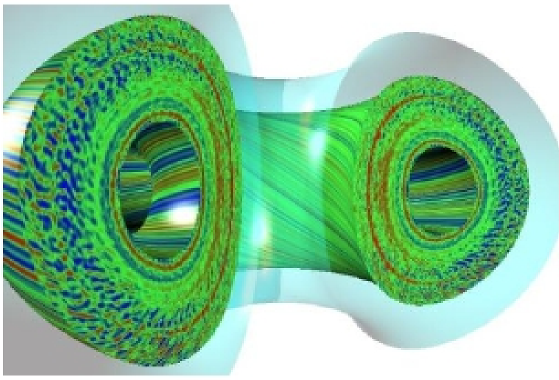
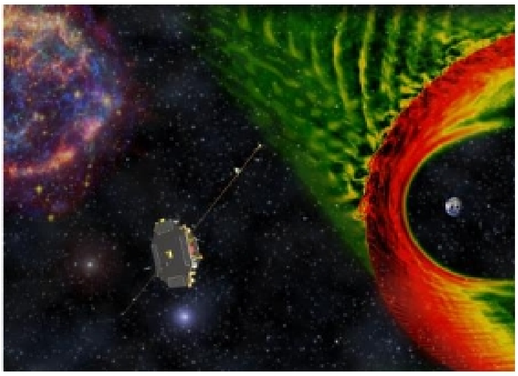
VLASOVIA 2016

Fifth International Workshop on the Theory and Applications of the Vlasov Equation

Copanello, Italy, May 30 – June 2, 2016





Scientific Topics

- *Space and astrophysical plasmas*
- *Gravitational systems*
- *Magnetic confinement plasmas*
- *Basic collisionless plasma physics*
- *Computational and theoretical approaches*

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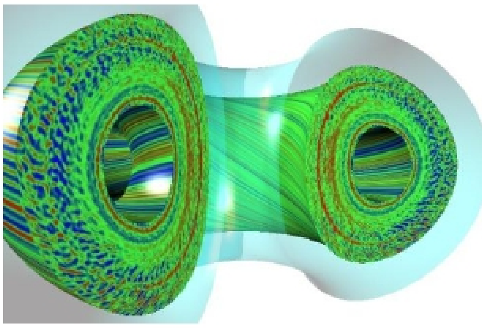
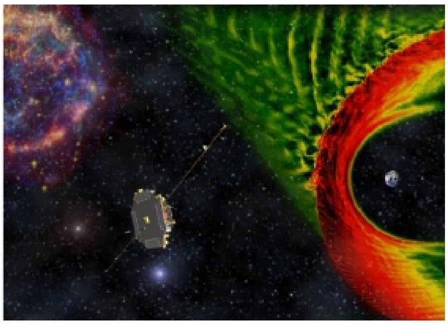




Description of the workshop

The workshop aims at providing an up-to-date summary for scientists working in the field of Vlasov theory. The Vlasov equation is used for the modeling of a wide range of phenomena occurring in natural and laboratory plasmas, as well as in other many-particle systems displaying a collective behavior. The present edition will focus on space and astrophysical plasmas. A special session will be devoted to the THOR mission (http://thor.irfu.se/) of the European Space Agency, which addresses the fundamental questions of turbulent energy dissipation and particle energization.

Scientific Topics

- Space and astrophysical plasmas
- Gravitational systems
- Magnetic confinement plasmas
- Basic collisionless plasma physics
- Computational and theoretical approaches

Website: http://www.fis.unical.it/astroplasmi/vlasovia2016

Em@il: vlasovia2016@gmail.com

Scientific committee

F. Califano (Università di Pisa)
G. Manfredi (CNRS Strasbourg, France)
F. Valentini (Università della Calabria, Italy)

Local organizing committee

T. Alberti, G. Brunetti, V. Carbone, F. Catapano, F. Chiappetta, E. De Giorgio, F. Di Mare, A. Greco, F. Lepreti, F. Malara, G. Nigro, S. Perri, O. Pezzi, L. Primavera, F. Pucci, C. Rossi, S. Savaglio, A. Sole, L. Sorriso-Valvo, F. Valentini, C. Vasconez, G. Zimbardo.

