Black Hole – Neutron Star Mergers

Numerical-Relativity Simulations of Black Hole – Neutron Star Systems

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In Short

- How can we do numerical simulations for a collision of a black hole and a neutron star or two neutron stars?
- How can we include more realistic physical processes, such as magnetic fields or radiation, in our simulations?
- How do the system dynamics and individual properties of neutron stars and black holes affect the emitted gravitational wave and electromagnetic signals?

Gravitational waves are tiny ripples in space-time caused by the acceleration of massive objects predicted by Einstein's general theory of relativity about a hundred years ago. Compact binary objects, i.e., black holes and neutron stars, emit gravitational waves when they orbit each other and eventually merge. The first detection of a merger of two black holes in 2015 was a breakthrough and ushered in a new era in gravitational-wave astronomy. Since then, about 100 such events have been detected, including binary neutron star and black-hole–neutron-star mergers. The study of these systems, particularly those involving neutron stars, enables new investigations and confirmations of general relativity and provides unique insights into the behavior of matter at supra-nuclear densities under conditions that are unreachable in any terrestrial experiments. In addition to gravitational waves, these mergers can also produce electromagnetic counterparts originating from the outflowing matter. The ejecta is thought to be the source of the heaviest elements in our Universe. Thus, the analysis of these signals additionally allows us to learn more about the origin of these elements.

However, to obtain actual physical information about the binary objects, we need theoretical predictions to compare the observational data with. For this purpose, we have to solve Einstein's field equations (for an accurate description of the gravitational field) together with the equations of general relativistic hydrodynamics (to describe the behavior of the fluid). Similarly, we need models for the electromagnetic signals related to the material ejected in the merger process. To further develop and improve our models, we require accurate simulations based on numerical relativity. The support from HLRN allows us to perform these simulations for the merger of black holes and neutron stars.

We use the BAM code [1], which allows us to perform state-of-the-art numerical-relativity simulations. BAM applies finite-difference stencils for spatial differences and high-resolution methods for capturing shocks in the fluid variables. To account for the different length scales that must be resolved (the strong-field region near the compact objects to handle the steep gradients of the gravitational field and the far-field region where the gravitational wave signals are extracted), an adaptive mesh refinement technique is adopted in which the domain consists of a hierarchy of refinement levels. The code employs a hybrid OpenMP/MPI parallelization strategy.

We are continuously working on our code to improve the quality of our simulations. The two most important code changes in the past year focused on the improvement of the physical descriptions. First, we have incorporated a more realistic microphysical treatment [2]. We are now able to use realistic descriptions for the interior of the neutron stars based on realistic nuclear-theory models. We have also implemented a scheme for the evolution of neutrino radiation, which is particularly important for the description of ejecta. Secondly, we included magnetic fields in our simulation. These also play a crucial role, especially in the dynamics after the merger.

In the second year of our allocation bbp00049, we have expanded our research prospects at HLRN from simulations of black-hole–neutron-star systems to binary neutron star systems. Below we summarise some highlights of our studies from the last year:

1. We contributed to the extension of the available gravitational waveforms of neutron star merger for the community. As such, results from our simulations have been published in the second data release of the Computational Relativity (CoRe) collaboration [3]. This database is used for comparison with observational data, which is particularly important given the start of the next gravitational-wave observing run in May 2023.

2. We used long-term simulations of binary neutron star systems to analyze the expansion characteristics of the outflowing matter [5]. For modeling kilonova light curves, the ejecta is typically assumed to expand homologously. We have performed radiative transfer simulations in combination with our numerical-relativity simulations to model the light

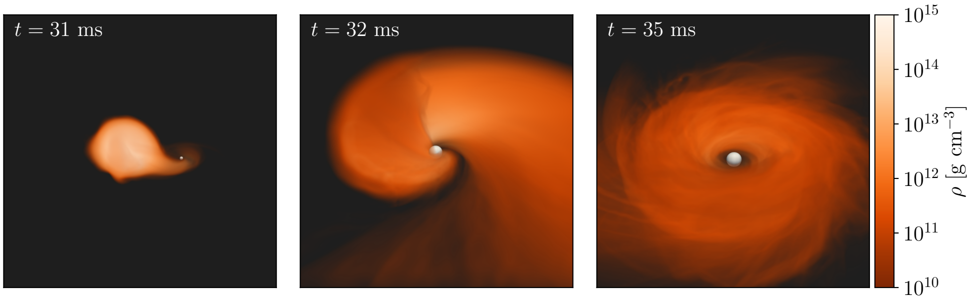

Figure 1: *Visualisation of our Neutron Star – Sub-Solar-Mass Black Hole simulation using the BAM code. Shown are the three stages: mass transfer, merger, and disk formation. The grey sphere represents the black hole. The full animation can be found at:* *https://youtu.be/C8UL_fktipQ*

curves and determine biases due to deviations from homologous expansion.

3. As first-of-its-kind simulation, we evolved a system of a neutron star merger with a sub-solar-mass black hole; cf Fig. 1. For this simulation, we created initial data using the FUKA code. We compared the gravitational-wave data with known waveform models and found that they were unable to reproduce the signal in this region of the parameter space. Phenomenological fitting formulas for the ejecta that have been derived from previous simulations were also not able to predict the amount of ejected material for this system. Additionally, we modeled and analyzed the kilonova light curve with three-dimensional radiative transfer simulations. We found a strong azimuthal dependence, which is neglected in most kilonova models. Overal, our simulations could serve as a testing ground for future model developments and improvements. The paper with our results will be submitted in the next weeks [4].

In total, our resources at HLRN allowed us to produce eight publications and one preprint in the last two years. For the continuation of project bbp00049, we plan to pursue our work on the simulation of black-hole–neutron-star mergers and to study a larger parameter space for these systems with different mass ratios and spins using realistic equations of state to describe the interior of neutron stars. We also want to investigate the influence of neutrino radiation on the merger of binary neutron stars for different spin configurations using our new scheme for the evolution of neutrino transport. Finally, we plan simulations of binary neutron stars with magnetic fields for different eccentricities. Overall, our simulations will help the community and us to develop more accurate gravitational-waveform models and electromagnetic models, and contribute to a better understanding of the physical processes and properties of these fascinating astrophysical systems.

WWW

https://www.uni-potsdam.de/en/theoretical-astrophysics/

More Information

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Project Partners

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