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Statement of Objectives

Through two and a half years of research experience paired with supporting coursework in physics, mathematics, and computer science, I have developed a well-founded interest in theoretical and computational astrophysics. More specifically, I am interested in the computational modeling of complex astrophysical systems. I'm applying to MIT's physics PhD program to dive deep into these interests and to conduct original and impactful research with top experts in the field.

Computational astrophysics with Professor Stuart Shapiro: Out of a pool of ~50 applicants, I was selected to join the Illinois Relativity Group, led by Professor Shapiro, the summer after my first year. I have continued doing research with the group for subsequent semesters and summers. The group does numerical relativity simulations of compact object systems in order to study their observational signatures. The simulations are carried out over multiple months on supercomputers and use a large three-dimensional grid to keep track of multiple scalar (e.g. fluid density) and vector (e.g. magnetic) fields. 3D visualizations are necessary to interpret and draw conclusions from the enormous simulation output. For instance, 3D integral curve visualizations of the magnetic field are required to confirm the existence of a relativistic jet, without which observable gamma-ray bursts cannot occur. Furthermore, 3D visualizations facilitate intuitive communication of ideas regarding abstract and complex astrophysical systems.

My work in the group is mainly in creating these 3D visualizations as well as developing and maintaining our 50,000-line visualization software stack. To properly test hypotheses with my visualizations, I work directly with Professor Shapiro and with the graduate and post-graduate researchers who run the numerical relativity simulations. Since the group is constantly working on new and exciting simulations, I had to constantly find, code up, and integrate novel visualization techniques to best communicate the most interesting and relevant phenomena. Some examples include tracking a kink that propagates along a helical magnetic funnel and assessing the angular momentum alignment between a black hole and its accretion disk. Overall, it has been an enriching experience to start off learning from my upperclassmen and then becoming an expert on numerical relativity visualization and leading a group of five undergraduates. I also have enjoyed the experience of working with massive data on many large high-performance computing clusters across the country. My visualizations of magnetized neutron stars, black holes with accretion disks, and black hole binaries have been featured in the Coalition for Advanced Scientific Computing 2023 brochure and three Phys. Rev. articles, and can be found on the Illinois Relativity Group's website. I have also presented my visualization work on black holes surrounded by accretion disks at the UIUC Undergraduate Research Symposium.

When I was working on the 3D visualization of black holes surrounded by accretion disks, the gravitational wave visualization software we usually use produced movies that didn't match our hypotheses. Since our black hole disk simulations are the first of their kind, we couldn't say for sure that the software we've ever only used for binaries generalized to black hole disks. Over the course of two semesters, I independently developed a new gravitational wave visualization package using Python/Bash/C++ that implemented a better algorithm for extracting gravitational waveforms from numerical relativity simulation data and employed a more intuitive contour plot rendering technique. The new algorithm generalized an assumption our old software made about the rotation period of the gravitational waves. The resulting gravitational wave visualizations were a success and matched the 3D visualizations of the black hole-disk system. I presented seven movies generated using my new package at the STEM Career Exploration and Symposium.

During my two-plus years in the Illinois Relativity Group, I've worked on multiple projects, and seeing them to completion has always been very fulfilling. I've of course had many setbacks and periods of confusion, but these experiences have only strengthened my determination to pursue a career in research. Currently, I am co-authoring a 75-page manual with Professor Antonios Tsokaros (another Professor in the group) that will serve as open-source documentation for the 3D visualization of numerical relativity simulation data. In the same vein, I am also working on a major update to the group's visualization software which we plan to open-source after the manual is released.

Numerical relativity with Professor Antonios Tsokaros: Wanting to dive deeper into the simulations I had been visualizing, I started working Professor Antonios Tsokaros the summer after my third year after taking coursework in numerical analysis and differential geometry, as well as self-studying general/numerical relativity. Over the past decade, Professor Tsokaros has been building and extending the Compact Object CALculator (COCAL), a code that solves the initial value problem in numerical relativity for a wide variety of astrophysical systems. The initial data that COCAL generates is then evolved in time by an evolution code which outputs the datasets I use for visualizations.

Under the supervision of Professor Tsokaros and with funding from an NCSA SPIN internship, I have been building an extension to COCAL that will compute initial data for a Rotating Neutron Star surrounded by a self-gravitating accretion Disk (RNSDisk). We are particularly interested in RNSDisks because the gravitational field from the accretion disk acts against the gravitational force that collapses a neutron star into a black hole. RNSDisks form after neutron star-neutron star mergers, but it is thought that gamma-ray bursts can only occur when the remnant neutron star collapses to a black hole. Thus, studying the limit at which this collapse occurs in an RNSDisk is an important effort in theoretical astrophysics. Our aim will be to quantitatively evaluate how different parameters, such as the relative mass between the neutron star and the disk, affect the equilibrium/quasi-equilibrium solutions for an RNSDisk.

The module I am building will first code that computes an RNSDisk in full three dimensions using numerical relativity. I started the RNSDisk module by refactoring existing COCAL modules that compute initial data for rotating neutron stars and for black hole disk systems. However, I soon discovered that the process wasn't as simple as stitching together existing code. Even though neutron stars and gaseous accretion disks are both modeled by a perfect fluid, they each require their own equation of state and differential rotation law to be completely described. The RNSDisk is the first system in COCAL that includes two types of gravitating fluids, so an entirely new set of fluid variables needed to be implemented to describe both fluids. While working on this project, I've gotten the chance to apply knowledge from math and physics courses rigorously. I've especially enjoyed working out the equations the code implements with the help of texts in general/numerical relativity. Once the RSNT code is complete, we will compute a spectrum of equilibrium/quasi-equilibrium solutions for a paper I will co-author with Professor Tsokaros.

Future work: Going to graduate school at MIT will allow me to pursue my interest in computational astrophysics at the field's forefront. Specifically, I would be excited to work with Professors Mark Vogelsberger, Lina Necib, and Salvatore Vitale. The cosmological simulation work Dr. Vogelsberger has done in the THESAN project amazes me. Although numerical relativity codes and THESAN simulate different systems, my experience working with numerical methods and high-performance computing would directly translate to the work done in his group. Dr. Necib's work using FIRE simulations of galaxies to study dark matter caught my attention for a similar reason. Having the opportunity to apply my experience working with large data sets to the work her group does comparing computational results to real observational data from surveys like Gaia sounds exciting. My research interests also align with Dr. Vitale's work in parameter estimation using gravitational wave data analysis. Although Dr. Vitale's work is not simulation-based, I would be thrilled to bring my experience working with gravitational waves in numerical relativity to the LIGO Lab.

While I have mentioned several faculty I'm interested in whose work is similar to the research I'm doing as an undergraduate, I look forward to getting a closer look at several other groups. If I am given this opportunity, I will make sure to leverage the world-class faculty and resources at MIT to jump-start my career as a physicist. After graduate school, I hope to work as a physics researcher in an academic or industry setting.