Dipartimento di Fisica, Università della Calabria, Ponte P. Bucci, cubo 31C, 87036, Arcavacata di Rende (CS), Italy; Em@il: vlasovia2016@gmail.com

Invited Speakers

Enrico Camporeale (Amsterdam)
Stéphane Colombi (Paris)
Bill Dorland (Maryland)
Matteo Faganello (Marseilles)
Xavier Garbet (Cadarache)
Pierre Henri (Orléans)
Giovanni Lapenta (Leuven)
William H. Matthaeus (Delaware)
Thierry Passot (Nice)
Jérõme Pétri (Strasbourg)
François Rinçon (Toulouse)
Sergio Servidio (Calabria)
Andris Vaivads (Uppsala)
Troy Carter (UCLA)
Steve Cowley (Culham)
Bengt Eliasson (Strathclyde)
Lazar Friedland (Jerusalem)
Alain Ghizzo (Nancy)
Gregory Howes (Iowa)
Nuno Loureiro (Lisbon)
Phil Morrison (Texas)
Francesco Pegoraro (Pisa)
Alessandro Retinò (Paris)
Alexander Schekochihin (Oxford)
Eric Sonnendrucker (Garching)
Pierluigi Veltri (Calabria)

PhD students and Post-Doc fellows

Fellowships covering the conference fee, 5 night accommodation and meals have been awarded to 20 PhD students and Post-Doc fellows, thanks to the funding from our sponsors.

Special Issue of Journal of Plasma Physics on Vlasov equation

Original papers based on the oral/poster presentations will be considered for publication as refereed articles in a Special Issue of the Journal of Plasma Physics.

Guest editors: F. Califano, G. Manfredi and F. Valentini

Paper submission before October 31st, 2016.

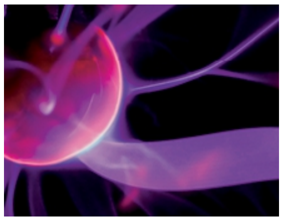
Location

The Vlasovia 2016 Conference will be held at the seaside resort "*Villaggio Guglielmo*" (http://www.villaggioguglielmo.it), located in the Calabria region in the south of Italy.

Sponsors

Dipartimento di Fisica – UNICAL, Tema Motori, Caseificio Artigianale Paese, Salumificio San Vincenzo, Tenute Ferrocinto, Colavolpe

JOURNAL OF **PLASMA PHYSICS**



Special Issue

"The Vlasov equation: from space to laboratory plasmas"

Paper Submission

The Scientific Committee and the Local Organizing Committee of VLASOVIA 2016 (International workshop on the theory and applications of the Vlasov equation, Copanello (CZ), Italy, 30 May - 2 June 2016 http://www.fis.unical.it/astroplasmi/vlasovia2016/index.html) are pleased to announce that a Special Issue of the Journal of Plasma Physics (JPP) entitled "The Vlasov equation: from space to laboratory plasmas", will be published in conjunction with VLASOVIA 2016. In accordance with the editorial policies of JPP, we invite all VLASOVIA 2016 participants and all interested researchers worldwide to submit articles containing original research results for inclusion in this issue.

This Special Issue intends

1. To provide a forum for the presentation of a broad variety of scientific results,
2. To involve the Vlasov equation community at large, ranging from the investigations of the physics and technological applications of the Vlasov equation, to its mathematical foundation and properties, to numerical methods,
3. To bring together results obtained within different communities, from laboratory to astrophysical and space plasmas, to nonlinear dynamics and applied mathematics.

All articles should be submitted through the usual JPP portal:

http://journals.cambridge.org/action/displaySpecialPage?pageId=2924

Paper submission will begin after the end of the VLASOVIA conference. Submissions should be clearly identified as intended for the Special Issue "The Vlasov equation: from space to laboratory plasmas" (use the pull down menu).

Please note that all contributions must be received no later than **October 31st, 2016**.

We look forward to receiving your submission!

