PHY 905-003: Computational Astrophysics and Astrostatistics

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Course Description

Astronomy and astrophysics are among the most computationally-focused disciplines in the sciences. In observational astronomy, dataset sizes are growing exponentially, with this growth powered by all-sky surveys and ever-larger cameras on telescopes. In theoretical astrophysics, a great deal of insight comes from increasingly large and sophisticated multiphysics simulations, with the capabilities of such calculations limited primarily (but not entirely) by the available computational resources and numerical algorithms used to simulate physics. Furthermore, the comparison of large, complex astronomical datasets with similarly large, physics-rich numerical models can require sophisticated statistical techniques. The overall goal of this course is to give you an introduction to a variety of numerical methods and statistical tools that will serve you well in your research and later in your career, and give you the background to be an intelligent consumer of the outputs of computational models and large-scale observations of astrophysical systems.

By the end of this course, you will be able to:

1. Gain insight into astrophysical systems through the use of computational algorithms and tools.
2. Have an understanding of standard numerical methods (e.g., numerical integration, differential equations, Monte Carlo) and astrophysical numerical methods (hydrodynamics, gravity solvers) and be able to use them to solve problems in astrophysics.
3. Perform statistical analysis on astrophysical datasets and compare these datasets to models.
4. Write modular, readable, and extensible software.
5. Be able to take results from a scientific computing problem and present it both verbally and in writing.

We will work toward the goals expressed above throughout this course using a range of activities – primarily by writing software both individually and in small groups, but also through discussion, presentations, and other types of exercises.

Topics covered

The primary topics covered in this course include:

- Standard numerical methods: integration and differentiation, root finding, interpolation, solving sets of ODEs, linear algebra, fast Fourier transforms
- Solving hyperbolic, elliptic, and parabolic partial differential equations
- Numerical methods for fluid dynamics and gravity
- Statistical tools: Fitting models to data, Monte Carlo techniques, Bayesian inference, statistical inference, time series analysis, supervised and unsupervised learning methods
- Scientific software development: writing modular, readable, code. Version control. Debugging. Use of modern integrated development environments (IDEs).

Expectations for you (prior to the start of the semester)

In order for you to fully participate in this class, you need to:

- Be able to use the Unix command line to do basic operations (creating and changing directories, listing their contents, creating, deleting, and moving files, and so forth).
- Be able to use the Git version control system to check out repositories, commit changes, and push them.
- Be able to program comfortably in the Python programming language.
- Have a computer that has Python installed, along with standard numerical packages such as matplotlib, numpy, scipy, h5py, and scikit-learn. I strongly urge you to install the Anaconda Python distribution, available at https://www.anaconda.com/download . Please install the most recent version of Python 3.
- Install Microsoft's Visual Studio Code integrated development environment, which is available at https://code.visualstudio.com/.
- Have a laptop that you can bring to class every week with the required Python distribution, along with a power cord and VGA or HDMI adapter. If you do not have a laptop, please let me know as soon as possible.

Required reading materials

This class uses two textbooks:

1. Computational Physics, by Mark Newman
2. Modern Statistical Methods for Astronomy, by Eric Feigelson and Jogesh Babu

Both are available in a variety of bookstores, as well as online. In addition, we will be using a variety of online resources as well as scanned sections of some books, which will be shared over the course of the semester.

Other required materials

In-class programming assignments are a critical part of the learning process in this course, as is collaborative learning. To that end, you are expected to have a laptop with Python installed (as described above) that you can bring to class every day.

Course activities

Class participation: Active class participation (led both by the instructor and by students) is critical to the success of this course. As such, you are expected to attend class every week, bring the required materials, and to actively participate in the in-class activities.

Pre-class assignments: I will assign short assignments that are due prior to class. The purpose of these assignments is to introduce new material and give you some practice with it so that we can focus on experimentation and implementation in class. These assignments may consist of one or more short videos or reading assignments and related questions or programming problems and will be **due at 11:59 p.m. the night before class** via the course's GitHub Classroom.

In-class programming assignments: Class sessions will be held twice a week, and will be broken up into presentations, discussions, and programming activities that will allow you to immediately implement (and get instant feedback on) what you have just learned. In-class programming activities will be turned in at the end of the class session via GitHub. I will be using Python for in-class assignments.

Homework: You will have periodic homework assignments (every ~3 weeks) that will provide a more in-depth exploration of the materials covered in class. These will be pursued either individually or in pairs and will be turned in by the given deadline on GitHub. Python must be used for homework assignments.

Semester Projects: This class will have a semester project that will involve synthesizing some subset of the techniques that you have learned about for a project that relates to your research interests. There will be substantial programming involved, as well as a brief writeup and a presentation at the end of the semester. More details will be available near the middle of the semester.

Course meeting time and location

This class will meet on Tuesdays and Thursdays from 10:20-11:40 a.m. in 1300 BPS. The first day of class is Tuesday January 13th. There will be no hybrid or online options for this course, since the course format is not conducive to that type of instruction.

