AST 191 - Special Topics in Astrophysics

Exoplanets and Their Orbits

Professor: David Martin (574 Boston Avenue, 3rd floor, office 312D)
Resources: www.davidvmartin.com
Description: Use of radial velocity and transit techniques to discovery new exoplanets and characterize existing ones. Celestial mechanics of n-body orbits. Evolution and interaction of orbits over time. Research tools in astrophysics/exoplanets.
Class style: 100% in person. Class will be 50% interactive **lectures/workshops** and 50% **computational labs.**
Logistics: 4:30 - 5:45 Tuesdays & Thursdays, CLIC 202, 574 Boston Avenue.
Pre-requisites: Physics 11, 12, Maths 34 (Calculus II) or instructor consent or graduate student.
Assessment:

- 20% Assignment #1 (research questions on orbital dynamics)
- 20% Assignment #2 (exoplanet discovery using real data from space and ground telescopes)
- 20% Midterm oral exam
- 20% Final presentation
- 20% Class participation/exercises

Learning objectives: Upon completing AST 191 the student will be able to…

- Describe orbits mathematically, geometrically and conceptually
- Simulate orbits and describe their evolution
- Discover and characterize exoplanets using transits and radial velocities
- Write and document new python code
- Orally explain difficult concepts to peers

Class Schedule & Syllabus (subject to minor changes) - Tuesday & Thursday 4:30 - 5:45

First class **Thursday** September 7 (no class Tuesday September 5)

- **Lecture #0 - Introduction**
  A summary of the course material and style. Will feature a survey of students' experience & coding level.
- **Lecture #1 - How orbits are a natural consequence of gravity**
  Calculate orbits as a function of position, derived from Newton's laws. Introduce polar coordinates.
- **Lecture #2 - Kepler's three laws**
  Derive the three laws. Demonstrate conservation of energy and angular momentum.
- **Computing Lab #1 - Kepler's three laws**
  Introductory python programming. Plotting orbits and defining orbital elements.
- **Lecture #3 - Two-body orbits over time**
  Calculating time-dependent orbital positions, relative positions, and moving from 2D to 3D.

- **Computing Lab #2 - Two-body orbits over time**
  Plotting 3D orbits over time, solving Kepler's equation.
- **Lecture #4 - Three- and N-body orbits**
  Demonstrating how adding one more body changes everything. Jacobi coordinates. Hill & Roche radii, Lagrange points, stability.
- **Computing Lab #3 - Numerical integration of differential equations**
  Solving first-order and second-order differential equations. Writing a simple Euler's method from scratch.
- **Computing Lab #4 - Solving the three-body problem**
  Solving the three-body problem both with our hand-written Euler's method and the more sophisticated REBOUND code.
- **Computing Lab #5 - Orbital dynamics with REBOUND (part 1)**
  Further introduction to REBOUND and simple functionality.
- **Computing Lab #6 - Orbital dynamics with REBOUND (part 2)**
  More sophisticated use of REBOUND. Evolving 3+ body orbits over long timescales and analyzing the evolution.
- **Mid-term oral exam**
  A conceptual exam based on the concepts learned in the first half of the class. A specific list of examinable concepts will b provided. No wrote memorization of equations or coding is required. The professor is there to help guide students who have any challenges answering questions. All questions can be given consequential and partial marks.
- **Lecture #5 - Observational Astronomy 101**
  In preparation for the more observationally-focused part of the class, a run down of some key observational astronomy concepts and jargon.
- **Computing Lab #7 - Fitting data**
  Fundamental concepts of Bayesian inference and writing a Markov Chain Monte Carlo (MCMC) from scratch.
- **Lecture #6 - Detection of exoplanets with radial velocities**
  Taking all of our earlier work on orbits and applying it to observations of exoplanets with radial velocities (RVs).
- **Computing Lab #8 - Finding, modeling & fitting RVs (part 1)**
  Finding RVs using our own hand-made MCMC.
- **Computing Lab #9 - Finding, modeling & fitting RVs (part 2)**
  Finding RVs using more sophisticated packages pymc3 & EXOPLANET. Introduction of discovery methods like Lomb Scargle perioodgrams and means of being confident in discoveries.
- **Lecture #7 - Detection of exoplanets with transits (part 1)**
  Introduction to transits, under many assumptions (circular orbits, uniformly bright stars).
- **Lecture #8 - Detection of exoplanets with transits (part 2)**
  Eccentric orbits, secondary eclipses, limb darkening.
- **Computing Lab #10 - Finding, modeling & fitting transits (part 1)**
  Plotting transit light curves for different orbital/physical parameters. Introducing to MCMC transit fitting with EXOPLANET.
- **Computing Lab #11 - Finding, modeling & fitting transits (part 2)**
  Transit detection with Boxed Least Squares (BLS). Detrending light curves with Wotan. More advanced EXOPLANET transit fitting.

- **Lecture #9 - How to give a good scientific presentation**

  Research-based methods that will help improve your scientific presentation. Workshop on slide design, body language, audience engagement and practice techniques.
- **Lecture #10 - Advanced topic of circumbinary planets**

  Planets orbiting two stars are challenging for both observational and theoretical reasons. Introduction to the theory and observations made so far of circumbinary planets.
- **Computing Lab #12 - Advanced topic of circumbinary planets**

  Simulating the orbital evolution of circumbinary planets and the observational consequences.
- **Lecture #11 - Advanced, cutting edge research topics in exoplanets**

  An overview of the current state of exoplanets, both theoretically and observationally, and plans over the coming years and decades
- **End of year final presentation**

  In lieu of a final written exam, there will be a final short class presentation, using the presentation skills learned in the early lecture. The presentation will be on the results obtained in either of the two assignments (student's choice), i.e. no new material needs to be learned solely for the presentation.