Best regards,

Francesco Califano, *Physics Department, University of Pisa, Italy (Editor of JPP)*
Giovanni Manfredi, *Institut de Physique et Chimie des Matériaux de Strasbourg, France (Guest Editor)*
Francesco Valentini, *Physics Department, University of Calabria, Italy (Guest Editor)*

Cover page

Used material: On the left, plasma turbulence generated in a tokamak from a numerical simulation (http://www.lpp.fr/Turbulence,170?lang=fr); On the right, plasma turbulence surrounding a bow shock in a hybrid-Vlasov simulation from the VLASIATOR code (M. Palmroth, http://vlasiator.fmi.fi/), the CAD drawing of THOR (OHB-Sweden), a false color image of Cassiopeia A (Cas A) using observations from the Hubble and Spitzer telescopes as well as the Chandra X-ray Observatory. Courtesy: Walter Puccio.

SUNDAY	MONDAY	TUESDAY	WEDNESDAY	THORSDAY
	WELCOME – F. Valentini 8:45 - 9:00			
	S. Colombi 9:00 – 9:30	**F. Pegoraro** 9:00 – 9:30	**P. Henri** 9:00 – 9:30	**A. Vaivads** 9:00 – 9:30
	A. Ghizzo 9:30 – 10:00	**S. Cowley** 9:30 – 10:00	**T. Passot** 9:30 – 10:00	**A. Retinò** 9:30 – 10:00
	I. H. Hutchinson 10:00 – 10:20	**D. Del Sarto** 10:00 – 10:20	**S. Cerri** 10:00 – 10:20	**L. Matteini** 10:00 – 10:20
	COFFEE BREAK 10:20 – 10:50	COFFEE BREAK 10:20 – 10:50	COFFEE BREAK 10:20 – 10:50	COFFEE BREAK 10:20 – 10:50
	X. Garbet 10:50 – 11:20	**P. Morrison** 10:50 – 11:20	**F. Rincon** 10:50 – 11:20	**B. Matthaeus** 10:50 – 11:20
	A. Bhattacharjee 11:20 – 11:40	**M Strumik** 11:20 – 11:40	**M. Kunz** 11:20 – 11:40	**P. Hellinger** 11:20 – 11:40
	M. Faganello 11:40– 12:10	**L. Friedland** 11:40 – 12:10	**N. Loureiro** 11:40– 12:10	**S. Servidio** 11:40– 12:10
	LUNCH 12:10 – 15:00	LUNCH 12:10 – 15:00	LUNCH 12:10 – 15:00	LUNCH 12:10 – 15:00
	E. Camporeale 15:00 - 15:30	**A. Schekochihin** 15:00 – 15:30	**B. Eliasson** 15:00 - 15:30	**G. Lapenta** 15:00 – 15:30
	J. Pétri 15:30 - 16:00	**B. Dorland** 15:30 – 16:00	**E. Sonnendrucker** 15:30 - 16:00	**P. Veltri** 15:30 – 16:00
	COFFEE BREAK 16:00 – 16:30	**R. Fedele** 16:00 – 16:20	COFFEE BREAK 16:00 – 16:30	**D. Perrone** 16:00 – 16:20
	POSTER SESSION 1 16:30 – 18:30	COFFEE BREAK 16:20 – 16:50	POSTER SESSION 2 16:30 – 18:30	COFFEE BREAK 16:20 – 16:50
REGISTRATION 18:00 – 22:00		**T. Carter** 16:50 – 17:20		**G. Howes** 16:50 – 17:20
		O. Pezzi 17:20 – 17:40		**K. Klein** 17:20 – 17:40
		F. Pucci 17:40 – 18:00		**Y. Maneva** 17:40 – 18:00
		J. Hurst 18:00 – 18:20		THOR APERITIF 19:00
DINNER 20:00	DINNER 20:00	DINNER 20:00	DINNER 20:00	DINNER 20:00

UNIVERSITÀ DELLA CALABRIA
DIPARTIMENTO DI FISICA

UNIVERSITÀ DI PISA

IPCMS
Institut de Physique et Chimie des Matériaux de Strasbourg

THOR

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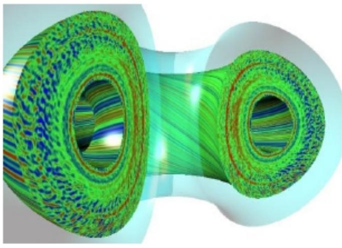