Other important information

Course Website, Calendar, and discussion channel: This course uses a GitHub repository for course organization. Accompanying course information, including the official course calendar, can be found in this repository. All assignments will be handed out and turned in via a GitHub Classroom – as a result, you will need to create a GitHub account and send it to me. We will also have a course discussion channel (#compastro-spring26) on the MSU astrophysics MatterMost group. If you need an invitation to the MatterMost group, please contact me and I will send that to you. Please note that the course nominally has a Desire2Learn page (at http://d2l.msu.edu), but it will not be used.

Class attendance: This class is heavily based on material presented and worked on in class, and it is critical that you attend and participate fully every week! Lack of attendance or habitual lateness will be dealt with first by sarcasm on the instructor's part, and then by more formal means.

Classroom behavior: Respectful and responsible behavior is expected at all times, which includes not interrupting other students, turning your cell phone off, refraining from non-course-related use of electronic devices, and not using offensive or demeaning language in our discussions. Flagrant or repeated violations of this expectation may result in ejection from the classroom, grade-related penalties, and/or involvement of the university Ombudsperson. In particular, behaviors that could be considered discriminatory or harassing, or unwanted sexual attention, will not be tolerated and will be immediately reported to the appropriate MSU office.

Academic Honesty: Intellectual integrity is the foundation of the scientific enterprise. In all instances, you must do your own work and give proper credit to all sources that you use in your papers and oral presentations – any instance of submitting another person's work, ideas, or wording as your own counts as plagiarism. This includes failing to cite any direct quotations in your essays, research paper, class debate, or written presentation. The MSU College of Natural Science adheres to the policies of academic honesty as specified in the General Student Regulations 1.0, Protection of Scholarship and Grades, and in the all-University statement on Integrity of Scholarship and Grades, which are included in Spartan Life: Student Handbook and Resource Guide. Students who plagiarize will receive a 0.0 in the course. In addition, University policy requires that any cheating offense, regardless of the magnitude of the infraction or punishment decided upon by the professor, be reported immediately to the dean of the student's college.

It is important to note that **plagiarism in the context of this course includes, but is not limited to,** directly copying another student's solutions to pre-class, in-class, or homework problems; copying materials from online sources, textbooks, or other reference materials *without citing those references in your source code or documentation*, or having somebody else do your pre-class work, in-class work, or homework on your behalf. Any work that is done in collaboration with other students should state this explicitly, and have their names as well as yours listed clearly.

More broadly, we ask that students adhere to the Spartan Code of Honor academic pledge, as written by the Associated Students of Michigan State University (ASMSU): "As a Spartan, I will strive to uphold values of the highest ethical standard. I will practice honesty in my work, foster honesty in my peers, and take pride in knowing that honor is worth more than grades. I will carry these values beyond my time as a student at Michigan State University, continuing the endeavor to build personal integrity in all that I do."

Generative AI usage: Generative AI tools such as ChatGPT can be extremely useful in an educational context (particularly in a class like this), but its use should not replace understanding of the material. To that end, while I do not prohibit the use of generative AI tools such as ChatGPT or GitHub Copilot in this course, **you are expected to use generative AI as a resource, not to produce answers in their entirety.** If you use generative AI tools for <u>any</u> course-related work you are **required** to cite your usage, including any prompts/outputs. If you use used code produced by generative AI tools you are responsible for understanding exactly how and why it works to solve the problem. If it seems like you're relying on generative AI too heavily for course assessments I reserve the right to base assignment and/or course grades on an oral exam that allows you the opportunity to demonstrate your understanding of the material.

Accommodations: If you have a university-documented learning difficulty or require other accommodations, please provide your instructor with your VISA as soon as possible and speak with them about how they can assist you in your learning. If you do not have a VISA but have been documented with a learning difficulty or other problems for which you may still require accommodation, please contact MSU's Resource Center for People with Disabilities (355-9642) in order to acquire current documentation.

Instructor information

Contact information:

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Office hours: By appointment – please contact me on MatterMost to schedule a time for us to speak either in person or on Zoom. I will typically have free blocks of time on both Tuesday and Thursday afternoons as well as on Friday afternoons, but can also make other times work.

Scheduled travel: As of the writing of this syllabus I am scheduled to be out of town on Tuesday February 3rd and Tuesday April 14th, and may be out of town a couple of other times during the semester as well. We will likely have class those days, however – I will have guest instructors!

Grading information

Activity	Grade percentage
Participation/attendance/in-class assignments	25
Pre-class assignments:	20
Homework assignments	30
Semester project	25
Total:	100%

Grading scale

4.0	≥ 90%
3.5	≥ 85%
3.0	≥ 80%
2.5	≥ 75%
2.0	≥ 70%
1.5	≥ 65%
1.0	≥ 60%
0.0	< 60%

Note: I am using the standard Physics department expectations regarding the grading scale for elective 900-level courses. Students that actively participate and do their best on all assignments will receive a reasonable grade!