SCIENTIFIC TRAINING PROGRAMME 2023-2024

The Vlasov-Boltzmann Equation in Astrophysics

Objective : These lectures cover several fields of applications of the Vlasov-Boltzmann equations in an astrophysical context, ranging from galaxies and extragalactic physics, to star-star interactions and collisional dynamics, to high energy phenomena such as pulsar atmospheres and relativistic particle interactions.

Format : A package of three (3) series of lectures will cover these topics in turn, each one focusing on a given range of linear scale (say, galaxies of c. 100 000 light-years of diameter). A series consists of 8 2h-lectures with added hands-on exercise classes, for a total of ten classes. The plan is to schedule one series (or, *lecture set*) per semester, spread over the academic year 2023-24. Each set is **self-contained** and there is **no pre-requisite** to attend any one of them.

Detailed layout of the lectures Set #2 :

The physics of compact sources & relativistic plasmas (Lecturer : J. Pétri)*

Lecture 1. Observational characteristics of compact sources in astrophysics, history **Lecture 2.** The origin of pulsars and neutron stars as remnant of supernovae events **Lecture 3.** The magnetosphere of pulsars: I. The MHD equations, perfect vs diffusive, examples for dipolar field **Lecture 4.** The magnetosphere of pulsars: II, with topical exercises (1h) The MHD equations, perfect vs diffusive, examples for dipolar fields **Lecture 5**. The relativistic magnetosphere: I. Basics of relativistic dynamics, pair creation **Lecture 6.** The relativistic magnetosphere: II. Higher order configurations, comparison with observations **Lecture 7.** General relativity I. Differential geometry, parallel transport, tensor algebra **Lecture 8.** General relativity II. The field equations, examples, pulsar arrays as GW detectors **Lecture 9.** The Kerr metric and relativistic emission (g-ray bursts, ..) **Lecture 10.** Q/A Session: Links to particle physics, and future (space) mission

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Calendar : for **Set #2** : 2nd Semester - weeks 8 - 15 (19 February - 11 April 2024)

Dates	Number of the lecture	Time slots
Monday 19 February 2024	1	09h00 to 11h00
Thursday 22 February 2024	2	09h00 to 11h00
Monday 26 February 2024	3	09h00 to 11h00
Thursday 29 February 2024	4	09h00 to 11h00
Thursday 14 March 2024	5	09h00 to 11h00
Monday 18 March 2024	6	09h00 to 11h00
Monday 25 March 2024	7	09h00 to 11h00rs
Thursday 28 March 2024	8	09h00 to 11h00rs
Monday 8 April 2024	9	09h00 to 11h00s
Thursday 11 April 2024	10	09h00 to 11h00rs

The Vlasov-Boltzmann Equation in Astrophysics

- ***General topics covered by each lecture set*** :

1. Stellar dynamics, stellar evolution, the formation of stellar black holes, introductory relativity (special, general) : Christian Boily ;
2. The physics of pulsars, their atmospheres, multipolar configurations, relativistic plasmas, pair-creation, pulsars as gravitational antennas, gravitational waves : Jérôme Pétri.
3. Galaxies as a fluid of stars, the formation of galaxies, equilibrium state and perturbative treatment, the Gaia mission : Giacomo Monari ;

- ***Proposed calendar for the academic year 2023-24*** :
  - Two lectures per week, usually Monday morning & Tuesday afternoon ;
  - **Set #1** : 1st Semester semaines 9 - 13 (13 November - 11 December 2023)
  - **Set #2** : 2nd Semester semaines 5 - 10 (11 March - 15 April 2024)
  - **Set #3** : 1st Semester semaines 8 - 12 (November - December 2024, tbc)

- ***Venue*** : all lectures to take place at the Observatoire astronomique or, in case of a change, at the European Doctoral College.

Detailed layout of the lectures

Set #1 : *The dynamics of stars and their evolution* *(Lecturer : C. Boily)*

Lecture 1. Observations of stars in galaxies:
review of scales, gravitational dynamics
Lecture 2. The Vlasov-Boltzmann equation of equilibrium states for stars
Lecture 3. The thermodynamics of self-gravitating Newtonian systems I.
Kinetic energy diffusion, phenomenology, experiments
Lecture 4. The thermodynamics of self-gravitating Newtonian systems II.
Fokker-Planck approach, 1D- vs 2D models, observations
Lecture 5. Hands-on Exercise, *The evolution of stars, stellar remnants*:
supernovae, stellar mass black holes (BH), mass vs light, numerical exploration
Lecture 6. The dynamics of galactic nuclei:
super-massive BH, accretion discs, observations & theory
Lecture 7. Merging BH and introduction to general relativity: I.
tensor algebra, coordinate transformation, metrics
Lecture 8. Merging BH and introduction to general relativity: II.
curvature, parallel transport, energy density tensor
Lecture 9. Merging BH and introduction to general relativity: III.
Einstein's Equations, Schwarzschild metric
Lecture 10. *Gravitational wave sources*: Q/A session on current issues
Collisional evolution of BH binaries, stellar vs super-massive BH

Set #2 : *The physics of compact sources & relativistic plasmas* *(Lecturer : J. Pétri)*