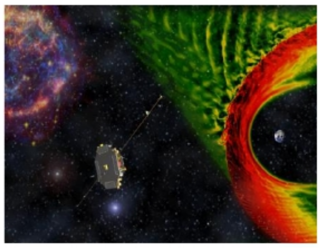

Poster Session 1 (Mon)

T. Akhter (BCPP)
G. Alì (CATA)
O. Allanson (BCPP)
H. Barminova (1 - CATA)
H. Barminova (2 - CATA)
D. Del Sarto (MPC)
P. Di Cintio (CATA)
L. Einkemmer (CATA)
G. Fruit (BCPP)
A. Geraldini (MCP)
P. A. Giorgi (BCPP)
Y. Güçlü (MPC)
A. Hallé (GS)
P. Kilian (CATA)
M. Jenab (CATA)
M. Lesur (CATA)
M. Masek (CATA)
P. Morel (1 - MCP)
P. Morel (2 - MCP)
D. Nunn (CATA)
S. Ogawa (MCP)
M. Perin (CATA)
M. Romé (BCPP)
M. Sarrat (BCPP)
A. Sgattoni (BCPP)
F. Skiff (BCPP)
E. Tassi (BCPP)
P. Trivedi (BCPP)
C. Tronci (CATA)

Poster Session 2 (Wed)

F. Boffa (SAAP)
G. Brunetti (BCPP)
D. Burgess (SAAP)
F. Catapano (SAAP)
R. De Marco (SAAP)
L. Franci (SAAP)
G. Inchingolo (SAAP)
C. Krafft (SAAP)
A. Osmane (SAAP)
S. Perri (SAAP)
D. Perrone (SAAP)
O. Pezzi (1-BCPP)
O. Pezzi (2- BCPP)
K. Pommois (SAAP)
L. Rakhmanova (SAAP)
A. Retinò (SAAP)
M. Riatzantseva (SAAP)
C. Rossi (SAAP)
S. Servidio (SAAP)
C. Shen (SAAP)
S. Stabile (SAAP)
B. Teaca (SAAP)
D. Terzani (BCPP)
D. Trotta (SAAP)
A. Vaivads (SAAP)
F. Valentini (SAAP)
M. Viviani (CATA)
F. Wilson (SAAP)
G. Zimbardo (SAAP)

CATA	Computational and theoretical approach
SAAP	Space and astrophysical plasmas
MCP	Magnetic confinement plasmas
BCPP	Basic collisionless plasma physics
GS	Gravitationsl systems

Monday, May 30th 2016

WELCOME – F. Valentini 8:45 - 9:00
S. Colombi 9:00 – 9:30
A. Ghizzo 9:30 – 10:00
I. H. Hutchinson 10:00 – 10:20
COFFEE BREAK 10:20 – 10:50
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A. Bhattacharjee 11:20 – 11:40
M. Faganello 11:40– 12:10
LUNCH 12:10 – 15:00
E. Camporeale 15:00 - 15:30
J. Pétri 15:30 - 16:00
COFFEE BREAK 16:00 – 16:30
POSTER SESSION 1 16:30 – 18:30
DINNER 20:00

Simulating Vlasov-Poisson equations with moving adaptive simplicial tessellation

S. Colombi[1], T. Sousbie[1,2,3]

[1] Institut d'Astrophysique de Paris, CNRS UMR 7095 and UPMC, Paris, France
[2] Department of Physics, The University of Tokyo, Tokyo, Japan
[3] Research Center for the Early Universe, School of Science,
The University of Tokyo, Tokyo, Japan

Resolving numerically Vlasov-Poisson equations for initially cold systems can be reduced to following the evolution of a three-dimensional sheet evolving in six-dimensional phase-space. After briefly reviewing various methods used in the literature to solve these equations, mainly in the astrophysical context, we present and illustrate a numerical algorithm consisting in representing the phase-space sheet with a conforming, self-adaptive simplicial tessellation of which the vertices follow the Lagrangian equations of motion. A six- and four-dimensional, fully parallel implementation of the algorithm, as described in details in [1], is publicly available.

