Astronomy 253: PLASMA ASTROPHYSICS
Course Syllabus (Spring 2014)

Instructors:	Steven R. Cranmer (scranmer@cfa.harvard.edu)
	Office: P–347 at 60 Garden Street, Phone: 495-7271
	Nicholas A. Murphy (namurphy@cfa.harvard.edu)
	Office: P–140 at 60 Garden Street, Phone: 384-7830

Times:	Mondays & Wednesdays, 3:30–5:00 pm
Location:	Classroom, A-101
Prerequisites:	Astronomy 151 (Fluid Dynamics) is recommended, not required
Web page:	http://www.cfa.harvard.edu/∼scranmer/Ay253/
Office hours:	By appointment, or drop in (see web page for available times)

SUMMARY

Plasma pervades the universe at all measurable scales. Most visible matter, from the Earth's outer atmosphere to the inter-cluster medium between galaxies, is magnetized and ionized. Thus, plasma physics effects can be pivotal in determining the flow of mass, momentum, and energy in all kinds of astrophysical systems. For example, magnetic fields convert kinetic energy in stellar interiors to heat in 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 and plasma processes in an astrophysical context. Topics include charged particle motions, kinetic theory, magnetohydrodynamics, waves, instabilities, dynamos, shocks, particle acceleration, and magnetic reconnection. Specific applications may include solar and stellar coronae (including flares), interplanetary space plasmas, 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 recommended textbooks, so attendance at the lectures is strongly encouraged. Some lecture materials will also be posted on the course web page. Active participation is an important component to learning, so please ask questions (either in class or afterward) if something does not make sense. Prior experience with using computers to solve mathematical problems would be very useful for this course, but it is not required.

COURSE MATERIAL

Primary textbook: *Plasma Physics for Astrophysics,* by Russell M. Kulsrud (Princeton U. Press, 2005). This book provides a good graduate-level overview of the majority of topics covered in this course.

Secondary resources: We recommend four other books for alternate approaches to some of the core concepts:

1. *The Physics of Fluids and Plasmas: An Introduction for Astrophysicists,* by Arnab Rai Choudhuri (Cambridge U. Press, 1998). Particularly good on conveying the linkage between concepts from non-magnetized fluid and kinetic theory (see Ay 151) to their corresponding generalizations in the world of magnetized plasmas.
2. *Introduction to Plasma Physics and Controlled Fusion,* by Francis Chen (Plenum Press, 2010). Although the focus is not on astrophysics, this beginning-level graduate text contains a strong introduction to basic

plasma processes that occur both in the laboratory and in astrophysics.

3. *Lectures in Magnetohydrodynamics,* by Dalton Schnack (Springer-Verlag, 2009). Lecture notes for a graduate course in MHD and its extensions.
4. *Introduction to Space Physics,* by Margaret Kivelson and Chris Russell (Cambridge U. Press, 1995). An undergraduate-level text that may be useful for going over some of the basic phenomenological ideas in a more exhaustive way than is found in the graduate-level books.

Online lecture notes: Quite a few intrepid instructors have assembled book-length versions of their lectures that often rival published texts in their completeness (though they sometimes lack the benefits of professional editing). We will link to PDF copies of some of our favorite notes on this course's web page.

SCHEDULE

The dates listed are approximate, and the relevant chapters/sections of Kulsrud's book are given on the right. These readings are not formally assigned, but it is highly recommended that students become familiar with these topics before their discussion in class.

