Astronomy 253: Plasma Astrophysics

Course Syllabus for Spring 2016

Instructors

- Xuening Bai (xbai@cfa.harvard.edu; P-216 at 60 Garden St; MS-51)
- Nick Murphy (namurphy@cfa.harvard.edu; P-140 at 60 Garden St; MS-83)

Times

- Mondays & Wednesdays, 3:30-5:00 pm

Location

- The first class on Jan 25 will be in the Pratt Conference Room at the 60 Garden Street facility of the Harvard-Smithsonian Center for Astrophysics. This room is wheelchair accessible, while the classroom A-101 is not. The course locations afterward will be discussed on the first day (possibilities include Pratt, B-105, B-106, and A-101).

Suggested Prerequisites

- Intermediate electromagnetism
- Some experience with vector partial differential equations

Course Web Page

- https://canvas.harvard.edu/courses/9132

Office Hours

- Xuening is generally available in his office after 2 pm in the afternoon on weekdays. Preferred times are 4-6 pm on Tuesdays, and 2-4 pm on Fridays. Feel free to stop by at other times, or by email appointment.
- Nick is usually in his office from late morning until mid-evening. The most likely times to find him there are early afternoons on weekdays, but he will generally be busy with preparations during the two hours before teaching. Feel free to stop by, or email to find a time to meet.

Summary

Plasma pervades the universe at all measurable scales. Most visible matter, from the Earth's outer atmosphere to the intracluster medium between galaxies, is magnetized and ionized. Plasma physics effects can thus be pivotal in determining the flow of mass, momentum, and energy in astrophysical systems. For example, magnetic fields convert kinetic energy from stellar interiors to heat their outer atmospheres. Magnetic fields tap the rotational energy of accretion disks to drive jets and outflows, and plasma transport processes determine the rates of accretion onto stars and supermassive black holes. In supernova remnants and the interstellar medium, magnetic fields oppose the tendency of plasmas to thermalize by accelerating cosmic rays.

This course provides an introduction to plasma physics in an astrophysical context. Topics include charged particle motions, kinetic theory, magnetohydrodynamics (MHD), waves, instabilities, dynamos, shocks, particle acceleration, and magnetic reconnection. Specific applications may include solar and stellar flares, space weather, magnetized accretion disks, cosmic rays, galactic dynamos, and interstellar turbulence.

The material in this course will be presented via a combination of lectures and readings. Not everything discussed in class will be found in the textbook, so attendance at the lectures is strongly encouraged. Some lecture materials will also be posted on the course web page. We encourage you to ask questions and participate in discussions, either in class or afterward.

Accommodations for Disabilities

This course has a two section policy on accommodations for disabilities. The first section is required by Harvard University. The second section is adapted from text by disability justice activist Lydia Brown.

Students needing academic adjustments or accommodations because of a documented disability must present their Faculty Letter from the Accessible Education Office (AEO) and speak with the instructors by the end of the second week of the term (Friday, February 5, 2016). Failure to do so may result in the Course Head's inability to respond in a timely manner. All discussions will remain confidential, although Faculty are invited to contact AEO to discuss appropriate implementation.

We are committed to creating a learning space where everyone can participate as fully as possible. We recognize that providing information and resources in multiple formats enables a wider range of access. If you have any access needs that we can better support by changing any aspect of our teaching (including class discussions) or the way we have handled assignments/readings, you are welcome and encouraged to let us know in public or in private how we can better support your access needs. We recognize that there are many reasons students may need to adjust their pace, style, or method of learning, including disability, personal circumstances, unexpected emergencies, or other learning differences. You need not have a specific reason or diagnosis; everyone deserves to learn in the way that makes the most sense for them in any given class at any point in time. All discussions on accommodations will remain confidential.

Course Material

The primary textbook will be *The Physics of Plasmas* by T. J. M. Boyd and J. J. Sanderson (Cambridge University Press, 2003). This textbook contains a general introduction to plasma physics, with several applications to laboratory and astrophysical plasmas. This text is available to Harvard students and affiliates as an ebook through HOLLIS+.

