Plasma Physics and advanced fluid dynamics

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I- Plasma Physics : principles, structures and dynamics, waves and instabilities

Besides ordinary temperature usual (i) solid state, (ii) liquid state and (iii) gaseous state, at very low and very high temperatures new exotic states appear : (iv) quantum fluids and (v) ionized gases. These states display a variety of specific and new physical phenomena : (i) at low temperature quantum coherence, correlation and indiscernibility lead to superfluidity, superconductivity and Bose-Einstein condensation ; (ii) at high temperature ionization provides a significant fraction of free charges responsible for instabilities, nonlinear, chaotic and turbulent behaviors characteristic of the "plasma state". This set of lectures provides an introduction to the basic tools, main results and advanced methods of Plasma Physics.

- **Plasma Physics :** History, orders of magnitudes, Bogoliubov's hierarchy, fluid and kinetic reductions. Electric screening : Langmuir frequency, Maxwell time, Debye length, hybrid frequencies. Magnetic screening : London and Kelvin lengths. Alfven and Bohm velocities.
- **Charged particles dynamics :** adiabaticity and stochasticity. Alfven and Ehrenfest adiabatic invariants. Electric and magnetic drifts. Ponderomotive force. Wave/particle interactions : Chirikov criterion and chaotic dynamics. Quasilinear kinetic equation for Landau resonance.
- **Structure and self-organization :** Debye and Child-Langmuir sheath, Chapman-Ferraro boundary layer. Brillouin and basic MHD flow. Flux conservation : Alfven's theorem. Magnetic topology : magnetic helicity conservation. Grad-Shafranov and basic MHD equilibrium.
- **Waves and instabilities :** Fluid and kinetic dispersions : resonance and cut-off. Landau and cyclotron absorption. Bernstein's modes. Fluid instabilities : drift, interchange and kink. Alfvenic and geometric coupling. Introduction to gyrokinetic. Wave/wave interactions and parametric instabilities.
- **Relaxation an dissipation:** Coulomb collisions : Landau equation. Electron impact ionization: Thomson's cross section. Friction and momentum transfer. Thermalization and energy transfer. Relaxation : Landau equation Green's functions. Fluids moments, coupled fluxes and entropy production.

II- Advanced fluid dynamics

These lectures aim to bridge the gap between classical introductory lectures on fluid mechanics and the more advanced problems addressed in academic research.
The first part of the course will be devoted to fundamental aspects, including the interplay between statistical physics and fluid dynamics. In particular, we will briefly discuss the theoretical process leading to the Navier-Stokes equations from the Boltzmann equation of the classical kinetic theory of gases.
This approach highlights the relation between transport coefficients (such as heat conduction) and microscopic data and will lead us to describe some features of the theory of thermal conduction and diffusion in fluids.
Similarly, a part of the course will focus on the fundamentals of compressible-fluid motions, which usually remain on the fringes of introductory courses. We will see that there exists a strong analogy between gas dynamics and shallow-depth interfacial waves, leading to interesting results on shock waves and solitary waves. An introduction to complex fluids, such as magnetohydrodynamics or quantum hydrodynamics will also be given.

- **Fundamentals:** - Introduction to fluid dynamics, conservation laws, - Inviscid irrotational flows, - Boundary layers, rotating fluids
- **Statistical Physics:** - Boltzman equation - Passage from Boltzman to Euler and Hilbert's problem - Chapman-Enskog expansion
- **Thermal effects:** - Boussinesq approximation - Transport of a passive scalar, effective diffusivities, mixing - Heat transport and scaling laws for turbulent convection
- **Compressible flows:** - Gas dynamics, self-similar compressible flows - Shock waves
- **Surface and Interfacial waves:** - Free surface wave theory, - Shallow-depth problem and Korteweg-de Vries equation - solitary waves
- **Complex fluids** - Introduction to quantum hydrodynamics and superfluidity - Magnetohydrodynamics

Bibliography:

• J. M. Rax, *Physique des Plasmas*, (Dunod Sciences Sup, 5e tirage, 2018).

• J. M. Rax, *Physique des Tokamaks*, (Editions de l'Ecole Polytechnique, 2011).

• L Chen, *Waves and Instabilities in Plasmas*, (World Scientific, 1987).

• L. Landau, E. Lifchitz, *Course of theoretical physics - Fluid mechanics*(1971)

• P. A. Thompson, *Compressible Fluid Dynamics* (1972)

• H.K. Moffatt, *magnetic field generation in electrically conducting fluids*, Cambridge Press (1978)

• J. Lienhard IV & J. Lienhard V *A Heat Transfer Textbook*, Cambridge Massachussets (1981)