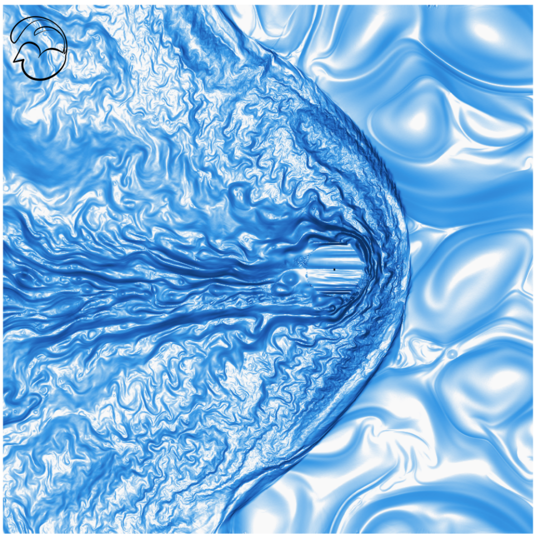
Astrophysical & space plasma



SUMMARY.

The vast majority of astrophysical visible matter is composed of plasmas, a state of matter with complex (i.e. non-linear and out-of-thermodynamic equilibrium) dynamics combining both small scale, individual particle interactions and large scale collective effects. The equations for plasmas are non linear and do not always have analytical solutions. The study of plasmas thus often requires numerical simulations for which a plethora of techniques and codes exist. In this METEOR, the student(s) will first learn theory to describe and understand space and astrophysical plasmas. The student(s) will then implement a numerical code to describe the dynamics of fundamental astrophysical and space plasma processes. This code will be optimized to introduce high performance computing basics (e.g. parallelization, GPU porting) and/or be used to study energy conversion processes in front of space plasma shocks.

OBJECTIVES

- Learn relevant theory to model astrophysical plasma phenomena and understand how to choose the relevant model for a given scientific question (**Eulerian, PIC, Hybrid PIC...**).
- Write, from scratch, a Vlasov-Poisson solver. Various numerical schemes will be taught, and the student will choose an appropriate spatial and temporal scheme.
- Understand high performance computing (HPC) code and architecture with the goal of preparing the student to work on large HPC machines.

PREREQUISITES

- ☒ S1. Data Sciences
- ☒ S1. Numerical methods
- ☒ S2. General mechanics

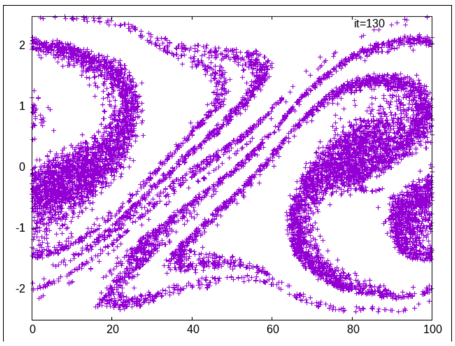
THEORY

by F. Sporykhin

Small and large scale interactions within space and astrophysical plasma arise from the self-consistent interaction between the electromagnetic field and charged particles that compose the plasma. At small scales, particles of opposing charges serve as a shield and lessen the single-charged particle electric potential in a phenomenon known as Debye shielding. At scales larger than the Debye length that characterized such screening, only large-scale interactions controlled by collective behavior occur in a plasma. Starting with the Poisson equation, the student will derive the (linear) Debye screening theory as well as single charged particle motion dictated by the Lorentz force, which results in cyclotron motion and drifts. This section will allow the student to understand what happens to individual charged particles within a plasma.

by P. Henri

Plasma waves and instabilities. The energy transport in astrophysical and space plasmas is significantly controlled by wave propagation. Such waves are often trigger by unstable configuration, source of free energy, that drive plasma instabilities. The student will study an archetype of space plasma waves (Langmuir waves) and of plasma instability driving such waves (bump-on-tail, two-stream instabilities).



Phase space representation (velocity w.r.t. space) of a PIC simulation of a two-stream instability.

APPLICATIONS

by P. Henri, F. Sporykhin

- **Common Project**: Write a 1D-1D Vlasov-Poisson solver capable of simulating the non-linear, out-of-thermodynamic equilibrium evolution of a distribution of charged particles. This can be done in the student's language of choice (e.g. C++, Fortran, Python). The solver must be then validated with a well studied case such as a two-stream instability or Landau Damping.
- **Personal Project**: depending on the progress of the common project, we then propose the following to the student(s):
  - Parallelising the solver on a GPU using, for example, (**CUDA, Kokkos, OpenMP, SYCL...**). The student may also be taught how to access large HPC centres to run on high end hardware.
  - Apply the developed code to model the nonlinear evolution of accelerated charge particles in front of an astrophysical or a space plasma shock. Perform a spectral analysis together with a phase space analysis of the simulation output. This will allow the student to familiarise themselves further with the data analysis

needed for astrophysical and space plasma simulations.
  - Expanding the code to a second dimension. This allows to study the symmetry breaking in the transverse direction of space plasma kinetic instabilities associated to accelerated charged particles.

MAIN PROGRESSION STEPS

- `Week 1 and 2`: Theory lectures and bibliographical work
- `Week 3`: Oral exam on the theory and a start on writing the code
- `Weeks 4 and 5`: Coding and debugging
- `Weeks 6`: Validation
- `Weeks 7`: Debugging and preparation for the defence

EVALUATION

- `Theory grade [30%]`
  - Oral exam (70%): theoretical questions
  - Curiosity and engagement (30%)
- `Practice grade [30%]`
  - Code quality (50%)
  - Validation report of the code (50%)
- `Defense grade [40%]`
  - Oral and slides quality
  - Context
  - Project / Personal work
  - Answers to questions

BIBLIOGRAPHY & RESOURCES

- Chapter 2 of Computer Simulation Using Particles. Hockney, R.W; Eastwood, J.W (ask for djvu file)
- Chapter 2 of Plasma Physics via Computer Simulation. Birdsall, C.K; Langdon, A.B (ask for djvu file)
- https://gitlab.com/etienne.behar/menura

CONTACT

☎ filipp.sporykhin@oca.eu
✉ pierre.henri@oca.eu