AST 51/151 - Astrophysics Laboratory

Tufts University - Spring Semester 2024 - Version #1 (January 8th, 2024)

Professor: David Martin (574 Boston Avenue, 3rd floor, office 312D)
TA: Wata Tubthong
Resources: **www.davidvmartin.com**, Canvas & Slack (invitation coming shortly)
Class philosophy:

- You learn better by doing than by listening.
- Repetition aids learning - you will come across each topic at least **3-4 times** in different ways
- You do not fully understand something until you can teach it to others.
- Science is a collaborative endeavour.
- You **can** do real scientific research at a young age.

Core material: Two of the most powerful and essential tools for modern astrophysics are statistics and computer programming. AST-51/151 aims to teach both, including key concepts:

- Fundamentals of python programming - logical statements, loops, plotting etc
- Analysing large datasets
- Probability and statistics theory - how much can I trust my result?
- Bayesian vs classical inference
- Fitting data, including with Markov Chain Monte Carlo (MCMC)
- Drawing from random distributions

We will be learning these concepts through applications to various astrophysics projects using real, cutting edge data to answer legit modern research questions:

- Populations of binary stars
- Stellar activity: spots, flares and rotation rates, and the various correlations between them
- Aperture photometry with TESS
- Stellar spectral types and magnitudes
- Light curve analysis: detrending, periodograms, auto correlation functions

In doing so, we will be learning various skills that will be essential for any scientist:

- Collaboration and team work
- Educating others through coding tutorials, video tutorials and public outreach
- Academic conference style presentations

Class time: 9:00 am - 11:30 am Friday mornings, room 404 in 574 Boston Avenue
Class style: 100% in person, no zoom. Classes will be interactive coding workshops, not traditional lectures. Class attendance and participation is worth 20% (see details below).
Equipment: All students must have a laptop they can bring to class. Any operating system is fine. Laptop does not have to be very new/fast as we will have cloud and cluster computing options.
Office hours: TBD - will be determined by a class poll to find the best time
Textbook: “Practical Statistics for Astronomers” - 2nd edition, Wall & Jenkins. You should be able to access the full PDF of the book through the library. You can find a paperback on Amazon for ~$30 if you prefer. I didn’t put it in the bookshop because it’s a rip off. I will also provide many other resources for each class, including Youtube videos, alternative textbook references and online tutorials.

Assessment: This class is project-based and has no exams. All projects are done in small groups (size TBD, depending on final class size). Groups will be picked to have a fair distribution of education age, coding experience and scientific background. Groups will change throughout the semester. Most grades as assigned by group.

- **10% Assignment #1 - Tutorial on making pretty plots**
  Your group will create a Jupyter notebook tutorial to teach a certain plotting technique (assigned at random) in Python (e.g. histograms, scatter plots, 3D). All tutorials will be collated to form one giant Python plotting knowledge base that the entire class can call upon in all future assignments. Submission will be in the form of a Jupyter notebook tutorial.
- **10% Assignment #2 - Random distributions of eclipsing binary stars**
  Your group will generate a synthetic, random population of binary stars from observed orbital characteristics (period, eccentricity, mass, mass ratio, inclination). Submission will be in the form of a Jupyter notebook tutorial.
- **15% Assignment #3 - Analysis of flares and spot rotation on CM Draconis**
  Your group will use statistical methods test correlations between flare occurrence and spot rotation on a known eclipsing binary CM Draconis. Submission will be in the form of a Jupyter notebook tutorial plus an accompanying short public outreach presentation in a format of your choice (e.g. Youtube, TikTok, radio interview).
- **15% Assignment #4 - MCMC tutorial**
  Your group will create a tutorial on the fundamentals and use of a Markov Chain Monte Carlo algorithm. It will be applied to modeling the structure and energy output of stellar flares. Submission will be in the form of a Jupyter notebook tutorial plus an accompanying video tutorial (e.g. like seen on Youtube).
- **20% Assignment #5 - Stellar activity correlations and functions of stellar mass**
  Your group will download and analysis TESS space telescope data to study a large sample of low-mass stars. You will measure rotation rates and detect and model flares. You will test for correlations between these different markers of stellar activity. Each group will be given a different subset of stars. Submission will be in the form of a Jupyter notebook tutorial plus an accompanying academic conference talk. Notebook tutorial will be a group submission but everyone must individually record their own academic talk.
- **10% Class recap**
  At the start of every class we will have ~3 - 4 short recaps of concepts learnt in the previous class. Every student in the class will give one of these recaps during the year. Students and topics will be chosen at random.
- **20% Class participation/exercises**
  We have 12 structured classes planned (plus 2 flexible classes near the end). Each of these 12 classes is worth 2% of your grade, capped at 20% max. Each class will be an interactive coding workshop where we work through a Jupyter notebook in groups to learn various statistics/programming/astrophysics concepts. If you come to class and make an attempt/ contribution, then you **automatically get a full 100% grade (i.e. 2%) for that class**. If you miss the class, then the workshop becomes homework and will be graded on a standard scale and will be due the week after. Ultimately, this system gives you flexibility to not stress if you have to miss the odd class, but it also behooves you to come to the majority of classes so you avoid extra homework on top of your assignments.

