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Abstract Book

Basic colllisionless plasma physics

Homogeneous collisionless plasma with a thermal boundary: the temporal coarse-graining method

Luca Barbieri (1), Lapo Casetti (1), Andrea Verdini (1), Simone Landi (1), Emanuele Papini (2), Pierfrancesco Di Cintio (3)

(1) Dipartimento di Fisica e Astronomia, Universita di Firenze,via G. Sansone 1, Sesto Fiorentino, I-50019, Italy. (2) INAF - Istituto di Astrofisica e Planetologia Spaziali, via del Fosso Cavaliere 100 Roma, I-00133, Italy. (3) Institute of Complex Systems, National Council of Research (ISC-CNR), via Madonna del piano 10 Sesto Fiorentino, I-50019, Italy

Prompted by the relevant problem of temperature inversion (i.e. gradient of density anti-correlated respect to the gradient of temperature) in solar physics, we introduce a novel method to model a gravitationally confined multi component collisionless plasma in contact with a fluctuating thermostat. The dynamics is worked out via a set of effective partial differential equations for the coarse-grained versions of the distribution functions of the plasma components and a temporal coarse-grained energy reservoir. We derive a stationary solution of this system naturally predicting the inverted density-temperature profiles of the two-species as observed in systems of astrophysical interest such as the solar corona.

We validate our method by comparing the analytical results against kinetic numerical simulations of the plasma dynamics in the context of the two species Hamiltonian mean-field model (HMF). Finally, we apply our theoretical framework to the problem of the temperature inversion in the solar corona obtaining density and temperature profiles in remarkably good agreement with the observations.

Kinetic effects in thin layers: effects on jump conditions and discontinuity properties

Gérard Belmont (1), Giulio Ballerini (1, 2), Laurence Rezeau (1), Francesco Califano (2)

(1) Laboratoire de Physique des Plasmas (LPP), CNRS, Ecole Polytechnique,Sorbonne Universite, Universite Paris-Saclay, Observatoire de Paris, 91120 Palaiseau, France (2) Dipartimento di Fisica E. Fermi, University of Pisa, Italy

In plasmas as in neutral fluids, there are a few types of well-established kinds of discontinuities: shocks, rotational discontinuities, etc., whose properties are based on the so-called "Rankine-Hugoniot" jump relations. In the classic theory, these relations are based only on universal conservation laws so that they are independent of the physics occurring inside the layer and of the theory used for describing it, fluid or kinetic. We will highlight what are the underlying assumptions behind the classic theory and show its limits. We will first make explicit the role of the pressure anisotropy, which is ubiquitous in magnetized plasmas. It makes in particular "evolutionary" the rotational discontinuity, so justifying its existence through wave steepening. Furthermore, we will show that the Finite Larmor radius (FLR) effects, implying non-gyrotropic pressure tensors, are of primary importance for the plasma equilibrium at thin layers, and that they can determine their stationary widths. Taking FLR effects into account results in discontinuity properties that are notably different from the classic ones in the quasi-tangential limit and can explain the observations at the terrestrial magnetopause. We show that the change concerning the rotational discontinuity is comparable to the change of the MHD Alfvén wave into a Kinetic Alfvén wave for the linear modes.

Current sheet formation and reconnection in collisonless turbulent plasmas

Jörg Büchner

Max-Planck-Institute for Solar System Research

N/A

A Kinetic Entropy Approach to Quantifying Dynamics of Plasmas out of Local Thermodynamic Equilibrium

Paul Cassak, Hasan Barbhuiya, Haoming Liang, Matthew Argall, Hasith Perera

West Virginia University, West Virginia University, NASA-GSFC/University of Maryland, University of New Hampshire, West Virginia University

Many plasmas are not in local thermodynamic equilibrium (LTE), so a kinetic theory approach to describe their evolution is crucial for capturing physical effects beyond ideal fluid models. Constructing an understanding of the evolution of non-LTE plasmas is often carried out by describing the evolution of the first few fluid moments of the phase space density, specifically focusing on evolution of the density, momentum, bulk kinetic energy, and internal energy. This approach captures important non-LTE effects, and has been used to understand important aspects of energy conversion in non-LTE systems. However, for a system not in LTE, there are an infinite number of possible moments of the phase space density that can be important, and the evolution of the higher order moments is typically not considered. One reason is the "closure problem", meaning that the fluid moment equations for the higher order moments cannot be closed without an assumed relation between transport coefficients and lower order moments, so an infinite number of higher order moments would have to be retained. In this presentation, we discuss an approach to describe the evolution of all of the higher order moments using the entropy in kinetic theory (Cassak et al., Phys. Rev. Lett., 130, 085201, 2023). It employs the so-called relative entropy (Grad, J. Soc. Indust. Appl. Math., 13, 259, 1965) which describes all the non-LTE structure of the phase space density. We derive an equation for its time evolution and argue it has a form related to the first law of thermodynamics. Moreover, we introduce a new quantity we call the "higher order non-equilibrium terms" (HORNET) which describes the rate that a phase space density is approaching or moving away from LTE, and has dimensions of power density so it can be directly compared to standard power densities such as the pressure-strain interaction, the vector heat flux divergence, and J dot E (Barbhuiya et al., Phys. Rev. E, submitted). We demonstrate the utility of the entropic approach in particle-in-cell simulations of magnetic reconnection, decaying plasma turbulence, and Landau damping of Langmuir waves.

Numerical simulations of positron plasma cooling in Penning-Malmberg trap

Sofia Cristofaro (1) Giovanni Manfredi (2) Francesco Valentini (1) Oreste Pezzi (3)

(1) Dipartimento di Fisica, Università della Calabria, I-87036 Rende (CS), Italy (2) University of Strasbourg and CNRS, Institut de Physique et Chimie des Matériaux de Strasbourg, UMR 7504, F-67000 Strasbourg, France (3) Istituto per la Scienza e Tecnologia dei Plasmi (ISTP), Consiglio Nazionale delle Ricerche, Via Amendola 122/D, I-70126 Bari, Italy

Simulations with the eulerian drift kinetic-Poisson algorithm PETER (PEnning Trap wavE simulatoR) [1] have been conducted to analyze the cooling process of low-energy positron beam in Penning Malmberg trap, for antimatter studies. The moderation technique considered for the confinement of the positron beam is based on electron cooling [2]: positrons lose their energy through Coulomb collisions with a cold electron plasma previously trapped in the machine.

The parameter regimes adopted are relevant for current laboratory experiments on anti-hydrogen production and manipulation, especially in the context of the GBAR [3] (Gravitational Behaviour of Anti hydrogen at Rest) experiment.

The development of a beam-plasma instability in the system, highlighted by numerical results, has been analyzed under different initial conditions.

[1] S. Cristofaro, O. Pezzi, T. M. O'Neil, P. Veltri, and F. Valentini, "Eulerian simulations of electrostatic waves in plasmas with a single sign of charge," Physics of Plasmas 29 (2022), 10.1063/5.0101194

[2] N. Oshima, T. M. Kojima, D. Dumitriu, A. Mohri, H. Oyama, T. Kambara, Y. Kanai, Y. Nakai, M. Wada, and Y. Yamazaki, "A new positron accumulator with electron plasma," Riken Review , 65–69 (2000).

[3] G. Chardin et al. (GBAR), "Proposal to measure the Gravitational Behaviour of Antihydrogen at Rest," (2011)

Non-thermal particle acceleration and power-law tails via relaxation to universal Lynden-Bell equilibria

Robert J. Ewart, Michael L. Nastac, Alexander A. Schekochihin

University of Oxford

Collisionless and weakly collisional plasmas often exhibit non-thermal quasi-equilibria. Among these quasi-equilibria, distributions with power-law tails are ubiquitous. It is shown that the statistical-mechanical approach originally suggested by Lynden-Bell (1967) can easily recover such power-law tails. Moreover, we show that, despite the apparent diversity of Lynden-Bell equilibria, a generic form of the equilibrium distribution at high energies is universal. The shape of the 'core' of the distribution, located at low energies, retains some dependence on the initial condition but it is the tail (or 'halo') that contains most of the energy. Thus, a degree of universality exists in collisionless plasmas.

