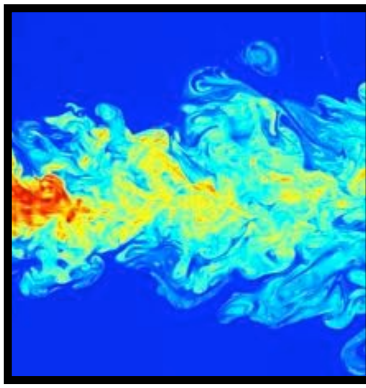
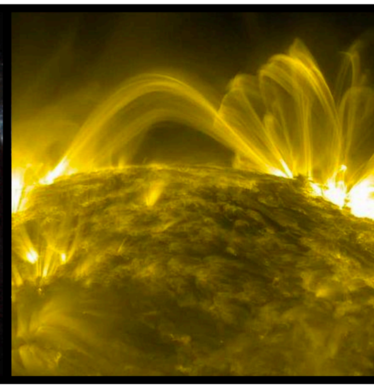
ASTR 501
Dynamics of Astrophysical Many-Body Systems






Course Description

This course presents an in-depth treatment of the dynamics of astrophysical systems, including gases, plasmas, and stellar systems. The course starts with a detailed formulation of the theoretical foundations, using kinetic theory and statistical physics to describe the dynamics of many-body systems. Special emphasis will be given to collisional processes in various astrophysical systems. Next, after deriving the relevant moment equations, we focus on specific topics related to (i) stellar dynamics, (ii) hydrodynamics, and (iii) plasma physics. Related to stellar dynamics we cover potential theory, orbit theory, Jeans modeling, gravitational encounters and secular evolution (bars and spiral structure). In the field of (non-radiative) hydrodynamics we study, among others, the Navier-Stokes equation, vorticity, transport coefficients, accretion flow, turbulence, fluid instabilities, and shocks. We end with a cursory overview of plasma physics, including the Vlasov equation and the two-fluid model, Langmuir waves, Alfvén waves, Landau damping, ideal vs. resistive magnetohydrodynamics (MHD), and dynamos. Throughout the course we shall focus on specific astrophysical applications.

Instructor : Prof. Frank van den Bosch (Office: KT 649)
e-mail: frank.vandenbosch@yale.edu

Course Website : https://campuspress.yale.edu/astro501/

Lecture Hours : TTh 9.00-10.15am **Location** KT 221 (Kline Tower)

Office Hours : TBD **Location** KT 649 (Kline Tower)

Grading : 35% Final Exam + 35% Problem Sets + 30% MidTerm Exam

Course Format : Blackboard presentations & in-class discussion

Course Outline

PART I: Theoretical Foundations [Lectures 1-5]

❖ **Time and length scales of astro-physical many-body systems**

❖ **Review of Classical Dynamics**
Lagrangian & Hamiltonian formalism, Poisson brackets, canonical transformations

❖ **Kinetic Theory:**
Liouville theorem, BBGKY hierarchy, Boltzmann and Vlasov equations

❖ **Collisional Dynamics:**
Langevin equation, fluctuation-dissipation theorem, relaxation time, Lenard-Balescu equation, diffusion coefficients, Fokker-Planck equation, Maxwell-Boltzmann distribution

PART II: Stellar Dynamics [Lectures 6-12]

❖ **Potential Theory**
Poisson equation, spherical systems, ellipsoidal systems, multipole expansion, disk potentials

❖ **Orbit Theory**
integrals of motion, action-angle variables, KAM theorem, surfaces of section, resonances

❖ **Jeans Theorem & Jeans Modeling**
Jeans equations of spherical, axisymmetric & triaxial systems, mass-anisotropy degeneracy kinematics, Schwarzschild modeling

❖ **Gravitational Encounters & Relaxation**
impulse approximation, dynamical friction, orbital decay, phase mixing, violent relaxation

❖ **Secular Evolution**
bars and spirals, swing amplification, radial migration, Toomre criterion, gravothermal catastrophe

PART III: Hydro Dynamics [Lectures 13-20]

- **Equations of HydroDynamics**
  continuity, momentum and energy equations, closure relations (equations of state)

- **Vorticity & Circulation**
  vortex tubes, vorticity equation, baroclinicity, Helmholtz theorems, turbulence

- **Transport Coefficients**
  Chapman-Enskog expansion, diffusion, viscosity & thermal conductivity, stress tensor

- **Navier-Stokes**
  viscous flow, accretion flow,

- **Fluid Instabilities**
  Klevin-Helmholtz, Rayleigh Taylor, thermal instability, Jeans criterion

- **Sound waves & Shocks**
  linear perturbation theory, sound speed, Rankine-Hugoniot jump conditions

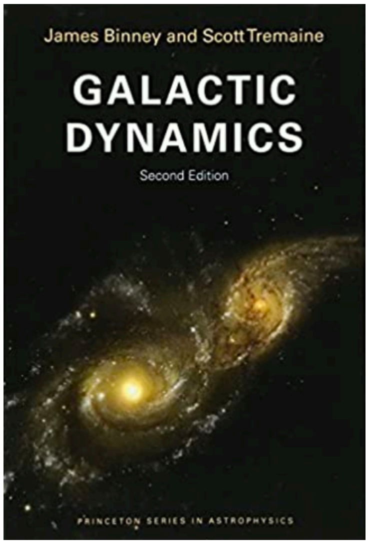
PART IV: Plasma Physics [Lectures 21-24]