Class Schedule & Syllabus (subject to minor changes) - Fridays 9:00am - 11:30am

- **Class #1 (Jan 19) - Overview & python setup**

  An overview of the course and a brief setup of Python using Jupyter-notebooks and SciServer.org

- **Class #2 (Jan 26) - Python and statistics basics**

  Basic python functionality (e.g. arrays, loops, logic, plotting). Fundamental statistics concepts (mean, median, standard deviation, quartile ranges, standard error).

  Commence assignment 1: Create a tutorial on pretty plots.

- **Class #3 (Feb 2) - Basic probability**

  Kolmogorov's axioms, conditional probability, Binomial, Normal and Poisson distributions, discrete vs continuous distributions, conditional probability

- **Class #4 (Feb 9) - More advanced probability**

  Central limit theorem, random number generators, Monte Carlo simulations. Astrophysics of stellar populations.

  Commence assignment 2: Binary star population synthesis.

- **Class #5 (Feb 16) - Statistics**

  Parametric vs non-parametric tests, p values, Kolmogorov-Smirnov tests, Student t-tests, correlation, bootstrapping

- **Class #6 (Feb 23) - Stellar activity**

  Astrophysics of stellar activity, starspots, rotation rates, flares, activity cycles, stellar spectral types, observational evidence for stellar activity.

  Commence assignment 3: Flares and rotation on the eclipsing binary CM Draconis

- **Class #7 (Mar 1) - Fitting data**

  Linear regression, maximum likelihood, least squares, Chi2 minimisation, quality of fit

- **Class #8 (Mar 8) - Bayes' theorem**

  Basics, philosophy (Bayesian vs classical), priors, Bayesian inference

- **Class #9 (Mar 15) - Markov Chain Monte Carlo (MCMC)**

  Fundamental principles, Metropolis-Hastings algorithm, Gelman-Rubin convergence tests, burn in, corner plots, marginalization.

  Commence assignment 4: Create a tutorial on MCMC.

- **Spring Break Mar 22)**

- **Class #10 (Mar 29, taught remotely due to conference travel) - TESS photometry**

  TESS spacecraft, downloading data with lightkurve, aperture photometry, detrending, outliers, data management.

  Commence assignment 5: Flares vs spot modulation vs stellar mass.

- **Class #11 (April 5) - Analysing flares and rotation rates**

  Periodograms, auto correlation functions, flare identification

- **Class #12 (April 19) - Flexible class**

  For completing the final assignments

- **Class #13 (April 12) - How to give a good academic talk**

  Research-based methods that will help improve your scientific presentation. Workshop on slide design, body language, audience engagement and practice techniques.

- **Class #14 (April 26) - Flexible class**

  For completing the final assignments

Grading scale:

- 90 - 100: A+ (GPA 4.0)
- 80 - 90: A (GPA 4.0)
- 77 - 80: A- (GPA: 3.7)
- 73 - 77: B+ (GPA 3.3)
- 70 - 73: B (GPA 3.0)
- 67 - 70: B- (GPA 2.7)
- 63 - 67: C+ (GPA 2.3)
- 60 - 63: C (GPA 2.0)
- 57 - 60: C- (GPA 1.7)
- 53 - 57: D+ (GPA 1.3)
- 50 - 53: D (GPA 1.0)
- < 50: F (GPA 0.0)

Note that these percentages are much lower than what you are probably used to. This flexibility allows for more realistic feedback on assessments without unfairly hurting your GPA. In this class you will be doing legitimate astrophysics research, and this grading scheme reflects the fact that real science can be messy and imperfect. All grades round up, e.g. 80% = A, not A-.