Landau damping for Vlasov-type system

Antoine Gagnebin

ETH Zürich (Switzerland)

N/A

Collisionless heating in Vlasov Plasma induced by filamentation aspects

A. Ghizzo1, D. Del Sarto 1, H. Betar 2, M. Antoine 1

(1) IJL CNRS UMR 7198 Université de Lorraine, Campus ARTEM, NANCY; (2) PIIM UMR 7345 Université de Marseille

Reversible energy conversion between magnetic and kinetic energies is demonstrated for tge first time in a system of counterstreaming electron beams. This regime is characterized by the appearance of filamentation modes with large wavenumbers driven by oblique Weibel-type modes. The reversal of the energy transfer from magnetic to kinetic energy highlights two physical mechanisms of the Vlasov equation: the phase synchronization of the Van Kampen eigenmodes versus the filamentation process of the distribution function. This possibly provides a new perspective on the non ideal collisionless dissipation mechanism that is observed in Vlasov-Maxwell simulations in the form of a thermodynamic cycle leading to strong plasma heating.

A new drift kinetic formalism and code to study the interplay of linear phase mixing and turbulence in plasmas

E.A. Gorbunov, B.Teaca, F.Bacchini

KU Leuven, University of Craiova, KU Leuven

Turbulence is a process happening at a large span of spatial scales. For collisionless plasmas, energy is being cascaded from large scales down to the finest of the velocity-space scales, where it is dissipated. One of the textbook processes responsible for such thermalisation is phase mixing. In magnetised plasmas, phase mixing can be separated into linear phase mixing, which creates finer velocity-space structures in the direction parallel to the background magnetic field, and a nonlinear phase mixing, which acts in the perpendicular-velocity direction. The gyrokinetic theory has been used successfully in literature to study such effects. To focus on the interplay between turbulence and linear phase mixing, the gyrokinetic formalism can be simplified from 5D to 4D, removing the perpendicular-velocity dependence. This is done by applying the Laguerre transform in the spatial perpendicular direction to the straight background magnetic guide field, and keeping only the dominant finite-Larmor-radius effects. The resulting set of equations is then represented in Fourier-Hermite space, allowing the study of kinetic (spatial and parallel-velocity) cascades. The resulting formalism is presented, as well as its implementation in the pseudo-spectral direct numerical simulation code Alliance.

Dynamics of interacting phase-space vortices in the two species, 1D Vlasov-Poisson system

M. Lesur, A. Guillevic, D. Mandal

Institut Jean Lamour, Lorraine University

In the two-species, 1D Vlasov-Poisson system with finite current, which describes e.g. ion-acoustic turbulence, phase-space vortices spontaneously emerge from nonlinear wave-particle interactions. These structures can significantly impact (or even dominate) the nonlinear evolution, which translates into qualitatively different saturated amplitude, and new channels for anomalous resistivity and transport.

In this talk, after reviewing these former findings, I will describe in more details the dynamics of phase-space vortices. Dupree et al theory, developed in the 70's, predicts the nonlinear growthrate of an isolated phase-space hole. Based on a series of highly accurate semi-Lagrangian numerical simulations, I will present the regime of validity and shortfalls of these theories, as well as clues for improvement. Furthermore, it is known that phase-space holes tend to attract each other, in a way that is reminiscent of galaxies. Here I will focus on the effective attractive force between two holes, and describe how it depends on plasma and holes parameters.

Phase-space turbulence in electrostatic plasmas

Michael Nastac (1), Michael Barnes (1) , Robert Ewart (1) , James Juno (2) , Alexander Schekochihin (1), Wrick Sengupta (2), William Dorland (3)

(1) University of Oxford; (2) Princeton Plasma Physics Laboratory; (3) University of Maryland

We propose a theory of Vlasov-Poisson kinetic plasma turbulence in which the cascaded invariant is not energy, but rather the generalized (negative) entropy $C_2 \propto \iint d\, x dv\, f^2$. As particles ballistically stream and get accelerated by turbulent electric fields, the particle distribution function stretches and folds in both position and velocity space, and C_2 cascades from large (injection) to small (collisional) phase-space scales. The phase-space eddy turnover time is determined by the 'critical balance' between the time scales of linear phase mixing and nonlinear mixing by the electric field. We derive scalings for the wavenumber spectrum of C_2 in phase space. The only electric field spectrum dimensionally consistent with a constant-flux, critically-balanced cascade is one that is $\propto k^{-(d+3)}$ where d is the dimension. This spectrum is sufficiently steep that the phase-space mixing is dominated by the largest scales of the electric field, and so the C_2 cascade is analogous to Batchelor turbulence in fluid passive scalars. The mixing is efficient—collisional dissipation is activated on a time scale that scales logarithmically with the collision frequency. The effect of the δf fluctuations (small scales) on the equilibrium f_0(large scales) is stochastic heating, viz., non-resonant energization of particles accelerated by the chaotic electric fields. We verify this theory using direct numerical simulations of a forced, 1D-1V plasma and find good agreement. We discuss the implications of our work on the turbulent dissipation and relaxation of particle distribution functions in nearly collisionless plasmas.

Whistler instability in beam plasma system using Vlasov Maxwell model

Anjan Paul and Devendra Sharma

Institute for Plasma Research, HBNI

One of the major challenges in tokamaks like ITER is the occurrence of disruptions and its control by taming runaway electrons. During disruption event bulk plasma temperature drops to very low value as a result large toroidal electric field is generated. This large field, force a fraction of electron to detach from the core to a very high energy is called the runaway electron. Whistlers are destabilized by runaway electrons both in space and laboratory plasma. Experiments shows [1] that there exist critical value for the generation of runaway electrons in fusion reactors. Possible explanation for this cutoff is the scattering of beam electrons to stops the beam from growing. The energetic electrons accelerated by the parallel electric field are thermalised by interacting with the whistlers in tokamaks. The faster primary runaways produce a secondary runaway beam, is strongly anisotropic

in velocity space [2]. The electromagnetic Vlasov simulations presented [3] here self consistently examine the collisionless interaction of anisotropic electron beams, with parallel propagating whistlers and dependence of this process on the magnetic field strength. The kinetic instability of whistlers in a high temperature plasma, arising from electron temperature anisotropy with respect to directions parallel and perpendicular to the ambient magnetic field, is also studied. Analysis of the interaction process also includes the simulations done using anisotropic bulk electron having the bi-Maxwellian, bi-kappa distributions.

Testing the validity of plasma kinetic theory

F. Pegoraro (1), P.J. Morrison (2) , D. Manzini (3) , F. Califano (1)

(1) Department of Physics, University of Pisa, Italy; (2) Physics Department, University of Texas at Austin; (3) Laboratoire de Physique des Plasmas, CNRS, Ecole Polytechnique, Sorbonne Universite,

A starting point for deriving the Vlasov equation with a collision operator is the BBGKY hierarchy that describes the dynamics of coupled marginal distribution functions. With a large plasma parameter (number of particles in a Debye sphere) one justifies dropping certain correlations and makes assumptions so as to eliminate 2-point correlations in terms of the 1-point function.

Because of the curse of dimensions, numerically testing the assumptions of the Vlasov-Landau-Lenard-Balescu theory is prohibitive.

In this presentation, I will describe a 1-dimensional model [1] composed of electrostatically interacting aligned charged disks in order to address in a computable model the validity of the Bogoliubov assumption on the decay of correlations, a basic premise of plasma kinetic theory.

A numerical project is presently underway in order to solve for the time evolution of the two point correlation function to first order in the plasma parameter by a suitable truncation of the he BBGKY hierarchy.

Preliminary results from this numerical investigation will be presented.

[1] F. Pegoraro, P.J. Morrison, Notes on a 1-dimensional electrostatic nplasma mode}, 2022, arXiv/2210.04254.

