AS727
Cosmic Plasma Physics

1 Description

The temperature of the sun's surface is 4000K-5000K, but just outside the surface, in a region called the corona, the temperatures exceed 20 million degrees K. The mechanism that heats and sustains these high temperatures remains unexplained. In the auroral regions of the Earth's ionosphere and magnetosphere large numbers of electrons have been measured traveling near the speed of light and the mechanism of acceleration has eluded thirty years of scientific inquiry. Magnetic fields weave around and through galaxies but astronomers have only recently begun to understand the importance of these fields on galactic formation and evolution. To address these questions we need to understand the behavior of electrically charged fluids called plasmas.

In AS727, we will study the physics and mathematics of fundamental plasma physics as it applies to space and astrophysical situations. We will begin the class by defining the fundamental interactions of charged particles and their motion in an electromagnetic field. Then, we will make a number of simplifying assumptions about the collective behavior of large numbers of particles in order to derive the “kinetic equations” of plasma physics. Under some conditions, these complex equations simplify further, generating a set of fluid equations which we will use to study waves and instabilities in plasma physics. Making still more simplifications will allow us to derive the equations of magnetohydrodynamics (often call “MHD”) which describe some of the behavior of plasmas near the sun, in magnetospheres and in man-made controlled fusion devices. We will then return to the kinetic equations and discuss how to solve them. Lastly, if time permits, we’ll address an advanced topic of the class’s choosing.

2 Mechanics

- Time: Tuesdays 3:30-5:00pm and Fridays 9:30-11:00am
- Place: CAS 500
- Instructor: Meers Oppenheim

3 Requirements and Grading

- Prerequisites: Junior level electrodynamics, mechanics, statistical mechanics, vector calculus, partial differential equations and complex analysis (or consent of the instructor).
- Problem Sets (25% of grade)
    - Seven problem set assignments.
    - Solutions will be handed out at the time problem sets are due in order to provide immediate feedback.
    - Grade will derive from top 5 problem set grades so no extensions or late problem sets accepted.
    - Students may work in groups but should write up solutions individually.
    - Recommendation: students should initially attempt problems individually.
- Midterm test (may be oral or a take-home) (25% of grade)
- Final exam (40% of grade)
- Class participation (10% of grade)
    - Recapitulation – for the 1st ten minutes of each class, a student will review and discuss the main point(s) from the previous class. We will choose the student for each class at the beginning of the semester.
    - Day to day participation.

4 Bibliography

- Assigned text: *Introduction to Plasma Physics and Controlled Fusion* by F. Chen
- Space physics oriented book: *Basic Space Plasma Physics* by W. Baumjohann and R. Treumann
- More advanced space oriented plasma physics book: *Plasma Physics* by Sturrock (also, costs less than $30)
- Book I was hoping to assign but was unavailable: *Introduction to Plasma Physics* by R. Goldston and P. Rutherford

5 Proposed Detailed Syllabus

I. Introduction
   a. Introduce instructor and students
   b. Why study plasma physics?
   c. Description of the course and requirements
   d. Intro to plasma physics and the particle-in-cell (PIC) method

II. Basic Concepts
   a. Define density and temperature
   b. Define Debye length and plasma parameter
   c. Introduce cold plasma oscillations and the plasma frequency
   d. Introduce quasineutrality
   e. Introduce collisions
   f. Introduce diffusion

III. Single Particle Motion I
   a. Lorenz force
   b. Pedersen drift
   c. Magnetized motion – Hall drift
   d. $\vec{\boldsymbol{E}} \times \vec{\boldsymbol{B}}$ and $\vec{\boldsymbol{F}} \times \vec{\boldsymbol{B}}$ motion
   e. $\vec{\nabla}$ drift and curvature drift
   f. Polarization drift
   g. Guiding center motion

IV. Single Particle Motion II
   a. Magnetic moment
   b. Mirror and $\mu\vec{\nabla}\boldsymbol{B}$ force – Van Allen belts
   c. Adiabatic invariance of μ
   d. Hamiltonian dynamics

V. Kinetic Theory I
   a. Simple derivation of Klimatovich and Vlasov equations
   b. Discuss meaning

VI. Diffusion and Collisions in a Weakly Ionized Plasma
   a. Collisions with neutrals – the ionosphere
   b. Diffusion in the ionosphere
   c. Ambipolar diffusion
   d. Ionization and recombination

VII. Diffusion and Collisions I a Fully Ionized Plasma
   a. Coulomb collisions
   b. Diffusion

VIII. Derivation and Discussion of Fluid Equations
   a. Derive continuity equation
   b. Derive acceleration equation
   c. Define pressure
   d. Discuss temperature equations
IX. Fluid Equations II
   a. Discuss convective derivatives – Eulerian vs. Lagrangian frame of reference
   b. Comparison to "simple" hydrodynamics
   c. Fluid drifts – parallel and perpendicular to B
   d. Quasineutrality
X. Linearization & Fourier-Laplace Transforms
   a. Demonstrate linearization
   b. Fourier& Laplace transformations
   c. Guess method
XI. Warm Langmuir Waves
   a. Derive equations
   b. Show dispersion equation
   c. Discuss relationship between $\vec{k}$ and $\vec{E}$
XII. Complex Dielectric Constants, $\varepsilon(\vec{k},\omega)$
   a. Mobility tensors
   b. Dielectric tensors
   c. Discuss problems with magnetization tensor
XIII. Ion Acoustic Waves and EM Waves without a $\vec{B}_0$
   a. Derive Ion acoustic dispersion relationship
   b. Discuss dispersion characteristics and kinetic modifications
   c. Derive EM waves without a $\vec{B}_0$
   d. Discuss dispersion characteristics
XIV. EM Waves with a $\vec{B}_0$
   a. Derive
   b. Discuss $B_0 \to 0$
   c. Discuss $B_0 \to \infty$
   d. Discuss $k \perp B_0 - O$ and X modes
XV. EM Waves with a $\vec{B}_0$ II
   a. $k \parallel B_0$
   b. Discuss left-handed and right-handed polarized waves
   c. Discuss Whistlers
   d. Discuss Alfen wanes
   e. Discuss waves at other angles
XVI. Single Fluid MHD
   a. Derive and discuss equations
XVII. MHD –Waves
   a. Alfen waves
XVIII. MHD – Instabilities

XIX. Kinetic Theory II
  a. Compare Fokker-Planck, Boltzmann and Vlasov equations
  b. Krook and BGK collision operators
  c. 1D Vlasov
  d. Plasma oscillations

XX. Kinetic Theory III – Landau Damping
  a. Landau contour
  b. Discussion
  c. Energy analysis

XXI. Nonlinear Plasma Physics – Time Permitting