PHYS-753

Dynamics of astrophysical fluids and plasmas

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Cursus	Sem.	Type
Physics		Opt.

Language of teaching	English
Credits	4
Session	
Exam	Oral
Workload	120h
Hours	**56**
Lecture	28
Exercises	28
Number of positions	

Frequency

Every year

Summary

The dynamics of ordinary matter in the Universe follows the laws of (magneto)hydrodynamics. In this course, the system of equations that describes astrophysical fluids will be discussed on the basis of selected astrophysical examples, from the physics of stars, to galaxies and the early Universe.

Content

Astrophysical objects, like stars, the interstellar medium, galaxies, and galaxy clusters, are typically modeled as fluids. Since baryonic matter (= non-Dark Matter) in the Universe is partially or sometimes even fully ionized, astrophysical fluids are coupled to cosmic magnetic fields which are detected by radio telescopes everywhere where we have to means to do so. Therefore, astrophysical flows follow the laws of magnetohydrodynamics (MHD), making this an essential tool for a modern theoretical astrophysicist.

In this course, I will review the basics of MHD with selected applications to astrophysics. The students will learn which different MHD effects are important in which astrophysical problem. They will also learn how to solve the MHD equations analytically (~60% of the exercises will be pen and paper work) for special problems and the basics of how to perform numerical simulations (the remaining ~40% of the exercises). For this, the publically available Pencil Code will be used (http://pencil-code.nordita.org/). The students will be running 2D sample simulations and analyze the output data with python. Python libraries for reading the simulation data will be provided.

In the first part of this course, I will focus on purely hydrodynamical aspects of astrophysical fluids. I will discuss the parameter space of astrophysical fluids and argue why a continuum description can be used in most systems. To set the stage, the basic system of equations for neutral fluids will be derived. A discussion of the role of viscosity follows that will include an overview of accretion disk physics. Next, I will introduce perturbation theory in hydrodynamics and the theory of waves, including shock waves such as the one generated by supernovae that expand into the interstellar medium. In that context, classical astrophysical hydrodynamical instabilities will be discussed as well, like the convective instability, the Rayleigh-Taylor instability, and the Kelvin-Helmholz instability. The students will explore these hydrodynamical instabilities in numerical experiments. As a natural next step, I will discuss turbulence, for which the linear perturbation theory is no longer applicable. I will introduce the phenomenological description of turbulence based on Kolmogorovâ##s theory and highlight the importance of turbulence in astrophysics, where e.g. it plays a major role in the formation of stars in the interstellar medium.
The second part of this course will be devoted to magnetohydrodynamics (MHD). I will discuss the extension of hydrodynamics to MHD and also give a motivation from a microscopic viewpoint. Astrophysical plasmas will be classified based on particle density and temperature. I will spend some time on the discussion of the induction equation in order to allow the students to get familiar with the dynamics of magnetic fields in specific astrophysical flows. Next, I will discuss the variety of MHD waves with a focus on the ones that are important in astrophysics. I will also introduce classical astrophysical MHD instabilities, such as the Parker instability which is thought to be critical for the evolution of galaxies and for the formation of giant molecular clouds in the interstellar medium. As an example of a space plasma where magnetic fields play a significant role, I will use the Solar corona. The fact that the corona is orders of magnitudes hotter than the surface of the Sun, is thought to be related to dissipation of magnetic energy and is closely tight to topological

considerations including magnetic reconnection. One further subject of the course will be MHD dynamos. These are processes that convert kinetic energy into magnetic energy exponentially in time. I will discuss mean-field turbulent dynamos using the example of the dynamo of the Sun which explains the 11-year Solar cycle. The values of the turbulent transport coefficients determine the efficiency of the mean-field dynamo and I will present analytical methods to estimate those. Next, I will discuss the small-scale turbulent dynamo that is sourced by astrophysical turbulence, using the Kazantsev theory. Compared to the mean-field dynamo, the small-scale dynamo is faster and generates no large-scale magnetic field component but only a fluctuating one. In the exercises, the students will perform a few simple dynamo experiments with numerical simulations. Finally, I present an overview of current theories on magnetogenesis, both in the early Universe and during cosmic structure formation. In comparison to the previous lectures that are mostly based on well-accepted textbook material, this final lecture will give the students a glimpse of the current state of the research.

Outline of the course:

1. Introduction to astrophysical fluids;
2. From a kinetic description to the hydrodynamic equations;
3. Viscosity and accretion disk physics;
4. Perturbation theory in hydrodynamics;
5. Turbulence in astrophysics;
6. Numerical methods in astrophysical fluid dynamics;
7. Description of astrophysical plasmas;
8. Properties of the induction equation;
9. MHD waves and instabilities in astrophysics;
10. Magnetic reconnection;
11. MHD Dynamos I: Mean-field dynamos and transport coefficients;
12. MHD Dynamos II: Small-scale dynamos and Kazantsev theory;
13. Numerical methods in astrophysical MHD;
14. Evolution of magnetic fields in cosmic history

Keywords

Theoretical Astrophysics, Magnetohydrodynamics

Learning Prerequisites

Required courses

Requirement: "Introduction to astrophysics"##, "##Electrodynamics"##

Recommended courses

Useful: "Hydrodynamics"##, "##Plasma physics"##, "##Statistical physics"##, "##Cosmology"##

Learning Outcomes

By the end of the course, the student must be able to:

- define and describe the equations that describe different astrophysical fluids
- solve simple astrophysical MHD problems analytically and numerically with the Pencil Code

Resources

Bibliography

Choudhuri, "The physics of fluids and plasmas. An introduction for astrophysicists"##, Cambridge University Press, 1998
Biskamp, "##Magnetohydrodynamic Turbulence"##, Cambridge University Press, 2003
Brandenburg & Subramanian, "##Astrophysical magnetic fields and nonlinear dynamo theory"##, Physics Report, 2005

Ressources en bibliothèque

- The physics of fluids and plasmas. An introduction for astrophysicists
- Magnetohydrodynamic Turbulence
- Astrophysical magnetic fields and nonlinear dynamo theory