In search of universality: towards a statistical mechanics of collisionless plasma

Robert Ewart, Michael Nastac, Alex Schekochihin

University of Oxford

Much of existing plasma (astro)physics is done hovering in the vicinity of a Maxwellian equilibrium, which is the maximum point of the standard Gibbs entropy and is achieved dynamically by means of two-particle collisions. In this lecture, I would like to discuss what I believe to be the next frontier for (astro-)plasma theoreticians and attempt to grapple with the fact that many astrophysical plasmas are too collisionless to be Maxwellian (in the sense that their dynamics occur on shorter timescales than interparticle collisions). The central question is then whether there exist universal collisionless equilibria, or classes thereof, and what they are. What is the meaning of entropy in a collisionless plasma? (Similar questions are asked in galactic dynamics, where the collisionless particles are stars.) I will discuss some simple ideas, going back to the work of Lynden-Bell in the 1960s, about the statistical mechanics of a collisionless plasma, leading to a class of universal collisionless equilibria — these are reminiscent of the equilibria of Fermi gases, with phase-volume conservation in a collisionless plasma imposing (an infinite set of) constraints that are analogous to the Pauli exclusion principle. The generalised Lynden-Bell equilibria obtained in this way cover quite a wide variety of distributions — most intriguing perhaps is that they will generically feature power-law tails and might tell us something about "nonthermal" particle energisation [1]. I will then outline a programme for how one might do to this statistical mechanics what Boltzmann did to Gibbs: derive a "collisionless collision integral" that describes the dynamical relaxation of a plasma towards the Lynden-Bell equilibria. It turns out that in order to make progress in this task, one must understand the structure of chaotic fluctuations in phase space. Lynden-Bell-like equilibria are recoverable under some very restrictive assumptions — roughly speaking, when these fluctuations are treated as structurally similar to a thermal noise [2]. In fact, they are more likely to behave like fully-fledged turbulence — with phase mixing ("Landau damping") and stochastic echoes conspiring to process a constant flux of energy [3]. What universal equilibria (if any) exist against such a background is a topic of ongoing research.

[1] R. J. Ewart et al., J. Plasma Phys. 89, 905890516 (2023) [e-print arXiv:2304.03715]

[2] R. J. Ewart et al., J. Plasma Phys. 88, 925880501 (2022) [e-print arXiv:2201.03376]

[3] M. L. Nastac et al., e-print arXiv:2310.18211

Derivation and properties of equation of Gravitation and Electrodynamics in the framework of Vlasov-type equations

Vedenyapin V.

Keldysh Institute of Applied Mathematics

Now there are exist Vlasov-Poisson equations, Vlasov-Maxwell equations, Vlasov-Einstein equations, the names were introduced mainly by Europian and USA mathematicians (Choquet-Brua, etc., see [1-15]), but have become generally accepted. The story of Vlasov-type equations will be presented. In classical textbooks (Pauli; Fock,; Landau and Lifshitz; Dubrovin, Novikov, Fomenko; Weinberg; Vlasov ...), equations for fields in the Einstein and Maxwell equations are proposed without deducing the right parts. Here we give the derivation of the right-hand sides of the Maxwell and Einstein equations within the framework of the Vlasov-Maxwell-Einstein equations from the classical, but slightly more general principle of least action. A method of transition from kinetic equations to hydrodynamic consequences is proposed, as it was done earlier by A.A.Vlasov himself. In the case of Hamiltonian mechanics, a transition from the hydrodynamic consequences of the Liouville equation to the Hamilton-Jacobi equation is possible [5-29]. Thus, in the non-relativistic case, Milne-McCree solutions are obtained, a non-relativistic analogue of Friedman-type solutions of the evolution of the Universe [30-43].

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Computational and mathematical approaches

Embedded grid refinement for Semi-Lagrangian parallelized relativistic Vlasov-Maxwell solver

M.Antoine (1), A.Ghizzo (1), E.Deriaz (2)

(1) IJL - UMR 7198, CNRS, Université de Lorraine, 54000 Nancy, France; (2) IRMA - UMR 7501, CNRS, Université de Strasbourg, 67000 Strasbourg, France

Numerical resolutions of Vlasov-Maxwell equation are mostly done either by particle-in-cell (PIC) or semi-lagrangian (SL) methods. PIC method is more common but introduces a numerical noise while SL is noiseless but requires much more computational resources.

One way to reduce the computational time of SL methods is mesh refinement but the implementation is challenging especially in the case of a parallelized code. Moreover, for a relativistic SL Vlasov-Maxwell solver the dependance of each advection due to the time splitting problem reduces mesh refinement possibilities.

All of those problems make it tricky to find methods that does not modify entirely the code. One way to solve this problem is to make the system as embedded rectangle grid in the velocity space. This method has been implemented in VLEM2D2V and VLEM2D3V and provides good results mostly for the transient time. Moreover, those kinds of methods are great to follow filamentation problems as they will adapt the grid to thin filaments.

Hamiltonian particle schemes for Vlasov-Maxwell equations

Martin Campos Pinto, Katharina Kormann, Eric Sonnendrücker, Jakob Ameres

Max Planck Institute for Plasma Physics

Variational discretizations are known for preserving key physical invariants in a natural way, leading to long-time stability properties. In this talk I will present a discrete action principle for the Vlasov-Maxwell equations that applies in a general structure-preserving discrete framework. In this framework the finite-dimensional electromagnetic potentials and fields are represented in a discrete de Rham sequence involving general Finite Element spaces, and the particle-field coupling is represented by a set of projection operators that commute with the differential operators. One application of this approach is a new variational spectral PIC method that has a discrete Hamiltonian structure and relies on particle-field coupling techniques very similar to those encountered in standard PIC schemes.

Symplectic coarse graining approach to the dynamics of spherical self-gravitating systems

Guido Giachetti (1), Luca Barbieri (2,3,4), Pierfrancesco Di Cintio (5,3,4), Alessandro Santini (6), Alicia Simon-Petit (2,3), Lapo Casetti (2,3,4)

(1) Laboratoire de Physique Théorique et Modelisation, CY Cergy Paris Université, CNRS; (2) Dipartimento di Fisica e Astronomia, Università di Firenze (3) INFN - Sezione di Firenze; (4) INAF - Osservatorio Astrofisico di Arcetri ;(5) Istituto dei Sistemi Complessi, Consiglio Nazionale delle Ricerche (ISC-CNR.

In many-body systems with long-range interactions mean-field effects dominate over binary interactions (collisions), so that relaxation to thermal equilibrium occurs on time scales that grow with the number of degrees of freedom N, diverging in the macroscopic limit. However, a faster and non-collisional relaxation process, referred to as violent relaxation, sets in when starting from generic initial conditions: collective oscillations (referred to as virial oscillations) develop and damp out on timescales not depending on the system's size. After the damping of such oscillations the system is found in a quasi-stationary state that survives virtually forever when the system is very large. During violent relaxation the distribution function obeys the collisionless Boltzmann (or Vlasov) equation, that, being invariant under time reversal, does not "naturally" describe a relaxation process. Indeed, the dynamics is moved to smaller and smaller scales in phase space as time goes on, so that observables that do not depend on small-scale details appear as relaxed after a short time. Here we present a coarse graining scheme allowing to derive an effective evolution equation for (a coarse-grained version of) the distribution function. According to this equation, violent relaxation can be seen as the result of a diffusion along the flow of the mean-field Hamiltonian. We apply our approach to one-dimensional system as well as to higher-dimensional systems with symmetry, as spherically symmetric models of self-gravitating systems. Using this equation we can extract a prediction on the dependence of the relaxation times towards the quasi-stationary state on the coarse graining scale and of the frequencies of oscillation of Fourier modes around the quasi-stationary state, having the form of a scaling law. We compare our analytical results with N-body simulations.

