Interm Report 2

Carter Anderson

August 2023

Project Update

As discussed in my previous report, in the first weeks of my project we shifted to focus on Simulating eXtreme Spacetime's (SXS) numerical relativity code, SpECTRE. SpECTRE is designed to investigate the universe's most complex astrophysics, including neutron star mergers which is the topic of my project.

My work on the SpECTRE algorithm began with expanding the library of simulatable equations of state (EoS), which describe stellar properties like mass, radius, density, and matter distribution throughout a given star. Our Sun and all other main-sequence stars are polytropic stars, meaning they are governed by a polytropic equation of state. Polytropic equations of state are relatively simple and easily modeled. However, neutron stars hold the densest matter in the universe and are governed by different processes.

Detected binary neutron star merger events have helped eliminate some potential EoS choices for neutron stars, but have not definitively asserted which equation of state best describes neutron stars. However, the LIGO and VIRGO gravitational wave projects are currently observing with unprecedented sensitivity, collecting data searching BNS events. Once detected, comparison with physical models will further inform how neutron stars and ultra-dense matter behaves.

Motivating the creation of more physical models. I began by expanding the possible EoS SpECTRE can simulate, adding two additional EoS's: Enthalpy and Spectral.

I first added the Spectral EoS, a generalized Fourier series presented by [1]. The Spectral, SLyΓ2, equation of state creates a smoother description of extreme-density matter where gravity crushes nuclei into a soup of free protons, neutrons, and electrons.[2]

The second was the Enthalpy Eos presented in [2] which parameterizes specific enthalpy or energy per unit mass to inject a unit of rest mass into the star at a given point in the star without breaching thermodynamic equilibrium. This approach is powerful as it can be implemented as a hybrid EoS, stringing together equations to better model matter as density increases in the interior of the star.

Four mass radius curves are shown below for typical NS equations of state. Shown is typical Polytropic model for a neutron star, a SLyΓ2 (Spectral) model, the DBHF (Enthalpy) EoS followed by a hybrid DBHF_2507 model featuring a phase transition.

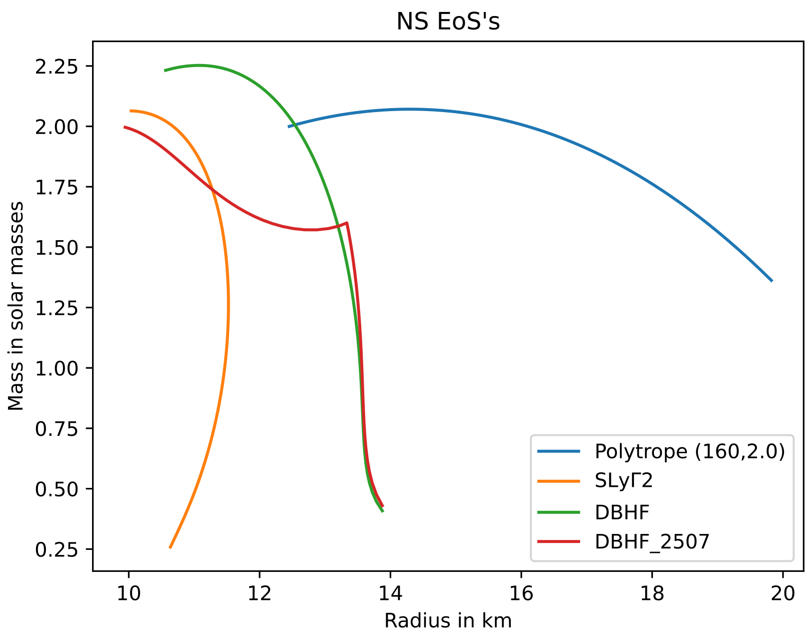
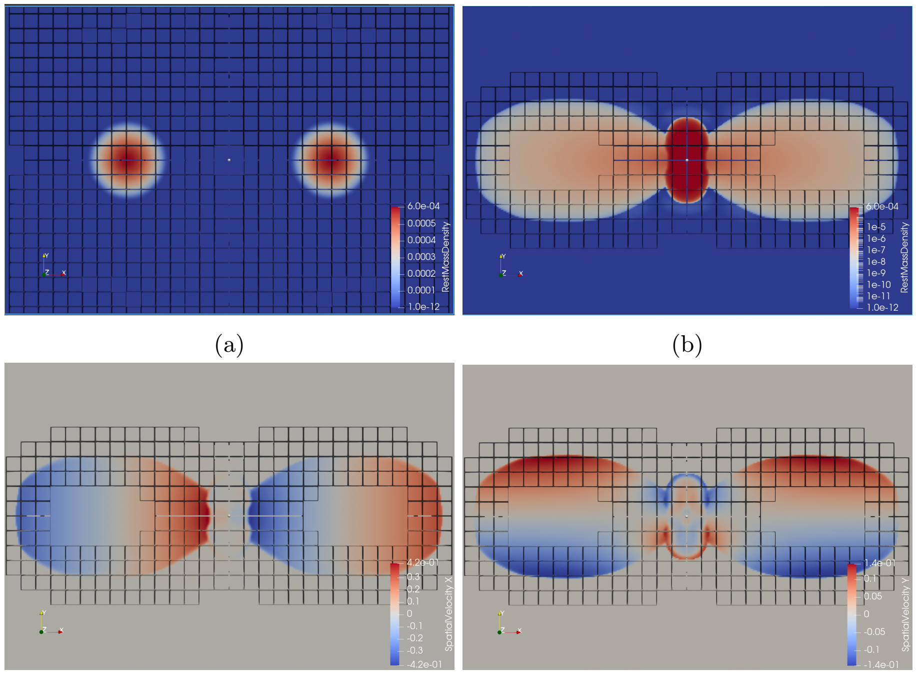


Figure 1: A comparison of various typical neutron star equations of state. SLyΓ2, DBHF, and DBHF_2507 are all now possible to simulate using SpECTRE

With bindings added to allow for simulations with these equations of state, I tried to simulate phase-transitions of the matter at the centers of the colliding stars. Phase transitions, occur when densities within the neutron star grow even higher crushing neutrons further into their quarks, their constituents. It's believed these ultra dense regions should exist in merging neutron stars. Recently we managed to create a phase-transition within the merging stars making progress towards more physically accurate simulations. The figure below shows images from the simulation with phase transitions:



(a) (b)

(c) (d)

Figure 2: Images from a simulation featuring a phase transition. Image *a* shows the star initial configuration, *b* shows the star post-merger where a highly rigid core ejects matter outwards during the formation of a new remnant, *c* and *d* show velocities of the ejecta, where notably matter is moving at significant percentages of the speed of light.

Next Steps

Over the next three weeks our goal is to analyze the efficiency of the added EoS, investigating their impact on simulation efficiency. The additional EoS are designed to be more physically accurate, and if they prove more computationally efficient to simulate - this could be an important step in SpECTRE's development. Additionally, we will be working on simulating more physically realistic scenarios, e.g orbiting binary system - although beyond the timeline of my project. The first step, to be implemented is giving the star initial momentum and initial offsets so they don't collide head-on and sheer together like they would in a cosmological setting.

References

[1] L. Lindblom, “Spectral representations of neutron-star equations of state,” *Phys. Rev. D*, vol. 82, p. 103011, Nov 2010.

[2] I. Legred, Y. Kim, N. Deppe, K. Chatziioannou, F. Foucart, F. m. c. Hébert, and L. E. Kidder, “Simulating neutron stars with a flexible enthalpy-based equation of state parametrization in spectre,” *Phys. Rev. D*, vol. 107, p. 123017, Jun 2023.