Fluid Instabilities, Waves and Turbulence

MWF 1:00-1:50pm Duane E126

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course website: Canvas (URL tbd)

Why more fluids?

When first learning fluid dynamics, it can be difficult to delve into regime of astrophysical and geophysical flows. In these systems, instabilities drive flows with strong non-linearities, and this very frequently results in turbulence. Further, these flows often occur under strong constraint (rotation, magnetic fields, stratification), and can involve (or arise from) wave motions. What a mess! This is challenging when you're learning up from down in a stratified system, or what nondimensional quantities mean. Here, with some background in the basics, we're going to start disentangling this mess and start developing an intuitive understanding of instabilities, waves and turbulence. Fluids are everywhere in astrophysical and geophysical systems. Despite this, our expertise in them is not strong. When astronomers say "rotation" or "magnetic fields" do something magical, what they generally mean is "fluid interactions with rotation and/or magnetic fields, under strong constraint" do something simple. Here we aim to transform magic into reason.

I have three major goals in this course. First, I want you to emerge with a broad set of tools for tackling problems which you will encounter in your future research. Many research problems require a diversity of approaches, and we'll build fluency with these different approaches here. Second, I want you to feel prepared for further learning in fluid dynamics. This course, by nature, must lightly touch many subjects, and there are more instabilities in fluids and plasmas then we can cover. Coming out of it however, you will have the fluency to dive deeper into subjects relevant to your research, and familiarity with ways to search for publications in applied math and physics. Third, I want you to emerge from this class with confidence in your research skills. We will jointly do a research project in magnetoconvection, an example of strongly constrained flows.

Content

Here is a rough guide to content we'll cover in the course. This is an advanced graduate course, and I want you as a class to take ownership of it. As such, if you collectively choose that we should focus in a particular direction, I'm happy to change the balance of topics.

- Instabilities
  - Bifurcations
  - Local and Global Analysis
  - Common instabilities in astro and geophysical fluids
    - Kelvin-Helmholtz
    - Thermal convection
    - Rayleigh-Taylor
    - Baroclinic instabilities
  - Instabilities under constraint
    - rotating convection
    - magnetoconvection
- Waves
  - Acoustic and gravity waves in stratified systems
  - Rotating systems
  - Magnetized systems
- Turbulence
  - cascades of energy and enstrophy
  - structure functions
  - inverse cascades

Course structure

Class: please come to class with questions. We will all learn more through interaction and discussion. I won't know all of the answers. When I don't, I'll find out and bring them to you. If you need to miss class, please discuss this with me in advance so we can make accommodations.

Homework: there will be homework, likely every other week, handed out and collected on Wednesdays. Most homeworks will involve some computational aspect. Please collaborate and work together, but please write up your work (and write your code) individually. Code will be submitted as part of the homework, via online hosting through bitbucket repositories. Homework will be written up in Latex and/or Jupyter notebooks. We will have readings from the textbook, and possibly online material, that I expect you to have studied before class. These will be communicated to you.

Midterm: there will be no midterm.

Final project: as a class, we will work together to solve an interesting problem in nonlinear instabilities. Each of you will contribute. Our goal is to submit a paper at the end of the semester. Everyone who contributes gets to be a co-author on the paper. Our target problem is strong-field magnetoconvection, an interesting landscape of constrained instabilities, competition between driving and constraint, and a problem that highlights many aspects of this course. You will give a short, AAS-style talk (5 min presentation, 3 min questions) about your contributions to the project. This will occur during Finals week. This is in lieu of a final exam.

In class participation: I want you to be engaged with this material; it's the only way to really learn it. As such, a portion of your grade is dependent on you showing that you're engaged with the material. This can be demonstrated by asking questions in class, answering questions that other people have asked, and/or actively participating in group exercises. This is graded on a "did you try" basis.

Grading: about 50% of your grade will come from assignments, 20% from in class participation and 30% from the project.

Technical Computing

You will need access to a computer (preferably a unix/linux or Mac) and technical computing software for this course. We will likely have some "laptop lab" days, where I expect you to have a computer with you here in class to do hands-on exercises. In this course, we will do all of our work in Python. Why Python? Traditionally, many astronomers, especially here in Colorado, have used IDL. IDL itself is a closed source platform, and it is difficult to execute parallel processing in IDL. There is a growing trend away from IDL and towards Python. Python is a free, open source, high-level interactive interpreted computing and scripting environment. Python is used for much more than scientific computing. One can easily wrap existing C, C++, or Fortran codes. Within the astronomical community, it is used for everything from telescope observing scripts to quick interactive data visualization, to sophisticated and complex analysis pipelines with hundreds of thousands of lines of code. My research group uses Python. Ask me if you need help deploying python on your computer. You need to use use and learn python3 (version 3); there are subtle array promotion differences between python2 and python3, and portions of our numerical work will leverage the Dedalus pseudospectral framework, which itself uses python3.