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Phase space dynamics of unmagnetized plasmas: collisionless and collisional regimes

Gabriele Celebre, Sergio Servidio, and Francesco Valentini

University of Calabria

Eulerian electrostatic kinetic simulations of unmagnetized plasmas (kinetic electrons and motionless protons) with high-frequency equilibrium perturbations have been employed to investigate the phase space free energy transfer across spatial and velocity scales, associated with the resonant interaction of electrons with the self-induced electric field. Numerical runs cover a wide range of collisionless and weakly collisional plasma regimes. An analysis technique based on the Fourier-Hermite transform of the particle distribution function allows to point out how kinetic processes trigger the free energy cascade, which is instead inhibited at finer scales when collisions are turned on. Numerical results are presented and discussed for the cases of linear wave Landau damping, nonlinear electron trapping, bump-on-tail and two-stream instabilities. A more realistic situation of turbulent Langmuir fluctuations is also discussed in detail. Fourier-Hermite transform shows a free energy spread, highly conditioned by collisions, which involves velocity scales more quickly than the spatial scales, even when nonlinear effects are dominant. This results in anisotropic spectra whose slopes are compatible with theoretical expectations. Finally, an exact conservation law has been derived, which describes the time evolution of the free energy of the system, taking into account the collisional dissipation.

Exponential integrators for Vlasov equations

Nicolas Crouseilles

INRIA

N/A

Wigner function with correlation damping

Lucio Demeio

Università Politecnica delle Marche

The Wigner-function (WF) approach to quantum kinetic theory, nowadays widely studied and used, presents open problems and difficulties of practical and theoretical nature which make the applications problematic. They arise from the fundamental assumptions under which the Wigner equation holds and which entail that the WF formalism in its standard formulation is applicable only to fully Hamiltonian, spatially infinite coherent systems, which are also confined. Among these fundamental assumptions we recall the absence of a mechanism which destroys the phase correlations of the individual states, i.e., the correlation length must be infinite. A numerical investigation aimed at studying the effect of a finite coherence length on a simple reflection-transmission problem was presented in Barletti, Bordone, Demeio, Giovannini, Phys. Rev. E. 104, 044112 (2021), based on the decoherence model proposed by Barletti, Frosali, Giovannini, Journal of Computat. and Theor. Transport 47, 209 (2018). The results confirm the predicted broadening and flattening of the Wigner function with time; they also indicate that a reduced coherence length favors transmission of low-energy electrons through the potential barrier, inhibiting reflection.

Instabilities in anisotropic systems with long-range interactions

Pierfrancesco Di Cintio

ISC-CNR & INAF OAA

In this talk I will review the radial-orbit instability in anisotropic gravitating systems and discuss the numerical evidence of its occurrence in systems of particles interacting with long-range forces of the form $1/r^{\alpha}$*. Moreover I will discuss the implications of discreteness effects and noise in enhancing or even suppressing said instability.*

A positivity-preserving, energy-conserving, discontinuous Galerkin algorithm for hyperbolic conservation laws.

Gregory W. Hammett, Noah R. Mandell, Ammar Hakim

Princeton Plasma Physics Laboratory

Preserving the positivity of a numerical solution is very important in some cases. Examples include avoiding unphysical negative densities or temperatures that could lead to numerical instabilities, such as imaginary sound speeds, or avoiding negative oscillations in the tail of a distribution function that could reverse the current-voltage relationship of a plasma sheath. Previous positivity-preserving variants of Discontinuous Galerkin (DG) algorithms typically introduce diffusion within a cell. This is okay for some problems but can break energy conservation for Hamiltonian problems. Here we present a novel positivity-preserving limiter [1] for DG that still preserves energy conservation. A useful property of DG spatial discretization for the Vlasov equation and other Hamiltonian problems is that they can conserve the energy quadratic invariant exactly even with limiters on fluxes. (Energy conservation in finite-volume or finite-difference algorithms is harder for the Vlasov equation than for the compressible Navier-Stokes equations, where one of the fluid equations directly represents conservation of energy, while energy conservation is an indirect property for the Vlasov equation.) Explicit Runge-Kutta time advancement will introduce some dissipation of energy, but energy convergence depends only on the time step, independent of spatial resolution. (Implicit time-advancement could be used to fully conserve energy.) Furthermore, an energy-conserving spatial discretization guarantees that aliasing errors don't amplify the energy, which can lead to numerical instabilities. This is similar to why the Arakawa finite-difference algorithm has been widely used, first in applications for 2D weather prediction. We previously developed a positivity algorithm that worked well in 1D and 2D tests, but failed in higher dimensions, while our latest algorithm is rigorous in arbitrary dimensions. To minimize how often limiters are turned on, we use a concept of "weak positivity", where a piecewise linear representation is allowed to go negative in part of a cell as long as there exists some representation that is positive definite and has the same moments. We focus here on piecewise linear DG, but will briefly discuss possible generalization to higher polynomial order.

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Novel parallel-kinetic perpendicular-moment model for magnetized plasmas

Jimmy Juno (1), Ammar Hakim (1), Jason TenBarge (2)

(1) Princeton Plasma Physics Laboratory; (2) Princeton University

Many astrophysical plasma systems, from pulsar magnetospheres to the solar wind, are highly magnetized. However, the derivation of large magnetization asymptotic models applicable to this wide variety of plasmas is challenging. Relativistic energies, strong flows, and temperature anisotropies complicate the asymptotics and even if the derivation can be made sufficiently rigorous, the subsequent equations may resist easy discretization via standard numerical methods.

I will discuss a recent innovation which addresses these challenges by separating the parallel and perpendicular dynamics starting from the kinetic equation while staying agnostic to the inclusion of effects such as relativity or strong flows. The key component of the derivation lies in a spectral expansion of only the perpendicular degrees of freedom, analogous to spectral methods which have grown in popularity in recent years for gyrokinetics, while retaining the complete dynamics parallel to the magnetic field. We thus leverage our intuition that a magnetized plasma's motion is different parallel and perpendicular to the magnetic field, while allowing for the treatment of complex phase space dynamics parallel to the magnetic field. This approach also naturally couples to Maxwell's equations, allowing easy transitions across energy scales and potentially novel hybrid approaches. A number of benchmarks and tests will be presented to demonstrate the power of this approach.

Relativistic electromagnetic particle-in-cell methods

Katharina Kormann

Ruhr University Bochum

Numerical schemes that preserve the structure of the underlying kinetic equations can provide new insights into the long time behavior of plasmas. In this talk we will present an electromagnetic particle-in-cell solver for the relativistic Vlasov–Maxwell equations that preserves at the discrete level the non-canonical Hamiltonian structure. The Maxwell equations are discretized by compatible spline finite elements that yield discrete differential operators that retain properties like div curl = 0. Along with a classical particle discretization of the Vlasov equation, this yields a system of differential equations that has a Poisson structure, that is the non-canonical analog of a symplectic structure. We will discuss the time discretization of this system based on a discrete gradients or splitting methods and discuss the additional difficulty due to the gamma factor compared to the non-relativistic case.

Canonical momentum based numerical schemes for the hybrid plasma models with kinetic ions and massless electrons

Yingzhe Li (1), Florian Holderied (1), Stefan Possanner (1), Eric Sonnendruecker (1) (2)

(1) Max Planck Institute for Plasma Physics, Garching; (2) Technical University of Munich, Department of Mathematics, Garching.

We study the canonical momentum based discretizations of a hybrid model with kinetic ions and mass-less electrons. Two equivalent formulations of the hybrid model are presented, in which the vector potentials are in different gauges and the distribution functions depend on canonical momentum (not velocity). Particle-in-cell methods are used for the distribution functions, and the vector potentials are discretized by the finite element methods in the framework of finite element exterior calculus. Splitting methods are used for the time discretizations. It is illustrated that the second formulation is numerically superior and the schemes constructed based on the anti-symmetric bracket proposed have better conservation properties, although the filters can be used to improve the schemes of the first formulation.