1. **Introduction & Overview** (Jan 27; SC & NM) .... Ch. 1
2. **Particle Motions & Kinetic Theory** (Jan 29, Feb 3; SC) .... Ch. 2
   Orbit theory, adiabatic invariants, magnetic mirrors, Debye shielding, Vlasov-Maxwell equations.
3. **Magnetohydrodynamics** (Feb 5, Feb 10, Feb 12, Feb 19; NM) .... Ch. 3–4
   Conservation equations, magnetic pressure, flux freezing, force-free fields, virial theorem.
4. **MHD Waves and Shocks** (Feb 24, Feb 26, Mar 3; SC) .... Ch. 5–6
   Linear oscillations in uniform & nonuniform media, wave energy, nonlinear steepening, shocks.
5. **MHD Instabilities** (Mar 5, Mar 10; NM) .... Ch. 7
   The energy principle, stability, line tying and shear.
6. **Coulomb Collisions** (Mar 12, Mar 24, Mar 26; SC) .... Ch. 8
   Binary collisions, Braginskii and Fokker-Planck collision time scales, transport coefficients.
7. **Collisionless Plasmas** (Mar 31, Apr 2; SC) .... Ch. 9–10
   Langmuir waves, Landau damping, cold plasma dispersion relations, wave-particle interactions.
8. **Turbulence** (Apr 7, Apr 9; SC) .... Ch. 11
   Wave-wave interactions, Kolmogorov cascade, anisotropic MHD effects.
9. **Energetic Particles** (Apr 14, Apr 16; NM) .... Ch. 12
   Cosmic ray propagation, Fermi acceleration, spatial diffusion & scattering.
10. **Astrophysical Dynamos** (Apr 21; NM) .... Ch. 13
    Cowling's theorem, mean-field & interface theories, diffusion versus advection.
11. **Magnetic Reconnection** (Apr 23, Apr 28; NM) .... Ch. 14
    Sweet-Parker & Petschek theory, Hall effects, anomalous resistivity, asymmetric reconnection.
12. **Partial Ionization Effects** (Apr 30; NM) .... N/A
    Ambipolar diffusion, ion-neutral drag, equilibrium and non-equilibrium ionization balance.

Depending on the time available at the end of the semester, we may introduce other astrophysical applications or review some material that may need extra discussion.

GRADING

The final grade is broken down into contributions from problem sets (50%), a term paper/project (25%), and the final exam (25%).

PROBLEM SETS

There will be approximately 6 problem sets assigned throughout the semester. Each homework will help you become more familiar with the concepts discussed in the prior 2 to 3 lectures. A detailed schedule of distribution and due dates will be given out in class and posted on the course web page.

Hardcopy submissions are preferred, but there will also be an email address to which you can submit electronic versions of the solutions. Students choosing the latter option are strongly encouraged to write out solutions long-hand and scan them. (That way you won't be tempted to leave out intermediate steps when typing in equations.) Scanners are available at the CfA Computation Facility and the Wolbach Library.

Problems are due on the dates listed. However, since it is our top priority that students have sufficient time to learn from the problem sets, we will grant one lateness exception per student: One problem set can be turned in up to three business days late with no penalty. Each subsequent problem set that is late wil incur a penalty of a 5% lower grade per business day that it is late.

TERM PAPER / PROJECT

There will also be a combined project and term paper that will count for 25% of the final grade. This will enable you to explore a chosen topic in more detail and gain some extra experience with scientific writing. The project itself needs to involve two components:

1. A detailed written review of a given topic, conveying both some historical background and a scientific motivation for why this topic is relevant, and
2. Some kind of mathematical or computational calculation that goes beyond what was presented in the lectures and problem sets. Example ideas include:
    - exploration of a wider "parameter space" of a textbook model,
    - construction of a numerical model or simulation,
    - analysis of some archival observational data, or
    - testing the claims made in a recent paper.

Students should begin thinking of ideas for their project during the first few weeks of the course and begin discussing and/or brainstorming them with the instructors. A project topic should be selected and submitted to the instructors by **Wednesday, February 26, 2014.** We will be available to discuss these ideas throughout this time period, and no points will be taken off if an initially proposed idea doesn't pan out.

The term paper that describes the results of the project should be no less than about 10 pages in length, not including references. Needless to say, all external sources used for the paper (whether quoted directly or just used as inspiration) should be clearly indicated and cited in the reference list. A summary of *Astrophysical Journal* style guidelines will be distributed as a guide. Depending on the type of work done, the term paper can be submitted along with electronic files (e.g., images, movies, data) that illustrate what was accomplished. The due date for the report is **Monday, April 21, 2014.**

FINAL EXAM

There will be a three-hour final exam that will be scheduled by FAS during the designated Spring Examination Period (May 9–17). Please do not make plans to leave campus during this time. The exam will be worth 25% of the course grade.

POLICY ON COLLABORATION

Problem sets are best done individually, but peer-to-peer collaboration can also be very helpful. Thus, we encourage discussion about the problem sets and projects. However, each student must submit his/her own individual, original solutions. Please note, at the top of your problem set, the names of people with whom you collaborated. Work that matches too closely that of another student or outside source is not acceptable.

ACCOMMODATIONS FOR STUDENTS WITH DISABILITIES

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 instructor by the end of the second week of the term. 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.