Secondary resources

The following secondary resources contain additional information on plasma physics and astrophysical plasmas.

1. *Lectures in Magnetohydrodynamics** by Dalton Schnack (Springer-Verlag, 2009). Lecture notes for a graduate course in MHD and its extensions. Contains discussions on tensor calculus as used in plasma physics, MHD, reduced MHD, force-free fields, instabilities, reconnection, turbulence, dynamos, and extended MHD.
2. *Plasma Physics for Astrophysics* by Russell Kulsrud (Princeton University Press, 2005). Contains discussions on particle motions, MHD, instabilities, shocks, collisionality, collisionless plasmas, turbulence, cosmic rays, dynamos, and reconnection.
3. *Magnetohydrodynamics of the Sun** by Eric Priest (Cambridge University Press, 2014). Contains detailed discussions of MHD including equilibria, waves, shocks, reconnection, instabilities, dynamo theory, and magnetoconvection. Solar physics topics include coronal heating, prominences, flares, coronal mass ejections, and the solar wind.
4. *Applications of Classical Physics*, online textbook by Roger Blandford and Kip Thorne. Contains chapters on fluid dynamics, turbulence,

MHD, plasma waves, and nonlinear plasma processes. Available at: http://www.pmaweb.caltech.edu/Courses/ph136/yr2012/

5. *Magnetic Fields in Diffuse Media** edited by Alex Lazarian, Elisabete de Gouveia Dal Pino, and Claudio Melioli (Springer, 2015). A compilation of chapters by experts on astrophysical magnetic fields. Topics include techniques for observing cosmic magnetic fields, ambipolar diffusion, turbulence, turbulent reconnection, star formation, galactic and extragalactic magnetic fields, and particle acceleration.

Books denoted by an asterisk are available as ebooks through HOLLIS+ to Harvard students and affiliates.

Course Schedule

The following is the approximate schedule for Astronomy 253. These dates may change. The readings are from Boyd and Sanderson unless otherwise noted. There are no classes on February 15, March 14, and March 16.

Introduction and overview (Jan 25; NM & XB)
Significance of plasma astrophysics, review of syllabus, units, fundamental plasma scales (Ch. 1).

Particle motions and drifts (Jan 27; XB)
Orbit theory, $\mathbf{E}\times\mathbf{B}$ drift, ∇B drift, curvature drift, polarization drift, magnetic mirrors, adiabatic invariants (Ch. 2).

Magnetohydrodynamics (Feb 1, 3, & 8; NM)
Equations of MHD, conservation equations, magnetic pressure, magnetic tension, frozen-in condition, force-free fields, helicity, virial theorem (Ch. 3-5). *Assign Problem Set #1 on Feb 1.*

MHD waves (Feb 10 & 17; NM)
Linear oscillations in uniform and non-uniform media, wave energy, nonlinear steepening (Chapter 4 of Priest). *Problem Set #1 due on Feb. 10. Assign Problem Set #2 on Feb. 17.*

Shocks (Feb 22; NM)

Rankine-Hugoniot relations, MHD discontinuities (rotational, tangential), shock thickness, intersecting characteristics (Section 5.6).

MHD instabilities (Feb 24; NM)
The energy principle, stability, classification of instabilities (Sections 4.5-4.7 and 5.3).

Accretion disks (Feb 29; XB)
Overview, magnetorotational instability, winds and jets. Optional readings: Balbus, 2003, ARA&A, 41, 555 (section 5); Spruit, 1996 (astro-ph: 9602022). *Problem set #2 due on Feb. 29.*

Collisionless plasmas (Mar 2, 7 & 9; XB)
Vlasov-Maxwell equations, waves in a cold plasma, thermal effects: Landau damping, non-linear effects (Sec. 6.3-6.5, 7.1-7.4, 10.2-10.3). *Assign Problem Set #3 on Mar 7. Provide a list of possible term project topics on Mar 9.*