An efficient energy conserving semi-Lagrangian scheme for plasma simulations

Hongtao Liu, Giovanni Lapenta

KU Leuven

Kinetic simulations, rooted in first principles, offer a powerful tool for understanding complex multiscale plasma phenomena. While explicit grid-based kinetic schemes are easily implemented for high-order accuracy, they require a well-resolved numerical time step size with respect to the plasma oscillation period and suffer from self-heating or cooling. Implicit kinetic schemes, although unconditionally stable and conserving total energy, require nonlinear iterative solvers. This study introduces an efficient energy conserving semi-Lagrangian (ECSL) scheme through the semi-implicit coupling of particle transport and electric field using moments of the Vlasov equation. ECSL maintains the efficiency of the explicit scheme while preserving the benefits of the implicit scheme. Numerical experiments validate the accuracy, efficiency, and conservation properties of ECSL.

Fine -scale instability and Macroscopic equations.

Steve Cowley

Princeton Plasma Physics Lab.

The extreme range of scales in astrophysical and laboratory plasmas prohibits direct simulation of the interaction of kinetic instabilities and macroscopic evolution. I will discuss approaches to this problem in fusi9n and astrophysical plasmas.

Magnetic and inertial confinement fusion plasmas

Self-organization due to phase synchronization of Fourier modes: an application to the suppression of low frequency tokamak turbulence by amplification of zonal flows in presence of energetic particles

Daniele Del Sarto (1), Alain Ghizzo (1), Juvert Nieck Sama (1), Homam Betar

(1) Université de Lorraine, IJL; (2) Aix-Marseille Université, M2P2

The classical Kumamoto model for the phase-synchronization of a system of coupled oscillators had already proven to be successful to model Landau damping and wave-particle interactions in an electrostatic plasma. Here we review this subject by showing that a Kuramoto-type approach to Vlasov plasmas is generalizable and can be applied to different regimes, ranging from low frequency gyrokinetic turbulence to electromagnetic mode coupling in relativistic regimes. We then consider an application of this approach, which is relevant to tokamak turbulence: namely, the suppression of the turbulent transport in gyrokinetic tokamak plasmas, due to the amplification of zonal flows, which emerge from the phase-locking of both trapped ion and electron modes in presence of a population of energetic ions. The result, which is relevant to model possible mechanisms of transition from low- to high-confinement scenarios experimentally observed in tokamaks, is interpreted in the light of a self-organization process induced by a Kuramoto-type transition to a globally synchronized state.

Kinetic aspects to the axisymmetric mirror as a fusion reactor

Cary Forest

University of Wisconsin, Madison

I will give an overview of recent theoretical and numerical calculations of confined magnetic mirror plasmas with the goal of creating a break even class axisymmetric mirror (Forest, JPP 2023). Fokker Planck solutions from the CQL3D code combined with magnetic equilibria tracking anisotropic pressures and self-consistent ambipolar electric fields provide the starting point. Hybrid VPIC is now being used to model both MHD and kinetic stability and GKYLL gyro kinetic approaches are not far behind. Major challenges for the mirror and building a digital twin will be discussed.

Theory and applications of linear gyrokinetics in a curved magnetic field

Plamen Ivanov, Toby Adkins, Param Luhadiya

University of Oxford

Starting from the equations of collisionless linear gyrokinetics for magnetised plasmas with an imposed inhomogeneous magnetic field, we present the first known analytical, closed-form solution for the resulting velocity-space integrals in the presence of resonances due to both parallel streaming and magnetic drifts. These integrals are written in terms of the well-known plasma dispersion function, rendering the subsequent expressions simpler to treat analytically and more efficient to compute numerically. Our results are shown to converge to the well-known ones in the straight-magnetic-field and two-dimensional limits. As an example of possible applications, we present a novel electromagnetic, temperature-gradient-driven instability, enabled by the gradient of electron temperature and the magnetic-field curvature, and discuss its impact on magnetic-confinement-fusion devices like tokamaks and stellarators.

Designing a mixed probe and a novel piezo drive amplifier to calibrate ball pen tips of the mixed probe in IR-T1 Tokamak.

Mahdi Mahjour, Mahmood Ghoranneviss, Mansoureh Lafouti, Mohammad Kazem Salem, Peter Manz, Richard O Dendy

Islamic Azad University, University of Greifswald, University of Warwick

In this talk I will report on designing a mixed probe and a novel piezo drive amplifier to calibrate ball pen tips of the mixed probe in IR-T1 Tokamak which are able to measure saturation current in poloidal direction by Langmuir tips to detect blobs. Also, measurement of plasma potential in radial and poloidal directions is provided in this probe by ball pen tips to study blobs movements.

Transform method for the Vlasov equation.

Martin Masek

Institute of Physics, Czech Academy of Sciences

It has been a long time since the transformation method was proposed to solve the Vlasov equation, but its use alongside other methods is becoming popular again in recent years. Our approach uses the Hermite expansion of the distribution function in velocity space and, in the case of periodic plasma, the Fourier expansion in coordinate space. This procedure leads to the solution of a system of the first order ordinary differential equations. This system of equations forms a tridiagonal matrix, which significantly reduces communication when using multiprocessor computing systems. The goal of the contribution is to present our implementation of the transform method and to discuss its numerical stability. The method is applied to the Vlasov-Maxwell system and used for the study of the stimulated Raman scattering in fusion relevant plasmas.

Kinetic plasma-wall interaction using immersed boundary conditions

Yann Munschy, Emily Bourne, Philippe Ghendrih, Guilhem Dif-Pradalier, Yanick Sarazin, Virginie Grandgirard, and Peter Donnel

CEA, IRFM, Saint-Paul-lez-Durance, F-13108, France

The interaction between the plasma and the solid wall at the divertor/limiter target in tokamak devices affects turbulence in the plasma edge, thus impacting the overall confinement [1,2]. While the gyrokinetic framework allows one to describe turbulence and transport in the core of tokamak plasmas, most of present gyrokinetic codes still lack an adequate description of plasma-wall interaction [3,4]. In this perspective, plasma-wall interaction is studied with the VOICE code in a (1D-1V) kinetic approach along magnetic field lines, assumed to have a normal incidence [5]. Immersed boundary conditions are used to model the wall. Two different choices are made for the penalized wall region: either currents are allowed to flow within the material boundary or not [6].

The main properties of the Debye sheath physics are recovered, whatever the description adopted for the wall region. The formation of a positively charged layer in front of the plasma boundary defines the transition to the so-called Debye sheath. This non-neutral layer is accompanied by a drop of the electric potential that confines slow electrons and accelerates ions.

Most interestingly, discrepancies are found with respect to fluid predictions [7]. First, the kinetic simulations find a strong non-vanishing heat flux across the sheath. This result is difficult to match within a fluid framework. Second, we show that the expression of the plasma sound speed strongly depends on the chosen closure of the fluid hierarchy. Consequently, Bohm's criterion used to define the Debye sheath entrance in terms of the Mach number, is modestly efficient in a kinetic framework. Last, even though the ratio between heat and convective energy fluxes differs between fluid and kinetic approaches, we find heat transmission factors at the wall comparable to what is usually predicted [8].

Parametric dependencies reveal that the observed kinetic sheath physics is robust: the sheath acts as a filter of high energy electrons to avoid any charge separation in the plasma on scales larger than a few Debye lengths. This observation opens important perspectives to incorporate sheath physics within the gyrokinetic framework without resolving the time and spatial scales of the Debye sheath.

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Electromagnetic trapped electron mode in general geometry

Alessandro Zocco

IPP Greifswald

Within the gyrokinetic formalism, we present the equations for an explicit treatment of the electromagnetic version of the collisionless universal/trapped-electrons, microtearing modes, and trapped-electron-modified kinetic ballooning mode, in general geometry. The gradient of the plasma $\beta = 8\pi p/B^2$, the ratio of kinetic to magnetic pressure, is taken to be small enough to avoid perturbations of the magnetic field strength. We highlight the role of trapped electrons in the resonant destabilization, or damping, via electromagnetic corrections to ideal Ohms's law, for electron-temperature-gradient driven modes whose frequency relates to the bounce-averaged electron curvature drift. Our result is general and applies to electromagnetic collisionless trapped-electron modes and microtearing modes.

