PETASCALE SIMULATIONS OF BINARY NEUTRON STAR MERGERS

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EXECUTIVE SUMMARY

The gravitational wave and electromagnetic data from the collision between two neutron stars, GW170817 [1], is revolutionizing our understanding of the origin of the heavy elements, of the nature of short gamma-ray bursts, and of the properties of matter at extreme densities. To fully exploit the potential of multimessenger observations, the research team performed *ab initio* simulations of binary neutron star mergers and computed their gravitational wave and electromagnetic signatures. These simulations were enabled by both Blue Waters' capacity for massively parallel high-resolution simulations and high throughput for large sets of simulations at smaller scales.

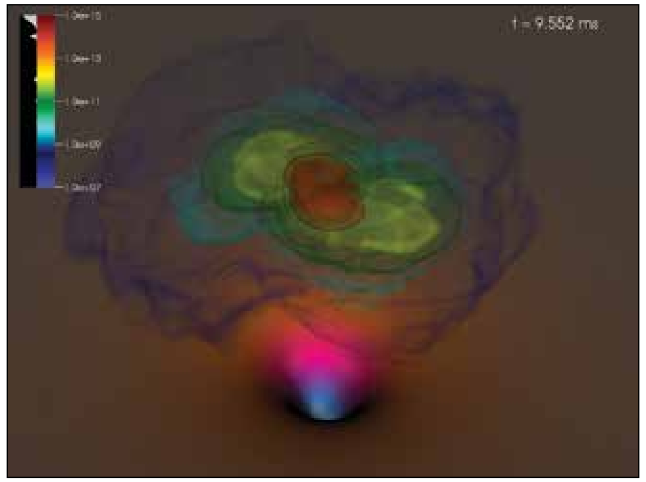

Figure 1: Volume rendering of the fluid rest–mass density (in g/cm^3) in a simulation performed on Blue Waters of the collision between two neutron stars. The figure also shows the value of the lapse function, a proxy for the curvature of spacetime in the orbital plane of the binary. Tidal streams and shocks generated during these mergers generate neutron-rich outflows that synthesize heavy elements and power bright optical transients.

RESEARCH CHALLENGE

The gravitational wave and electromagnetic data from the collision between two neutron stars, GW170817 [1], is revolutionizing our understanding of the origin of the heavy elements, of the nature of short gamma-ray bursts, and of the properties of matter at extreme densities. There are analytical and semianalytical models with various degrees of complexity and sophistication that can be used to separately interpret gravitational wave and electromagnetic data. However, to fully harness this and future multimessenger observations, it is necessary to construct models that can combine the different "messengers." Toward this aim, the research group performed *ab initio* simulations of binary neutron star mergers and computed their gravitational wave and electromagnetic signatures.

METHODS & CODES

The research team used two simulation codes: WhiskyTHC [2], and GRHydro [3]. Both codes are based on the Einstein Toolkit [4] but implement different treatments for matter and use different numerical schemes. WhiskyTHC is optimized for the study of the merger phase. It models neutron stars using finite-temperature tabulated nuclear equations of state and has a simplified treatment for neutrino radiation. GRHydro has a similar treatment of the neutron star matter but was originally designed to study core-collapse supernovae, so its neutrino treatment is specialized to the case where there is a centrally condensed source. GRHydro can model magnetic effects directly by solving the equations of general-relativistic magnetohydrodynamics, while WhiskyTHC treats angular momentum transport owing to magnetic stresses using a subgrid model. This project leverages the strengths of both codes; the team performed merger simulations using WhiskyTHC, and then mapped the results into GRHydro to study their long-term evolution.

RESULTS & IMPACT

The simulations revealed a new mechanism that could power mildly relativistic outflows during mergers and could be revealed by radio observations months to years after merger. The team also found that the electromagnetic (EM) signal is very sensitive to the merger outcome; *i.e.*, whether a black hole was formed promptly or with some delay. They used this observation to develop a novel way to constrain neutron star radii using joint electromagnetic and gravitational wave observations of neutron star mergers. The simulations showed that the outflows powered by mergers could inject positrons in the interstellar medium, and the researchers suggested that neutron star mergers could provide a solution to the decades-old puzzle concerning the origin of cold positrons in the galactic center and some of the dwarf galaxies. Gravitational waveforms, ejecta data, and nucleosynthesis yields from the simulations are publicly available at www.computational-relativity.org and zenodo.org.

The team has performed the first general-relativistic magnetohydrodynamics (MHD) turbulence simulations of neutron star merger remnants including nuclear and neutrino physics. These simulations allowed them to quantify the role magnetic fields play in angular momentum transport in the remnant, and they showed that the lifetime of the remnant can change significantly when including magnetic field effects. The results from these simulations will also be used to inform initial conditions for long-term follow-up simulations of merger remnants.

WHY BLUE WATERS

The MHD turbulence simulations of neutron-star merger remnants that resolve the magneto-rotational instability would have been impossible without Blue Waters' capability. Blue Waters' capacity is also crucial for a quick turnaround in the team's numerical relativity neutron-star merger simulations. No other machine allows for the throughput of many of these simulations concurrently to generate the theoretical predictions needed for Laser Interferometer Gravitational-Wave Observatory and EM follow-up.

PUBLICATIONS & DATA SETS

A. Perego, S. Bernuzzi, and D. Radice, "Thermodynamics conditions of matter in neutron star mergers," *Eur. Phys. J. A*, vol. 55, no. 8, Art. no. 124, Aug. 2019, doi: 10.1140/epja/i2019-12810-7.

G. M. Fuller, A. Kusenko, D. Radice, and V. Takhistov, "Positrons and 511 keV radiation as tracers of recent binary neutron star mergers," *Phys. Rev. Lett.*, vol. 122, no. 12, p. 121101, Mar. 2019, doi: 10.1103/PhysRevLett.122.121101.

D. Radice and L. Dai, "Multimessenger parameter estimation of GW170817," *Eur. Phys. J. A*, vol. 55, no, 4, art. 50, April 2019, doi: 10.1140/epja/i2019-12716-4.

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D. Radice, A. Perego, K. Hotokezaka, S. A. Fromm, S. Bernuzzi, and L. F. Roberts, "Binary neutron star mergers: mass ejection, electromagnetic counterparts and nucleosynthesis," *Astrophys. J.*, vol. 869, no. 2, p. 130, Dec. 2018, doi: 10.3847/1538-4357/aaf054.

P. Mösta and D. Radice, "3D general-relativistic MHD simulations of binary neutron-star merger remnants," in preparation, 2019.