PLASMA ASTROPHYSICS (Physics 805)

Basic information

- **Instructor:** Professor Ellen Zweibel

- **Contact information:**
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  - Office: 6281 Chamberlain
  - Office hours: No fixed hours. You are always welcome to drop by or make an appointment.

- **Mailboxes:** 5th floor of Sterling (Astronomy mailboxes) and 1323 Sterling (Physics mailboxes). If you put something in either one, please alert me by email. I don’t check them very often.

- **Course web page:** [http://www.physics.wisc.edu/graduates/](http://www.physics.wisc.edu/graduates/); then click under Graduate Courses: Current Offerings & Home Pages.

Why study plasma astrophysics?

Most of the visible matter in the Universe is magnetized. How did that happen, and what are the consequences? Although magnetic energy rarely dominates astrophysical systems, magnetic fields are pivotal in transferring energy and momentum from one form to another: converting kinetic energy in stellar interiors to heat in their outer atmospheres, tapping rotational energy in accretion disks to drive jets and outflows, transporting angular momentum outward so that accretion disks accrete. In the interstellar medium of galaxies, magnetic fields oppose the tendency of plasmas to thermalize by putting up to half the plasma energy into a billionth of the particles: the so-called cosmic rays. These are only a few examples.

Plasma astrophysics is a wonderful way to learn plasma physics, and even to extend it. The dimensionless parameters that describe astrophysical systems are often so extreme that astrophysical problems push plasma theory to its limits. Effects that may be peripheral in the laboratory - interactions with neutrals, radiative cooling, or open or fieldline tied boundaries, for example - may be central in an
astrophysical problem. Plasma physics became powerful and sophisticated primarily through laboratory applications. It has much to contribute to astrophysics, and becomes stronger through astrophysical applications.

This is a unique time to be studying plasma astrophysics at the University of Wisconsin. The NSF is funding a new Physics Frontier Center, led by Stewart Prager, on the theme of Magnetic Self-Organization in Laboratory and Astrophysical Plasmas. The Center research is organized around laboratory, computational, and theoretical study of basic plasma physics processes of importance to astrophysics. I will tie much of the material in this course to the research goals of the Center.

Content

Here, in order, are the topics we will cover. We have some flexibility on this, and can emphasize or de-emphasize based on your interests.

An overview of the basic physics. In this part of the course we will lay out the framework of magnetohydrodynamics, justify it in the astrophysical context, and use it to develop some intuition about astrophysical magnetic fields.

Magnetic fields in galaxies. We will begin with a brief overview of galactic structure and the measurement of galactic magnetic fields. Then we will look focus on two areas, acceleration and propagation of cosmic rays, and galactic dynamos. This will carry us into MHD turbulence.

Magnetic fields in stars. First, a brief introduction to stellar structure and stellar magnetic fields from the very young (protostars) to the very old (neutron stars). Then we will focus on the evolution of magnetic fields over the entire age sequence, including stellar dynamos. Our second topic will be magnetic field dissipation and plasma heating, including flares.

Magnetic fields in accretion disks. Once more, an introduction to disks, from the cold protoplanetary variety to the hot disks surrounding massive black holes. We will focus on angular momentum transport through instabilities. This will take us into turbulence in collisionless plasma, winds, and jets.
Course Structure

In Class: Please come with questions and be prepared to join discussions. You are expected to present some material in class; see below.

Reading: There is no textbook for this course. Four books are currently on reserve in the Physics Library (http://physics.library.wisc.edu/reserves.htm, then click on Physics 805). Plasma Physics, by P.A. Sturrock (1994), and Physics of Fluids & Plasmas, by A.R. Choudhuri (1998), are two fairly current plasma physics textbooks with an astrophysical slant. Solar Magnetohydrodynamics, by E.R. Priest (1982) is old, but still widely used. Cosmic Ray Astrophysics, by R. Schlickeiser (2002), is a good, up to date reference with substantial discussions of the background plasma physics and astrophysics. I will rarely assign readings from these books, but you may find them useful to complement or supplement what we do in class. I am writing a book (Astrophysical Magnetohydrodynamics, under contract with Cambridge University Press) and will make pieces of it available. I will assign some journal articles over the course of the term. Check the library web page for details.

Homework: I will assign homework (typically 2 problems per week) on Thursdays, collect it the following Thursday, and return it, with solutions, the following Tuesday. This system will break down if you are not prompt about turning in assignments. If you are going to turn in homework late, please let me know beforehand so we can make arrangements. I encourage collaboration on homework, but write up your assignments individually. Problem sets and solutions will be available from the class web page.

Small Research Projects: These projects are your opportunity to do a research project on plasma astrophysics and report on it to the class. The project may be original work or a critical review of the literature. You may, if you like, work in common with up to 2 other people. Please set up a meeting with me before you start work to discuss the scope of the project. The papers are due December 9. The presentations will take place that week. Here are a few possible topics, just to give you a flavor. I will add others, and you may propose your own.

- The atmospheres of so-called brown dwarf stars are so cool that they are almost entirely neutral, and have relatively low electrical conductivity. Yet, brown dwarfs are observed to have radio and x-ray flares
which are thought to be powered by magnetic fields. Investigate the
dynamics of magnetic fields in a brown dwarf envelope.

- Galactic cosmic rays are thought to be accelerated by turbulence in
  the vicinity of shocks driven by supernova explosions. Write a Monte
  Carlo code to simulate this process. Try to reproduce the power law
  spectrum predicted by theory and study its evolution over time.

- Escape of galactic magnetic fields plays a crucial role in their evolu-
  tion, including operation of a galactic dynamo. Evaluate the various
  mechanisms that have been proposed for the vertical escape of mag-
  netic fields from disk galaxies.

- Magnetic reconnection: beyond MHD. As we discussed in class, the-
  ories of magnetic reconnection based on MHD predict that reconnec-
  tion is very slow. Alternative theories have been proposed based on
  enhancement of the resistivity by instabilities or separating electron
  and ion dynamics through the Hall effect. Survey at least one of these
  theories and discuss astrophysical applications.

**Grading:** There are two ways to take this class.

- If you want a letter grade, about 60% of it will be determined by home-
  work, and 40% by the research project, including your presentation to
  the class. The word “about” recognizes the inherent subjectivity of
  the grading process, and allows me to raise your grade on the basis of
  outstanding class participation.

- If you want a Pass, participate in class discussion and give a talk on
  your research. According to the Registrar, you must declare this option
  by September 26.