We prove that maximum J devices (where J is the second adiabatic invariant) enjoy relatively good stability properties at finite β, but the coupling of trapped-electron and kinetic ballooning modes might induce modes rotating in the ion direction, thus eluding good maximum J properties.

Space and astrophysical plasmas

Experimental evidence of the role of non-gyrotropy in magnetopause equilibrium

G. Ballerini (1,2), G.Belmont (1), L.Rezeau (1), F. Califano (2)

(1) Laboratoire de Physique des Plasmas (LPP), CNRS, Ecole Polytechnique,Sorbonne Universite, Universite Paris-Saclay, Observatoire de Paris, 91120 Palaiseau, France (2) Dipartimento di Fisica E. Fermi, University of Pisa, Italy

Determining whether the magnetosphere is closed or open has remained an enduring question in space physics, and it continues to drive current research in the field. In the context of the magnetopause boundary, the key question arises: is this boundary a tangential discontinuity or not? In its simplest approximation, when Finite Larmor radius effects are disregarded, we know that compressive and rotational characteristics are mutually exclusive, except for cases of a "tangential discontinuity".

Observations at the Earth's magnetopause actually reveal mixed compressive and rotational properties. Does it mean that this boundary is indeed always "tangential", i.e completely impermeable, with strictly null normal components of the magnetic field and of the relative plasma velocity?

In this study, we address the inadequacy of classic theories of discontinuities in explaining the magnetopause's observed characteristics, due to its small thickness. We introduce the concept of "quasi-tangential" discontinuities, wherein both compressive and rotational properties coexist, without requiring strictly null normal fluxes. This transition bears resemblance to the shift from a shear Alfvén wave to a Kinetic Alfvén wave in the context of linear modes.

We explore the role of anisotropy in discontinuities between different plasmas and present a typical example of Earth's magnetopause crossing data using the Magnetospheric Multiscale (MMS) mission. Through this analysis, we demonstrate that Finite Larmor Radius and the non-gyrotropic pressure tensor indeed play a significant role in the equilibrium of the magnetopause boundary.

Interplay of Magnetic Reconnection and Current Sheet Kink Instability in the Earth's Magnetotail

G. Cozzani1, M. Alho1, I. Zaitsev1, H. Zhou1, S. Hoilijoki1, L. Turc1, M. Grandin1, K. Horaites1, F. Tesema1, Y. Pfau-Kempf1, M. Battarbee1, U. Ganse1, M. Dubart1, L. Kotipalo1, K. Papadakis1, J. Suni1, V. Tarvus1, A. Workayehu1, and M. Palmroth1 2

1Department of Physics, University of Helsinki, Helsinki, Finland 2Finnish Meteorological Institute, Space and Earth Observation Centre, Helsinki, Finland

Magnetic reconnection is a fundamental process in plasmas and a major cause of energy conversion and transport through magnetic field topology reconfiguration. It is one of the key mechanisms in the Earth's magnetosphere, driving geomagnetic activity and promoting plasmas mixing. Magnetic reconnection occurs in current sheets, regions of enhanced electric current and strong gradients. Current sheets are also the seedbed of a variety of instabilities, including the extensively studied kink instability. Despite the vast amount of work on both reconnection and the kink instability, their interplay is still largely unexplored.

We present results of a 3D global magnetospheric hybrid-Vlasov Vlasiator simulation where we investigate the interaction of magnetic reconnection and the kink instability developing in the magnetotail current sheet and propagating obliquely to the reconnection plane. We identify different phases of the instability (notably a growth phase and a saturation phase) and investigate the time evolution of the reconnection rate during the same time interval. Our findings indicate that the reconnection rate decreases during the instability growth phase, especially at the locations where the current sheet is perturbed the most by the kink mode. These results highlight the intricate three-dimensional relationship between reconnection and kink instabilities in the magnetotail, suggesting that the kink instability plays a significant role in modulating the reconnection efficiency.

Reconnection-driven agyrotropic electron distributions in turbulent plasmas and the role of electron velocity shears

Luca Franci(1), Daniele Del Sarto(2), Emanuele Papini(3), Domenico Trotta(1), Harry Lewis(1)

(1) Imperial College London, UK; (2) Institut Jean Lamour - Université de Lorraine, Nancy France; (3) IAPS Italian Institute of Astrophysics Rome, Italy;

Deformations of the particle distributions are both expected and observed in collisionless space plasmas. These are typically correlated with heating mechanisms and pressure anisotropy can be an important source of instabilities. The mechanisms allowing for the generation of non-thermal distributions and their direct connection with other fundamental plasma mechanisms such as turbulence and magnetic reconnection, however, still represent an open issue.

We investigate their interplay by means of high-resolution 2D fully kinetic simulations of plasma turbulence. We observe intense electron-scale current sheets forming as the result of the interaction of ion-scale magnetic vortices and then undergoing standard or electron-only magnetic reconnection. We compute the agyrotropy of the ion and the electron pressure tensors and find the latter to peak in correspondence of X points and separatrices, which are also regions of intense electron velocity shears. We also compare the agyrotropy of the pressure tensors with the non-Maxwellian measure of the particle velocity distributions. Finally, we compute and discuss the agyrotropy and the non-Maxwellian measure in observations by Magnetospheric Multiscale.

Our results agree with those from previous simulations of magnetic reconnection in a single current sheet and extend the analysis to multiple reconnection events that are spontaneously driven by sub-ion scale turbulence. They also agree with theoretical models of anisotropy generation driven by velocity shears.

Self organization in high beta, collisionless turbulence

Stephen Majeski, Matthew Kunz

Princeton University

Using analytical theory and CGL-MHD simulations, we investigate Alfvénic turbulence in collisionless, high-beta plasmas, with particular emphasis on the volume-filling fraction of kinetic micro-instabilities and the cascade of compressive fluctuations. In these plasmas, the production of pressure anisotropy by conservation of the double adiabats is well known to trigger the growth of kinetic micro-instabilities like the mirror or firehose. The associated Larmor-scale magnetic fluctuations scatter particles in pitch angle, thus it has been predicted that turbulence in high-beta collisionless plasmas might behave in a collisional MHD-like manner. We demonstrate that because of the effects of magneto-immutability-–a self-organizational process that limits the production of pressure anisotropy-–the volume filling fraction of such micro-instabilities is instead quite small (≲10%), regardless of forcing. As a result, the turbulence is largely collisionless in nature. To understand how this affects the cascade of compressive fluctuations, we study the interactions between ion-acoustic and Alfvén waves, contrasting them with the slow-mode--Alfvén-wave interactions that dictate the compressive cascade of MHD turbulence. We find that, due to the separation of linear timescales between ion-acoustic and Alfvén waves at high beta, the turbulent cascade of compressive fluctuations in these plasmas is dramatically different from that of MHD. Alfvénic mixing of compressive modes, which normally drives a strong cascade in collisional MHD, becomes weak with respect to effects like magneto-immutability and Landau damping of acoustic modes. This leads to the formation of a compressive cascade that steepens with increasing beta, eventually producing effectively no cascade at beta≳100. These results have implications for topics like cosmic-ray diffusion and thermal stability in the intracluster medium of galaxy clusters (ICM), and ion-electron heating fractions due to turbulence in black-hole accretion flows.

Cascade-Dissipation Balance in space plasma

D.Manzini (1,2), F.Sahraoui (1), F.Califano (2)

(1) LPP, Laboratoire de Physique des Plasmas; (2) Università di Pisa

The differential heating of electrons and ions by turbulence in weakly collisional magnetized plasmas and the scales at which such energy dissipation is most effective are still debated. Using a large data sample measured in the Earth's magnetosheath by the Magnetospheric Multiscale mission and the coarse-grained energy equations derived from the Vlasov-Maxwell system we find evidence of a balance over two decades in scales between the energy cascade and dissipation rates. The decline of cascade rate at kinetic scales (in contrasts with a constant one in the inertial range), is balanced by an increasing ion and electron heating rates, estimated via the pressure-strain. Ion scales are found to contribute most effectively to ion heating, while electron heating originates equally from ion and electron scales. These results can potentially impact current understanding of particle heating in turbulent magnetized plasmas as well as their theoretical and numerical modeling.

