High Performance Computing for Neutron Stars

<u>Investigators</u>

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<u>Hypothesis, Research Questions, Goals of Project</u>

The main goal of the project is to perform *self-consistent* simulations of Neutron Stars (NSs) by solving the combined Einstein-Euler-Maxwell equations *either in isolation or in a binary system*. Although simulations of NSs with EM fields in general relativity (GR) have been done over the past 15 years [1-2], they are not self-consistent. In a typical investigation one solves the Einstein-Euler equations to obtain the gravitational field as well as the fluid distribution, and then the EM field *is imposed artificially "by hand"* on the system. All observable quantities, either in the gravitational or in the EM sector are then calculated based on such assumptions, which raises questions about their realism. Through these simulations we will be studying the physics of NSs with realistic magnetic fields to understand the plethora of phenomena associated with them and contribute to the burgeoning field of multimessenger astronomy.

One other question that I will be answering would be "How best do we visualize these simulations?". I will be building upon the visualizations that I created for Dr. Tsokaros last summer [3].

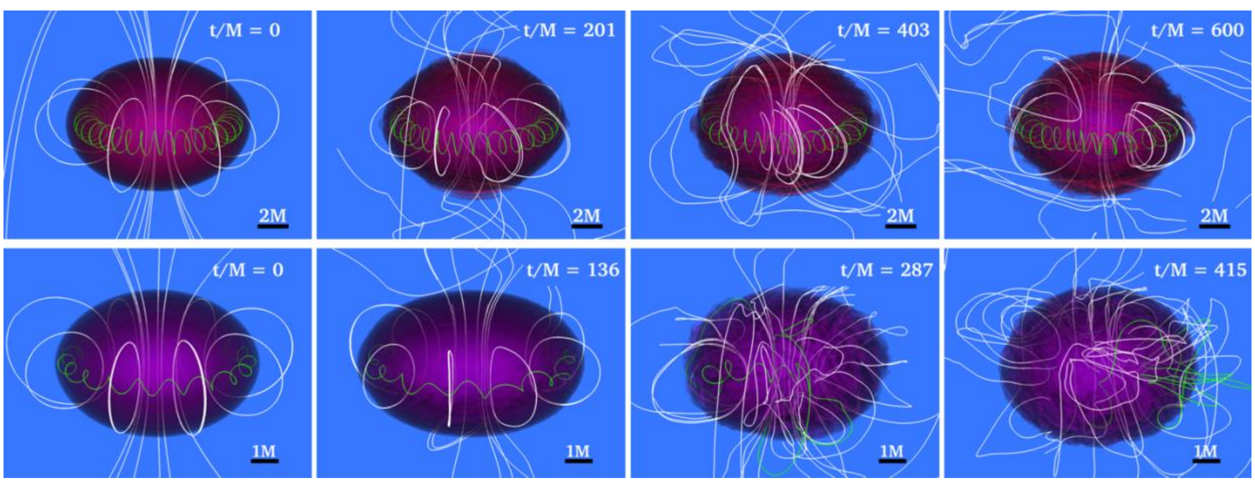

FIG. 1. Three-dimensional renderings of self-consistent NSs. White lines show the poloidal field lines while green lines show a poloidal + toroidal one. The tighter the coil of the helix, the smaller the toroidal magnetic field.

<u>Background / Significance</u>

Neutron stars (NSs) are extraordinary not only because they are the densest form of matter in the visible Universe but also because they can generate magnetic fields ten orders of magnitude larger than those currently constructed on Earth. The combination of extreme gravity with the enormous electromagnetic (EM) fields gives rise to spectacular phenomena like those observed on August 2017 with the merger of a binary NS system, an event that generated a gravitational wave (GW) signal, a short γ-ray burst (sGRB), and a kilonova.

Due to the extreme densities and magnetic fields found in the interior of a NS these compact objects are irreplaceable sources for the ground-based GW observatories (LIGO/Virgo), as well as the NASA EM observatories (such as NICER or INTEGRAL). Recent observations by NICER of the heavy pulsar J0740+6620 was able to set tight constraints on the softness of the NS core thereby bringing us closer to understanding the nature of the NS equation of state. Furthermore, the NICER observations showed that the magnetic field of a NS has a non-trivial topology, far from the well-known dipole.

References

[1] M. D. Duez, Y. T. Liu, S. L. Shapiro, and B. C. Stephens, Phys. Rev. D 72, 024028 (2005), astro-ph/0503420.

[2] M. Shibata and Y.-I. Sekiguchi, Phys. Rev. D 72, 044014 (2005), astro-ph/0507383.

[3] https://inspirehep.net/literature/1957159

Research Methods, Design, Statistical Analysis

(i) Construction of multiple sets of initial data using different assumptions.
(ii) Evolutions of these initial data to evaluate their possible deficiencies as well as the physical properties of the system under consideration.
(iii) Adjustment of the initial value assumptions, and possibly formulations, and repetition of step (ii)

To achieve this goal, we will employ two GRMHD codes, one for the construction of the initial data (COCAL) and one for their evolution (Einstein Toolkit) to investigate a large class of magnetized NS equilibria and study their properties.

Potential Benefits

Our research will provide the first robust and self-consistent modeling of a NS with both its magnetic and gravitational fields. This knowledge will *bring us closer in understanding the nature of matter at the most extreme densities and magnetic fields in the Universe*, far beyond any experiment can reach on the Earth. At present no other group in the world has developed the combined infrastructure needed for this research and *therefore the opportunity to establish NCSA and UIUC as global leaders in this field is unique*.