AST 521: Introduction to Plasma Astrophysics

Fall 2025
Lectures: MW 10:40am – 12:00pm, (room TBD)

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Summary:
More than 99% of the known Universe is composed of plasma. It should then come as no surprise that a solid understanding of basic fluid and plasma dynamics has been the foundation of many of the greatest successes in theoretical astrophysics. This course is designed to provide students with a broad overview of topics and techniques in the study of fluid and plasma dynamics, as applied to a wide variety of space and astrophysical systems. Topics are chosen from classic work that has made a lasting impact on the field, as revealed by contemporary research directions in theoretical space and astrophysics. The solar wind and corona, the intracluster medium of galaxy clusters, the interstellar medium of galaxies, and a wide variety of accretion flows are used throughout the course to motivate a rigorous mathematical and physical description of plasmas.

Prerequisites:
This course is nominally intended for graduate students in astrophysics and in plasma physics, although senior undergraduates have taken the course successfully with some hard work. It is assumed that you are familiar with vector calculus, linear algebra, ordinary and partial differential equations, (very basic) contour integration, Fourier and Laplace transforms, Newtonian and Lagrangian mechanics, basic thermal physics and statistical mechanics, and Maxwell's equations. If you are not comfortable with any of this material, please let us know and we can formulate a plan for getting you up to speed. No prior knowledge of plasma physics or astrophysics is needed: the course is designed to be entirely self-contained in this regard.

Academic Integrity:
University rules regarding academic integrity and the Honor System apply to all work in this course. As a part of these rules, you must give credit to any book, article, or web page that you use in completing homework assignments. These rules also apply to unpublished sources of information. Students are strongly encouraged to discuss assignments and other class material with each other, but, as for other courses, copying or paraphrasing from other students' written solutions is not permitted.

Course Materials:
Materials for the course, include homework assignments and extensive lecture notes, are made available. As a supplement to the lecture notes, the following textbooks on plasma physics and fluid dynamics may prove useful:

R. M. Kulsrud	*Plasma Physics for Astrophysics*
N. A. Krall and A. W. Trivelpiece	*Principles of Plasma Physics*
R. D. Hazeltine and F. L. Waelbroeck	*The Framework of Plasma Physics*
D. J. Acheson	*Elementary Fluid Dynamics*
F. H. Shu	*The Physics of Astrophysics: Gas Dynamics*
NRL Plasma Formulary	

Here are also some recommended pedagogical review articles on topics in plasma physics and astrophysical fluid dynamics to supplement the lecture notes, which will also be made available:

S. I. Braginskii	*Transport Processes in Plasma*
R. M. Kulsrud	*MHD Description of Plasma*
F. L. Hinton	*Collisional Transport in Plasma*
S. A. Balbus	*Enhanced Angular Momentum Transport in Accretion Disks*
S. A. Balbus and J. F. Hawley	*Instability, Turbulence, and Enhanced Transport in Accretion Disks*
N. F. Loureiro and D. Uzdensky	*Magnetic Reconnection: From the Sweet-Parker Model to Stochastic Plasmoid Chains*
A. A. Schekochihin	*MHD Turbulence: A Biased Review*
F. Rincon	*Dynamo Theories*
C. F. McKee and E. C. Ostriker	*Theory of Star Formation*

Grading Scheme (tentative):
70% weekly problem sets
25% written portion of final exam
5% oral portion of final exam

Course Schedule:

W Sep 3	Course welcome. Introduction to plasmas [Kunz] *course welcome; what is a plasma? fundamental scales and speeds (Debye length, skin depth, Larmor radius, mean free path, plasma frequency, Larmor frequency, collision frequency, Alfvén speed, thermal speed); dimensionless parameters (plasma parameter, beta parameter); hierarchy of plasma descriptions*
M Sep 8	Single-particle motion [Kunz] *particle motion in constant and nearly constant fields; guiding-center motion (E×B, g×B, grad-B, curvature, and polarization drifts); adiabatic invariance* **HW01 assigned**
W Sep 10	Kinetic description of plasma [Kunz] *why is kinetic theory needed? Klimontovich equation and Liouville distribution; qualitative explanation of BBGKY hierarchy; Vlasov-Landau equation; example collision operators*
M Sep 15	Moment equations and closures [Kunz] *derivation of moment equations; Maxwell-Boltzmann distribution and moment hierarchy closures; single-fluid HD and MHD equations*
W Sep 17	Formulations of hydrodynamics (HD) and magnetohydrodynamics (MHD) [Kunz] *MHD equations from conservation laws; Lorentz force (tension/pressure); ideal induction and Alfvén's theorem; Maxwell and Reynolds stress tensors and conservation-law form of equations*
M Sep 22	HD and MHD: equilibria and steady flows [Ostriker] *magnetic virial theorem; equilibrium of self-gravitating magnetized systems; general considerations for steady flows (critical points, Bernoulli); Bondi/Parker problem* **HW01 due; HW02 assigned**
W Sep 24	HD and MHD: linear waves [Ostriker] *linear theory: Alfvén, fast, and slow waves*
M Sep 29	HD and MHD: linear instabilities [Ostriker] *Kelvin-Helmholtz, Rayleigh-Taylor, and other instabilities; Schwarzschild criterion for convection*

W Oct 1	HD and MHD: linear instabilities and wave amplification in rotating and shearing systems [Ostriker] *rotating frame equations; Rayleigh instability; magnetorotational instability; magneto-Jeans and magnetized swing amplifier*
M Oct 6	HD and MHD: Nonlinear waves and discontinuities [Ostriker] *Rankine-Hugoniot jump conditions; parallel and perpendicular MHD shocks* **HW02 due; HW03 assigned**
W Oct 8	MHD extensions [Ostriker] *Radiation hydrodynamics (RHD), heating and cooling effects, thermal instability*
	Fall break
M Oct 20	Non-ideal MHD [Kunz] *simple derivation of generalized Ohm's law; ambipolar diffusion; applications to molecular clouds and protostellar accretion disks*
W Oct 22	Non-ideal MHD, continued [Kunz] *Hall effect; whistler and ion-cyclotron waves; applications to protostellar accretion disks*
M Oct 27	Non-ideal MHD, continued [Kunz] *Ohmic dissipation; linear theory of tearing modes: Furth, Killeen, Rosenbluth, Coppi* **HW03 due; HW04 assigned**
W Oct 29	Non-ideal MHD, continued [Kunz] *Sweet-Parker reconnection; Petschek; plasmoid instability; current trends*
M Nov 3	Turbulence [Kunz] *Kolmogorov; Iroshnikov-Kraichnan; weak turbulence; applications to solar wind*
W Nov 5	Turbulence, continued [Kunz] *strong turbulence; Goldreich-Sridhar; Boldyrev; imbalance; application to solar wind*
M Nov 10	Dynamo theory [Kunz] *Cowling's and Zel'dovich's anti-dynamo theorems; kinematic dynamo; application to ICM* **HW04 due; HW05 assigned**
W Nov 12	Dynamo theory, continued [Kunz] *nonlinear dynamos; mean-field theory; helicity; application to galaxies and stars*
F Nov 14	Braginskii MHD [Kunz] *discussion of collisional transport; anisotropic transport in a magnetized plasma*
M Nov 17	Cosmic ray (CR) basics [Ostriker] *CR properties, acceleration mechanisms*
W Nov 19	CR–ISM interactions [Ostriker] *CR streaming instability, wave damping, CR-MHD and the ISM*
M Nov 24	Braginskii MHD, continued [Kunz] *convective and rotational stability; application to ICM and proto-galaxies* **HW05 due; HW06 assigned**
	Thanksgiving break
M Dec 1	Magnetokinetics [Kunz] *drift-kinetic equation; Landau damping of ion-acoustic waves*
W Dec 3	Magnetokinetics, continued [Kunz] *Barnes damping of slow waves; microscale kinetic instabilities*
F Dec 12	**HW06 due**
Th Dec 18	University deadline for submission of take-home exams