Unveiling plasma energization and energy transport with multi-scale observations in the Earth's Magnetospheric System: the Plasma Observatory mission.

M. F. Marcucci (1), A. Retinò (2), T. Amano (3), V. Angelopoulos (4), S. D. Bale (5), M. Berthomier (1), R. D'Amicis (2), J. De Keyser (6), A. Dimmock (7), M. Dunlop (8), C. Forsyth (9), M. Fränz (10), H. Fu (11), A. Galli (12), V. Genot (13), K. Kauristie (14), Y. Khotyaintsev (7), L. Kistler (15), M. Kretzschmar (16), H. Kucharek (15), K. Issautier (17), B. Lavraud, (13,18), O. Le Contel (1), I. Mann (19), L. Matteini (20), K. McWilliams (21), M. Maksimovic (17), R. Nakamura (22), Astrid Cecilia Norgren (23), M. Palmroth (24), E. Panov (22), O. Pezzi (25), F. Plaschke (26), H. Rothkaehl (27), E. Roussos (10), Y. Saito (28), J. Soucek (29), M. Steller (22), M. Yamauchi (30), R. Vainio (31), A. Vaivads (32), F. Valentini (33), R. F. Wimmer-Schweingruber (34) and the PO Science Team

1) INAF-IAPS, IT, 2) LPP, FR,3) Univ. of Tokyo, JP, 4) UCLA, US, 5) Univ. California, Berkeley, US, 6) BIRA, BE, 7) IRF-U, SE, 8) RAL, UK, 9) MSSL-UCL, UK, 10) MPS, DE, 11) Beihang Univ., CN, 12) Univ. of Bern, CH, 13) IRAP, FR, 14) FMI, FI, 15) UNH, US, 16) LPC2E, FR, 17) LESIA, FR, 18) LAB, FR,19) Univ. of Alberta, CA, 20) ICL, UK, 21) Univ. of Saskatoon, CA, 22) IWF/ÖAW, AT, 23) Univ. of Bergen, NO, 24) Univ. of Helsinki, FI, 25) ISTP, IT, 26) TU Braunschweig, DE, 27) CBK, PL, 28) ISAS-JAXA, JP, 29) IAP-CAS, CZ, 30) IRF-K, SE, 31) Univ. of Turku, FI; 32) KTH, SE, 33) Univ. of Calabria, IT, 34) Univ. of Kiel, DE

Particle energization and transport of energy are key open problems of space plasma physics. Their comprehension has major implications on research fields that span from space weather to the understanding of distant astrophysical plasmas.

Plasma energization is driven by fundamental processes such as shocks, magnetic reconnection, turbulence and waves, plasma jets, and their combination. Key aspects of energy transport are field-aligned currents, instabilities and partition of energy flux. All these processes are at the core of current space plasma physics research.

The Magnetospheric System is the complex and highly dynamic plasma environment where the strongest energization and energy transport occurs within near-Earth space. Previous multi-point observations from missions such as ESA/Cluster and NASA/MMS have greatly improved our understanding of plasma processes at a given scale However, simultaneous measurements at both

large, fluid and small, kinetic scales are required to resolve scale coupling and to ultimately fully understand plasma energization and energy transport processes. Such measurements are currently not available.

Here we present the Plasma Observatory (PO) multi-scale mission concept tailored to study plasma energization and energy transport in the Earth's Magnetospheric System through simultaneous measurements at both fluid and ion scales. These are the scales at which the largest amount of electromagnetic energy is converted into energized particles and energy is transported. PO baseline mission includes one mothercraft and six identical smallsat daughtercraft in an HEO 8x18 RE orbit, covering all the key regions of the Magnetospheric System including the foreshock, the bow shock, the magnetosheath, the magnetopause, the magnetotail current sheet, and the transition region. Along the orbit, the separations between the spacecraft range from fluid (5000 km) to ion (30 km) scales. MSC payload provides a complete characterization of electromagnetic fields and particles in a single point with time resolution sufficient to resolve kinetic physics at sub-ion scales (for both protons and heavy ions). The DSCs have identical payload, simpler than the MSC payload, yet giving a full characterization of the plasma at the ion and fluid scales. Moreover, PO takes advantage of the massive progresses made in supercomputer simulations during the last decades. The simulations support PO mission design and provide theoretical predictions on particle energization and energy transport which will help interpretation of PO data.

PO will be the next logical step after Cluster and MMS. It targets the two ESA Voyage 2050 themes "Magnetospheric Systems" and "Plasma Cross-scale Coupling" and will allow us to resolve for the first time scale coupling in the Earth's Magnetospheric System, leading to transformative advances in the field of space plasma physics.

PO is one of the three ESA M7 candidates, which have been selected in November 2023 for a competitive Phase A with a mission selection planned in 2026 and launch in 2037.

Turbulent dissipation in collisionless plasmas: insights from kinetic simulations.

Emanuele Papini (1), Luca Franci (2), Alfredo Micera (3), Petr Hellinger (4), Simone Landi (5)

(1) INAF - Istituto di Astrofisica e Planetologia Spaziali; (2) Imperial College London; (3) Ruhr-Universität Bochum; (4) Astronomical Institute - CAS Prague; (5) Università degli studi di Firenze

Understanding how magnetic energy dissipates in the solar wind and other turbulent space plasma environments is a major open question. The main difficulty arises because at scales where the ions decouple from magnetic fields, the turbulent dynamics become increasingly complex: wave fluctuations become dispersive and particle kinetic effects come into play.

Moreover, impulsive events such as magnetic reconnection instabilities, which occur in spatially-localized coherent structures, lead to an enhancement of energy dissipation, heating, and acceleration of particles. In this context, numerical simulations are an invaluable tool for studying turbulence, as they allow us to perform realistic experiments in a controlled environment. In this talk, I will present recent results from a multiscale statistical analysis of kinetic simulations of decaying plasma turbulence under typical solar-wind conditions, that investigate the spacetime structure of turbulent fluctuations at sub-ion scales. In particular, I will highlight the interplay between magnetic reconnection and turbulence, and discuss how the reconnection activity relates to cross-scale energy transfer, intermittency, and dissipation.

Isochrony and gravitationnal collisionless plasmas

Jerome Perez

ENSTA Institut Polytechnique de Paris

Isochrony is a fundamental property governing orbits in collisionless gravitationnal equilibria. It was first studied by M. Henon sixty years ago and was recently revealed as a cornerstone of the hamiltonian dynamics of 3D spherical gravitationnal plasmas. After a brief review of these hamiltonian aspects of this problem, I will explain how this equilibria could appear as the fundamental state of the evolution of self gravitating stellar systems.

