Statement of Purpose

MIT Department of Physics · Doctoral Program · Fall 2024

Introduction

My first simulation study at NASA's Flight Sciences Lab produced puzzling results. Unexpected bifurcations had emerged in the dispersed spacecraft trajectories, and with hundreds of models integrated by thousands of engineers, the cause was unclear. I have since learned to consult previous studies, and isolate models to explain emergent dynamical effects. Now, I hope to build and execute similar simulation studies to explain and predict observations of galaxy & stellar evolution, the universe's large-scale structure, and other astrophysical phenomena.

Cosmological simulations produce domain-specific results, but their development demands expertise across many computational and scientific disciplines. With cultivated expertise in computational labs, and scientific research teams, MIT is uniquely prepared to drive this moment in astronomy and train the next generation of astrophysicists. I hope you will consider me for admission to this training as part of the MIT Department of Physics' Doctoral Program. My experience across multiple disciplines, including scientific software development and nonlinear dynamics, has prepared me for the interdisciplinary work of computational astrophysics research.

Robotics Research

Under Dr. Dave Akin's advisement, I led Space Systems Lab (SSL) software development as an undergraduate research assistant, as a graduate Dean's Fellowship recipient and research assistant. SSL's primary application, an 8DOF dexterous manipulator known as Ranger, required consistently fast and precise control loops. As I developed kinematic solvers and Cartesian controllers for Ranger, I learned techniques for improving mathematical software: parallelism for reducing jitter, in-place calculations for removing memory allocation bottlenecks, and careful benchmark design for algorithm selection. My final research paper presented benchmarks for one such selection: analytical Jacobian codes, generated with my personal contributions to Julia's `Symbolics.jl`, which halved computation time relative to standard iterative methods. With these techniques applied, Ranger successfully completed spacecraft manipulation demos, and I developed fluency in mathematical software development.

Dynamics Research

My graduate astrodynamics coursework introduced computation as a means for physical discovery. For my final term project, I replicated halo orbit and invariant manifold solver implementations, as summarized by Megan Rund's **thesis** on low-cost interplanetary transfer techniques. Multiple differential correction flavors are documented in literature, but I found no published guidance for algorithm selection. My final paper presented a decision tree which maps desired orbit characteristics to compatible flavors of differential correction, several open source Julia **packages**, and over 130k **initial conditions** for periodic orbits.

Scientific Computing

All of my astrodynamics research codes are available as a series of Julia **packages**. I have enjoyed developing other scientific convenience packages in spare time, such as **`SPICEKernels.jl`**. My open source software projects are hosted at **`github.com/cadojo`**, and described on my personal website: **`loopy.codes`**. Professionally, scientific software has been critical to my role as an integrated GN&C analyst in NASA's Artemis Program. I have used linear analysis, model reduction, and parameter sweeps to explain & improve results in tens of thousands of monte-carlo simulations. In 2022, I wrote over 150 pages of technical reports which documented such investigations. While I have enjoyed contributing to human space exploration projects, and I am eager to apply similar computational investigations to scientific research.

Research Aspirations

I believe that my simulation studies at NASA echo MIT's massive astrophysical simulation projects, i.e. **`IllustrisTNG`**. While different in scope and purpose, both aim to study emergent dynamical consequences of known or hypothesized physical laws. At NASA, I frequently change specific dynamical models to determine their effect on simulated vehicle trajectories. I have been encouraged to find similar methods used in astrophysics research, such as Dr. Josh Borrow's **characterization** of the impact of the epoch of reionization on simulated galactic formation. As an astrophysics student, I hope to discuss similar such studies with my advisor, and work to characterize the sensitivity of astrophysical phenomena to other categories of dynamics, i.e. further quantifying galaxy formation's sensitivity to rates of stellar formation and Lyman-α radiation dynamics.

In my view, cosmological & galactic simulation codes have two distinct roles: fast implementations for research, and convenient interfaces for education. Fitting my graduate astrodynamics coursework into convenient open source software was an incredibly productive educational exercise, and I plan to similarly explore my astrophysics coursework through software. When appropriate, I hope to publish astrophysics codes to help undergraduate and early-graduate students learn foundational concepts through computational exploration. Julia, and its package ecosystem, provide excellent tools for such a computational playground. MIT's **Julia Lab** is revolutionizing scientific computing, and I am interested in applying their novel codes to astrophysical contexts. Julia's ease of expression, in combination with **Dr. Rackauckas'** surrogate modeling & differentiable simulation codes, may allow for faster cosmological & galactic model exploration. If an advisor found similar ideas promising, I would welcome such interdisciplinary research opportunities. I have been delighted to find astrophysics research methods which align with my technical skill set: dynamical analysis and scientific computing. I look forward to learning more about our universe, and growing new technical skills as a scientist.

Future Plans

I hope I have the opportunity to learn from MIT's excellent instructors and researchers. Thank you for your time and consideration.