We will also likely use either AWS or the CU Summit supercomputer to conduct some of the numerical experiments in the project portion of the course. To do this, it's important that you have familiarity with using SSH to log into a remote machine. We'll dedicate some lab sessions to doing just this, likely with help from CU's Research Computing.

Books to learn from

Course Textbooks

- **required:** *Introduction to hydrodynamic stability*, Drazin, 2002
  A modern introduction to instability theory. Much more readable than Drazin & Reid. Done in the context of fluid instabilities. About $60.
- **optional:** *Hydrodynamic and hydromagnetic stability*, Chandrasekhar, 1961
  Has a bit of everything on convective instabilities, including in rotating and strongly magnetized regimes. Not easy to read, but very useful, especially as we work on the final project. If you don't buy it, you'll need to borrow it to read some sections. About $20.

Fluids

- *The Physics of Fluids and Plasmas*, Choudhuri, 1998
  Our course textbook from ASTR 5400; a good, broad introduction to fluid dynamics with an astrophysical slant to the material. Think more helioseismology, supernova shock waves, and convection, less pipe flow turbulence and wings (though some examples of those too). Covers basic plasma physics and magnetohydrodynamics.

- *Fluid Mechanics* Landau & Lifshitz 1959 (1966 for 3^{rd} ed)
  Volume 6 (of 9) in Landau & Lifshitz's sweeping "Course of Theoretical Physics". Everything is here, if you can understand it.
- *Physical Fluid Dynamics* Tritton 1988
  Beautiful book on incompressible flow with a focus on geophysical fluid dynamics. Highly recommended by one of the best fluid dynamicists I know.
- *Waves in Fluids*, Lighthill, 2001 for 2^{nd} ed
  If there's a wave that can happen in water, it's probably in this text. I will draw material from this throughout the course.
- *Turbulent Flows*, Pope, 2000
  Masterwork on turbulence; I will pull material from this for the course. This is where to go if you ever need to implement a Smagorinsky dynamic self-similarity model, or understand what those words mean.

Math

- *A First Course in Numerical Methods*, Ascher & Greif, 2011
  A broad introduction to linear algebra, numerical techniques, differential equations, etc. Good reference for understanding packaged library routines (e.g., QR factorization, Krylov methods, etc.) and the code examples, though in Matlab, are helpful. Freely available as a PDF from a campus IP address (http://epubs.siam.org/doi/book/10.1137/9780898719987).

- *Numerical Methods for Evolutionary Differential Equations*, Ascher, 2008
  Graduate level text on differential equations in particular, which get only brief treatment in Ascher & Greif. Freely available as a PDF from a campus IP address (https://epubs-siam-org.colorado.idm.oclc.org/doi/book/10.1137/1.9780898718911).
- *Computer methods for ordinary differential equations and differential-algebraic equations*, Ascher & Petzold, 1998
  The book I was first handed when I asked to learn about modern techniques for solving differential equations. Freely available, though in awkward form, from a campus IP (search CU library website).

Numerical techniques and coding

- Oreilly, Linux in a Nutshell, or Unix in a Nutshell, is a comprehensive linux/unix command, shell, and text editor reference.
- Press et al, Numerical Recipes 3rd Edition. In addition to offering specific numerical algorithms, this book contains excellent introductory text on statistics and data analysis techniques. Beware the restrictive licensing clauses in this book.

Python

- Basic Python tutorial: http://docs.python.org/tutorial/
- Scientific computing using Python: Scipy and Numpy: http://scipy.org/
- Using Python for Interactive Data Analysis in Astronomy: http://stsdas.stsci.edu/perry/pydatatut.pdf
- Interactive computing with Python using Jupyter: https://jupyter.org
- Matlab-like interactive plotting with Python: http://matplotlib.sourceforge.net/
- UC Berkeley Astronomy Departments Python Boot Camp: https://sites.google.com/site/pythonbootcamp/
- OReillys Learning Python, 3rd edition: http://oreilly.com/python/
- Resources for installing a base python system (with python, numpy, scipy, etc.):
  - Dedalus stack: http://dedalus-project.readthedocs.io/en/latest/installation.html
  - Anaconda: https://www.continuum.io/downloads

Latex

- *A (Not So) Short Introduction to LaTeX 2$_\varepsilon$*, Oetiker
  https://www.ctan.org/tex-archive/info/lshort/english/ or
  https://tobi.oetiker.ch/lshort/
  Good go-to reference for using Latex. Freely available as PDF.