Emergent phase-space complexity in turbulent nearly-collisionless plasmas

Oreste Pezzi

Institute for Plasma Science and Technology (ISTP/CNR)

N/A

Fully kinetic simulations of proton instabilities driven by anisotropic two-component velocity distributions observed by Parker Solar Probe

L. Pezzini (1,2), A. Zhukov (2,5), F. Bacchini (1,3), G. Arrò (1), R. A. López (6), A. Micera (4), M. E. Innocenti (4), G. Lapenta (1)

(1) Centre for mathematical Plasma Astrophysics, Department of Mathematics, KU Leuven, Leuven, Belgium; (2) Solar-Terrestrial Centre of Excellence—SIDC, Royal Observatory of Belgium, Brussels, Belgium; (3) Royal Belgian Institute for Space Aeronomy, Solar-Terrestrial Centre of Excellence, Brussels, Belgium; (4) Institut für Theoretische Physik, Ruhr-Universität Bochum, Bochum, Germany; (5) Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow, Russia; (6) Departamento de Física, Universidad de Santiago de Chile, Santiago, Chile

The expanding solar wind plasma ubiquitously exhibits anisotropic non-thermal particle velocity distributions. Observations have revealed that thermal anisotropies in the solar wind often result in higher temperatures along the direction parallel to the local magnetic field. However, the observed anisotropy is weaker than that expected from an adiabatic expansion, indicating the presence of instabilities that mitigate the temperature anisotropy. In this study, we use a 2.5D fully kinetic simulation to investigate the stability of anisotropic proton velocity distribution functions (VDFs) observed by the Parker Solar Probe (PSP) in the innermost heliosphere. Our setup consists of a core and a beam population that drift with respect to each other. This configuration triggers a firehose-like instability from which parallel fast magnetosonic modes develop. Our results demonstrate that before this instability reaches saturation, the waves resonantly interact with the beam protons, causing significant perpendicular heating at the expense of the parallel temperature. Furthermore, the proton perpendicular heating induces a hammerhead-like shape in the resulting VDF, consistent with recent observations made by PSP.

Hybrid Vlasov simulations of solar wind interacting with a comet

Francesco Pucci (1), Etienne Behar (2,3), Pierre Henri (3,4), Cyril Simon Wedlund (5), and Giulio Ballerini (6,7)

(1) Institute for Plasma Science and Technology, National Research Council, Bari, Italy (francesco.pucci@istp.cnr.it); (2) Swedish Institute of Space Physics, Kiruna, Sweden; (3) Laboratoire Lagrange, Observatoire Côte d'Azur, Université Côte d'Azur, CNRS, Nice, France; (4) LPC2E, CNRS, Univ. Orléans, CNES, Orléans, France; (5) Space Research Institute, Austrian Academy of Sciences, Graz, Austria; (6) LPP, CNRS/Sorbonne Université/Université Paris-Saclay/Observatoire de Paris/Ecole Polytechnique Institut Polytechnique de Paris, Palaiseau, France; (7) Dipartimento di Fisica, University of Pisa, Italy

We present a numerical work in which the interaction between a comet and the solar wind is studied. Our simulations are conducted with the hybrid Particle-in-Cell (PIC) code Menura, which allows us to model a turbulent solar wind.

First, we present a study on the equivalent Mach number of the two-ion-species (cometary and solar wind) plasma surrounding the comet. Through numerical simulations of different cometary activity, we show how our Mach number can unambiguously describe the existence and location of the cometary shock.

Second, we describe the properties of plasma turbulence in our numerical model. By dividing the simulation domain into the regions upstream and downstream of the cometary shock, we analyze how solar wind plasma turbulence properties are affected by the passage through the shock and how they influence downstream turbulence. Then, we analyze the downstream region in more detail by further diving it into three regions identified by different solar wind-to-cometary ion density ratios.

We compare our simulation results with Rosetta observations and discuss our study's application to the future Comet Interceptor mission.

Electrostatic Solitary Waves and Weak Double Layers in the Solar Wind at 1 AU: New Insights.

Chadi Salem

University of California Berkeley

TBD

Characterizing Magnetic Reconnection Regions Using Unsupervised Machine Learning Techniques On MMS Data

Beniamino Sanò - Giovanni Lapenta - Francesco Valentini

Università della Calabria - KU Leuven

This presentation comes from the collaboration with KU Leuven and University of Calabria in the study of regions of interest in particle velocity distributions from Magnetospheric Multiscale mission, using unsupervised machine learning techniques. The data is downloaded and preprocessed through AIDApy and PySpedas, two Python packages for the analysis of spacecraft data from heliospheric missions. A Gaussian Mixture Model search through the particles and identify the presence of different subpopulations within an overall population. The optimal number of subpopulations is determined by a model selection technique, and the presence of certain distributions can be utilized to find magnetic reconnection regions. The final goal is to run the algorithm on spacecrafts, increasing the analytical efficiency of data from space missions.

Sub-proton-scale turbulent dynamics and energy conversion: Recent observations and paths forward

Julia E. Stawarz (1), Harry C. Lewis (2), Luca Franci (2), Lorenzo Matteini (2), Tai Phan (3), Imogen Gingell (4), Prayash Pyakurel (3), Naoki Bessho (5), Michael A. Shay (6)

(1) Northumbria University; (2) Imperial College London; (3) University of California Berkeley; (4) University of Southampton; (5) NASA Goddard Space Flight Center; (6) University of Delaware

Plasmas throughout the Universe are filled with complex, highly-nonlinear turbulent fluctuations. In the context of collisionless plasmas, some of the key challenges are understanding how multi-fluid and kinetic physics – of which there are a multitude of relevant processes – at the smallest scales in the plasma alter the nonlinear dynamics and ultimately lead to energy conversion and dissipation. The most recent generation of space plasma missions – notably NASA's Magnetospheric Multiscale mission – have provided an unprecedented opportunity to examine the nonlinear dynamics operating at scales smaller than the proton scales within the turbulent plasmas in near-Earth space. These observations have enabled the detailed study of turbulent electric fields, as well as the direct identification and examination of key plasma physics processes – such as magnetic reconnection and kinetic instabilities – and their role in energy conversion and dissipation. In this talk, I will discuss some of the recent observational work on these processes with an eye toward the key open questions which remain to be answered and how they can be addressed with the next generation of space plasma missions.

Phase space transport in the shock-turbulence interaction

Domenico Trotta

Imperial College London

Shock waves and plasma turbulence are ubiquitous phenomena in the Universe that are pivotal to understand several key features of astrophysical systems. Novel insights about this interaction will be discussed.

I will present kinetic simulations of the shock-turbulence interaction. The role of turbulence strength, a crucial ingredient to enhance phase space diffusion leading to efficient particle acceleration, is addressed using a novel technique, relying on the coarse-graining of the Vlasov equation. These results will then be put in the context of in-situ observations of long-lasting anisotropic field-aligned beams before the passage of interplanetary shocks.

Finally, I will expand of further aspects of the shock-turbulence interaction, mainly discussing it in the context of two- and three-dimensional simulations of perpendicular shocks in presence of a turbulent upstream, where I will describe how small-scale shock irregularities (such as ripples) are modified by such a complex interaction.

Statistical mechanics of the electrons in the solar wind: stability and instability of whistler waves

Daniel Verscharen, Alfredo Micera, Maria Elena Innocenti, Elisabetta Boella, Jesse Coburn, Jingting Liu, Joel B. Abraham, Christopher J. Owen, Georgios Nicolaou, Kristopher G. Klein, and Vivianne Pierrard

University College London, Ruhr-Universität Bochum, Lancaster University, Daresbury Laboratory, University of Arizona, UCLouvain, Royal Observatory of Belgium

The electrons in the solar wind often exhibit non-equilibrium velocity distribution functions. Observed non-equilibrium electron features in the inner heliosphere include a field-aligned beam (called "strahl"), a suprathermal halo population, a sunward deficit in the distribution, and temperature anisotropy. These features are the result of a complex interplay between global expansion effects, collisions, and local interactions between the particles and the electromagnetic fields. Global effects create, for example, the strahl via the mirror force in the decreasing magnetic field and the sunward deficit via reflection effects in the interplanetary electrostatic potential. Local wave-particle interactions such as instabilities and wave damping change the shape of these signatures and thus the overall properties and moments of the electron distribution. In these processes, it is necessary to treat electrons statistically as a globally inhomogeneous plasma component due to their subsonic nature.

We will discuss the kinetic physics of these processes and focus on the stability and instability of whistler waves in the solar wind. We will present results from the ALPS code that solves the equations of linear Vlasov-Maxwell theory for a plasma with arbitrary background distribution functions. In addition, we will highlight science opportunities that the high-resolution data of Solar Orbiter's particle and field instruments open up for unprecedented studies of the causes and effects of non-equilibrium electron distributions in the expanding solar wind.