which pressure is a function of density, internal energy, and temperature in EOS table. The simulation result shows that post-merger behavior is affected when we use different adiabatic indexes in the simulation and when the index Gamma=2(G2), the most potent peak frequency is near the finite temperature case. Fig.1 shows the maximum density evolution, ρ_0 represent the saturation density for nuclear matter. In the ideal-gas approximation case, a larger thermal index means more thermal pressure contributing to the remnant so that the system could survive longer. Usually, the Gamma=2 for ideal-gas is the high limit since it would cause causality problems if the index is larger. The simulation based on finite-temperature EOS is different from them, which shows a much longer delay time to collapse, indicates that the ideal-gas approximation in the thermal part is not good enough to represent the properties of the real finite-temperature EOS.

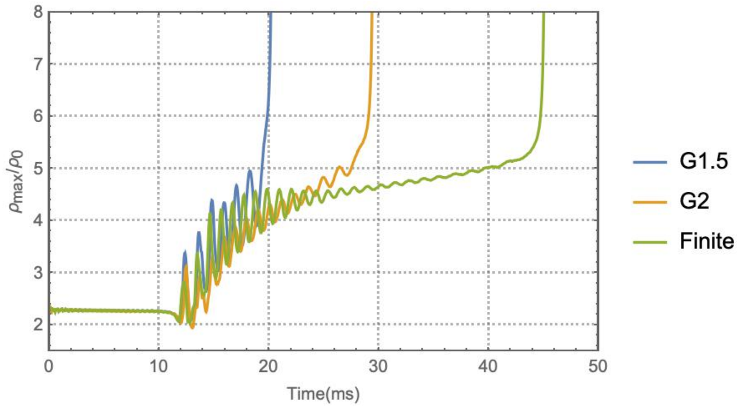

Fig.1

Fig.2 shows the time-domain gravitational wave. In the inspiral phase, all of the three cases are same; since the temperature is almost zero, there is no thermal pressure contribution to neutron stars. After the binary merger, they show different behaviors, one is the delay time to collapse as discussed above, and another one is the shape of the GW template. For a detailed comparison, we analyzed the power spectrum of GW.

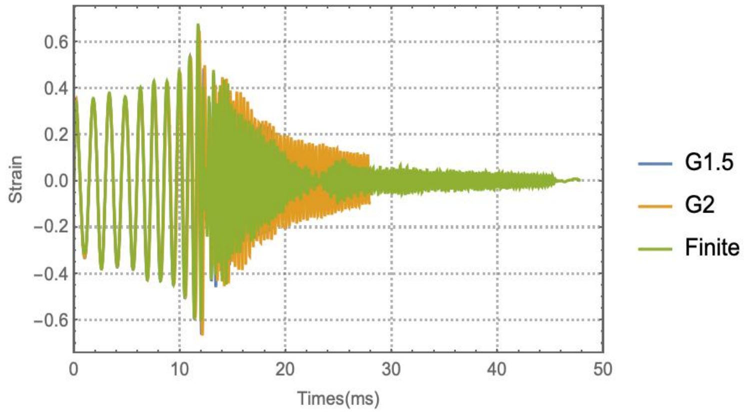

Fig.2

From Fig.3, all of the peaks in G1.5 case shift to higher frequency compared to G2 case. This is because there is more thermal pressure in G2 case, and it makes remnant less compact so that the oscillation frequency would decrease. Also, the G2 case seems to be much closer to the finite-temperature case at the first and second peak, but separate at a higher frequency, it causes the difference shown in the time-domain GW template. As we would like to extend our work to EOS with first-order phase transition and hardon-quark crossover, the simulation based on finite-temperature EOSs would be more reliable when we analyze the post-merger spectrum.

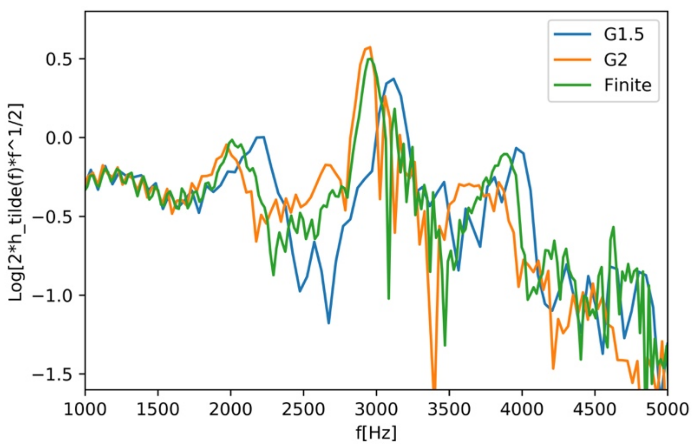

Fig.3