Lecture 1. Observational characteristics of compact sources in astrophysics, history
Lecture 2. The origin of pulsars and neutron stars as remnant of supernovae events
Lecture 3. The magnetosphere of pulsars: I.
The MHD equations, perfect vs diffusive, examples for dipolar fields
Lecture 4. The magnetosphere of pulsars: II, with topical exercises (1h)
The MHD equations, perfect vs diffusive, examples for dipolar fields
Lecture 5. The relativistic magnetosphere: I.
Basics of relativistic dynamics, pair creation
Lecture 6. The relativistic magnetosphere: II.
Higher order configurations, comparison with observations
Lecture 7. General relativity I.
Differential geometry, parallel transport, tensor algebra
Lecture 8. General relativity II.
The field equations, examples, pulsar arrays as GW detectors
Lecture 9. The Kerr metric and relativistic emission (g-ray bursts, ..)
Lecture 10. Q/A Session: Links to particle physics, and future (space) missions

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Set #3 : ***The dynamics of galaxies in equilibrium*** ***(Lecturer : G. Monari)***

Lecture 1. Observations of galaxies / their components, colours, stellar components (chemical composition, ..)

Lecture 2. The Vlasov-Boltzmann state of equilibrium for galaxies: Distribution functions, Jeans's theorems

Lecture 3. Hamiltonian dynamics applied to galaxies I. Euler-Lagrange equations, Action-angle formalism

Lecture 4. Hamiltonian dynamics applied to galaxies II. Resonances, pattern speed, the formation of a bar

Lecture 5. Q/A session, exercises on *Perturbation analysis*: Orbital migration, central bulge - disc coupling, observations

Lecture 6. The Milky Way in the Gaia era: I. Coordinate systems, historical review (Hipparcos, Rave, ..)

Lecture 7. The Milky Way in the Gaia era: II. Disc dynamics in the Solar neighbourhood (Hercules stream, ..), the central bar (strength, pattern speed, ..)

Lecture 8. Stellar streams and the shape of the dark matter halo

Lecture 9. The path to equilibrium: galaxy formation in cosmology, timescales

Lecture 10. Q/A Session : *Future (space) missions and surveys of galaxies.*

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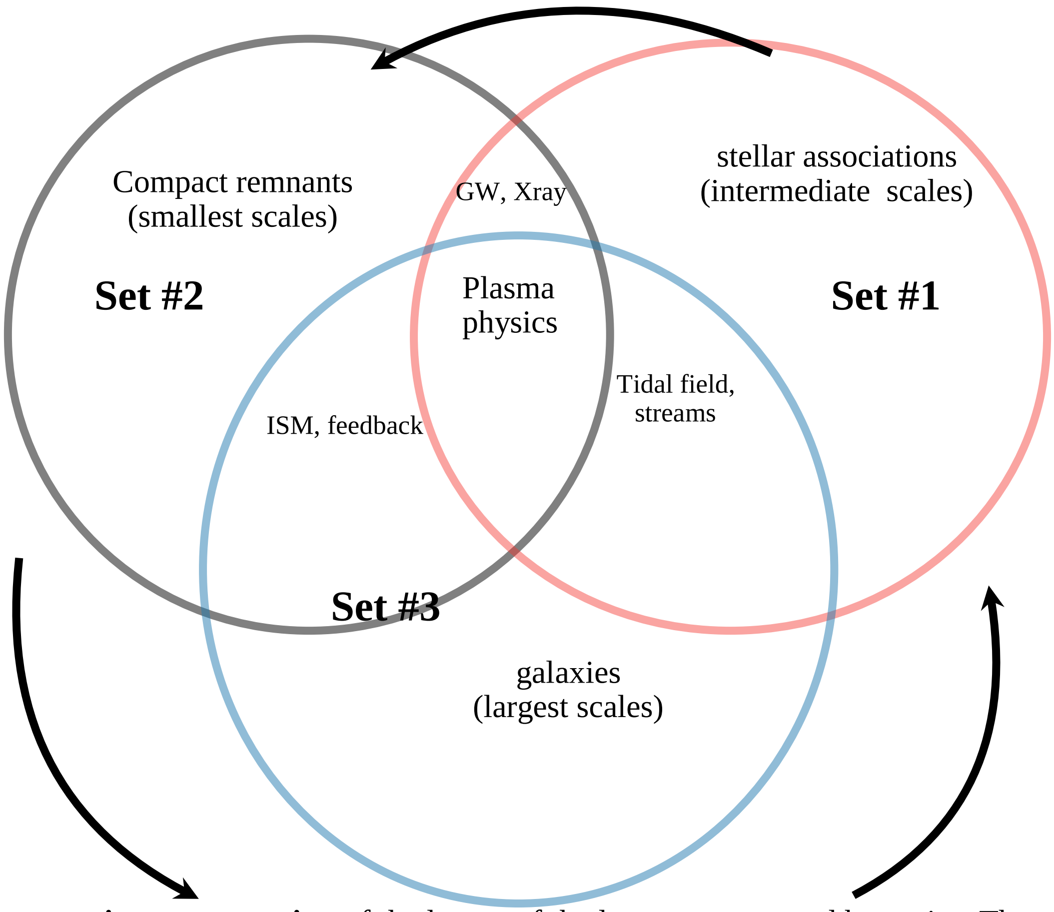

Diagrammatic representation of the layout of the lectures regrouped by topics. The core and common approach to all is the Vlasov-Boltzmann system of equations as applied to plasma physics in various situations. By changing scale (of energy density) the equations can be adapted to treat the equilibrium state of galaxies ; the evolution of stellar associations in the Fokker-Planck limit ; and the high energy regime of ionised interstellar medium (ISM) and compact remnant atmospheres. The diverse phenomena may all be described from a “plasma” (fluid) approach, including gravitational wave emission.