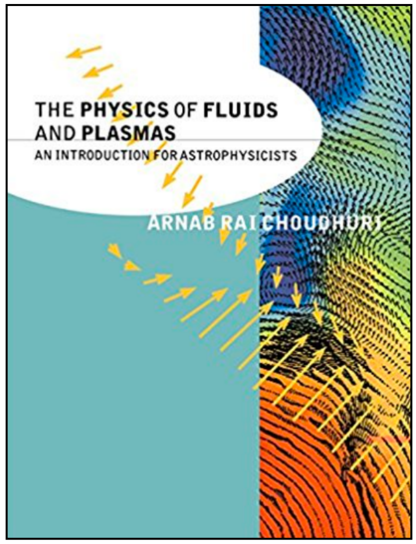
- **Introduction to Plasmas**
  length scales, Debye length, plasma frequency, plasma parameter, collision frequency

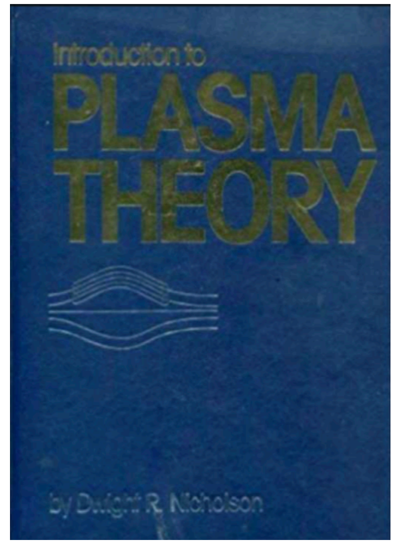
- **Collisionless Plasmas**
  Vlasov equation, Langmuir waves, Landau damping, two-fluid model

- **MagnetoHydroDynamics (MHD)**
  resistive vs. ideal MHD, Ohms' law, induction equation, dynamos

Recommended Textbooks







- **Galactic Dynamics (second edition)**
  Author: *James Binney & Scott Tremaine* *(ISBN-978-0-691-15902-7)*

- **The physics of fluids and plasmas: an introduction for astrophysicists**
  Author: *Arnab Rai Choudhuri* *(ISBN-0-521-55543)*

- **Introduction to Plasma Theory**
  Author: *Dwight R. Nicholson* *(ISBN-978-0-894-6467705)*

Recommended Clothing

Preliminary Schedule

week	Date	Topic
1	Thu 08/31	**Theoretical Foundations:** Introduction
2	Tue 09/05	**Theoretical Foundations:** Classical Dynamics; a primer
2	Thu 09/07	**Theoretical Foundations:** Hamilton-Jacobi Theory
3	Tue 09/12	**Theoretical Foundations:** Action-Angle Variables
3	Thu 09/14	**Kinetic Theory:** from Liouville to Boltzmann
4	Tue 09/19	**Kinetic Theory:** from Boltzmann to Navier-Stokes
4	Thu 09/21	**Kinetic Theory:** stochasticity & Langevin equation
5	Tue 09/26	**Kinetic Theory:** the Fokker-Planck equation
5	Thu 09/28	**Fluid Dynamics:** Introduction to hydrodynamics
6	Tue 10/03	**Fluid Dynamics:** Transport Mechanisms & Constitutive equations
6	Thu 10/05	**Fluid Dynamics:** hydrodynamic equations
7	Tue 10/10	Fluid Dynamics: vorticity & circulation
7	Thu 10/12	**Fluid Dynamics:** hydrostatics and steady flows
8	Tue 10/17	**Fluid Dynamics:** viscous flow and accretion flow
8	Thu 10/19	**NO CLASS [OCTOBER RECESS]**
9	Tue 10/24	**MIDTERM EXAM**
9	Thu 10/26	**Fluid Dynamics:** turbulence
10	Tue 10/31	**Fluid Dynamics:** sound waves & shocks
10	Thu 11/02	**Fluid Dynamics:** fluid instabilities
11	Tue 11/07	**Collisionless Dynamics:** Jeans equations & dynamical modeling
11	Thu 11/09	**Collisionless Dynamics:** virial theorem & gravothermal catastrophe
12	Tue 11/14	**Collisionless Dynamics:** collisions & encounters
12	Thu 11/16	**Plasma Physics:** introduction
13	Tue 11/21	**NO CLASS [THANKSGIVING BREAK]**
13	Thu 11/23	**NO CLASS [THANKSGIVING BREAK]**
14	Tue 11/28	**Plasma Physics:** plasma orbit theory
14	Thu 11/30	**Plasma Physics:** Plasma kinetic theory
15	Tue 12/05	**Plasma Physics:** Vlasov equation & the two-fluid model
15	Thu 12/07	**Plasma Physics:** magnetohydrodynamics (MHD)

The Road To Success

This course will make use of **vector calculus** and **multi-variable calculus**, and the students are expected to be familiar with this. Appendices **A**-**C** in the lecture notes summarize these materials, and the students are strongly encouraged to read these Appendices in detail.

➢ Attend **lectures**, and actively participate; ask questions in class!

➢ Carefully read **Lecture Notes** on related material. Study the relevant material using text books, internet etc. (**self-study**)

➢ Seek **help** from instructor
(after class, during office hours, or by arranging for an appointment via e-mail)

➢ **Problem Sets**:

* submit problem sets on time (points will be subtracted for late submissions)
* explain how you came to the solution (derivations), and use words/text to explain your line of thoughts. Failure to do so results in points being subtracted.
* Write clearly and neatly: if I can't read it, I won't give points for it.
* Work on the problem sets individually! That is the only way in which you will be able to gauge your level of understanding. If you get stuck, you may briefly consult with fellow students, but remember that the work must be yours!
* Plagiarism is strictly forbidden, as is the use of ChatGPT or other AI.