Collisions and transport (Mar 21, 23 & 28; XB)
Coulomb collisions, transport coefficients, kinetic MHD, anisotropy-driven instabilities (Ch. 8). *Problem Set #3 due on Mar 23. Assign Problem Set #4 on Mar 28.*

MHD turbulence (Mar 30; Blakesley Burkhart)
Wave-wave interactions, Kolmogorov theory, anisotropic MHD effects. *Due date for students to choose their term project topics.*

Energetic particles and cosmic rays (Apr 4 & 6; XB)
Observational overview, Fermi II acceleration, diffusive shock acceleration, cosmic-ray propagation. *Problem Set #4 due on Apr 6.*

Computational methods for plasma astrophysics (Apr 11 & 13; XB & Lorenzo Sironi)
Fluid and kinetic simulation methods. *Assign Problem Set #5 on Apr. 13.*

Astrophysical dynamos (Apr 18; NM)
Cowling's anti-dynamo theorem, mean field theory, alpha-omega dynamos (Chapter 8 of Priest).

Magnetic reconnection (Apr 20; NM)
Sweet-Parker and Petschek theory, the plasmoid instability, collisionless reconnection, 3D effects, reconnection in GRBs and jets.

Space weather (Apr 25; NM)
Solar wind, solar flares, coronal mass ejections, solar energetic particle events, geomagnetic storms, application to exoplanet habitability.

Partially ionized plasmas (Apr 27; NM)
Ambipolar diffusion, ion-neutral drag, equilibrium/non-equilibrium ionization, solar chromosphere, protoplanetary disks. *Due date for Problem Set #5.*

Problem Sets

There will be five problem sets assigned throughout the semester. These problem sets are designed to help you become familiar with the concepts from the prior two to four lectures. The course schedule lists the estimated dates when the problem sets will be assigned, and the target dates for them to be handed in. Students may either hand in hardcopies of their solutions to one of the instructors (preferably during the class), or email electronic versions to both.

Each problem (and sub-problems within it) weighs a certain number of points. Grading will be based on the accuracy of the solution, the inclusion of intermediate steps, and communication of how the solution was found. Students may use symbolic manipulation software such as SymPy, Mathematica, and Maple but must include adequately commented and understandable code in their solution sets.

Problems sets are due on the dates listed. However, since it is our top priority that the students have sufficient time to learn from the problem sets, an extension (generally up to 1 week) will be granted on special cases (such as illness, conference travel, family obligations, or multiple deadlines) if the students inform the instructors on or before the due date. If the instructors are not consulted, then each problem set that is late will incur a penalty of a 5% lower grade per business day that it is late.

Term Project

There will be a combined project and term paper that will count for 35% of the grade. This will enable you to explore a chosen topic in more detail and gain experience with scientific writing. We will provide a potential list of topics on March 9, and students are welcome to choose their own topics in consultation with the instructors. The students are required to discuss with the instructors before deciding on the topics for the final projects by March 30 (though the topic may be changed at a later time without penalty). The topic should be chosen to require a reasonable and not overwhelming time commitment.

The tentative date of the final project presentations will be Wednesday, May 4th. The tentative due date for the final project paper is Friday, May 6th. We will do our best to schedule the final presentations at a time during the exam period that works for all students and allows time afterward for feedback from the presentation to be incorporated into the paper.

Grading

The final grade will be broken down into contributions from problem sets (65%) and the term paper/course project (35%). There will be no final exam.

Units

The course lectures will be in Gaussian cgs units because of their prevalence in astronomy. However, the textbook uses SI units. Problem sets and course projects may be completed using either Gaussian cgs or SI units.

Policy on Collaboration

Discussion and the exchange of ideas are essential to doing academic work. For assignments in this course, you are encouraged to consult with your classmates as you work on problem sets. However, after discussions with peers, make sure that you can work through the problem yourself and ensure that any answers you submit for evaluation are the result of your own efforts. Similarly, you must list the names of students with whom you have collaborated on problem sets.