References

[1] Sousbie T., Colombi S., *Journal of Computational Physics*, submitted, eprint arXiv:1509.07720

Semi-Lagrangian relativistic Vlasov solvers: key issues and impact on Weibel-type instabilities

A. Ghizzo[1], D. Del Sarto[1]

Address: 1. I.J.L. UMR 7198, Université de Lorraine, BP 239 F-54506 Vandoeuvre les Nancy, France.

Abstract

Abstract: This overview summarizes the concepts and the lastest developments in collisionless Vlasov-Maxwell plasma simulations in the relativistic regime and their impact on phase space topology and on the modelling of Weibel-type instabilities. Numerical experiments were carried out using a semi-lagrangian 2D3V full parallel Vlasov solver and comparisons with a "multi-stream" model Phys. [A. Ghizzo, P. Bertrand, Physics of Plasmas 20, 082109 (2013)] based on a Hamiltonian reduction technique using the invariance of generalized canonical momentum. Applications of this model are presented for relativistic plasmas where specific problems are addressed pertaining to the nonlinear and relativistic dynamics of magnetically trapped particles met in the saturation regime of the Weibel or Current Filamentation instabilities. The generation of magnetic field, together with the electrostatic activity is also investigated by means of an analytical pressure tensor tool [S.S. Cerri et al, Physics of Plasmas 20, 112112 (2014)]in the fluid framework to characterize the coupling mechanisms.

Nonlinear electron-hole kinematics in moon wakes

I H Hutchinson, C Zhou, C B Haakonsen

Plasma Science and Fusion Center
Massachusetts Institute of Technology, Cambridge, MA, USA

The rapid motion of planetary bodies such as moons relative to the solar-wind or magnetospheric plasma gives rise to a plasma wake. The wake plasma is depleted immediately trailing the body, acquiring a negative potential and filling in by electron and ion inflow along the magnetic field. The resulting non-Maxwellian particle distribution functions are unstable to electrostatic perturbations and show a variety of nonlinear phenomena; most importantly the formation and growth of electron holes. A plasma electron hole is a soliton-like positive potential structure maintained self-consistently by a deficit of electron phase-space density on trapped orbits. Recent satellite observations have identified electron holes as an important component of space-plasma turbulence.

Particle in Cell simulations of the moon wake show that the instability onset of *hybrid* simulations (treating only the ions kinetically) are accurately predicted by linear theory. However, when the electrons are also treated kinetically, instability begins and the ion streams are disrupted much earlier in the wake than can be accounted for by linear or quasi-linear theory. The reason is the formation and growth of electron holes, as illustrated by Fig. 1. Holes with speeds

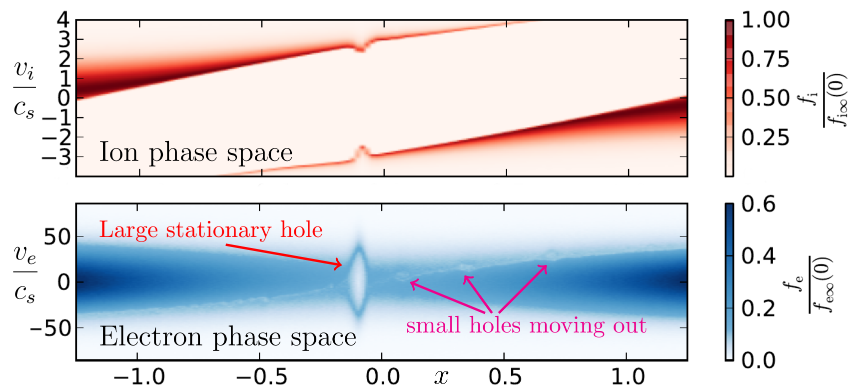

Figure 1: Distribution function contours in phase space of a wake simulation, showing small convecting holes and a large stationary hole. The x position is in units of the object radius.

much greater than the ion acoustic speed c_s move out of the simulation along orbits that are practically the same as the background electrons, as determined by the large-scale potential gradients of the wake as a whole. However, the most important holes are a different class that have almost zero velocity on the electron scale and therefore remain in the wake for a long time, growing by a new mechanism until they cause nonlinear disruption of the ion streams.

To understand why, we have developed a new theory that governs the *kinematics* of electron holes: their motion based upon the conservation of momentum. Holes interact with untrapped ions and electrons energizing them and giving rise to momentum transfer analogous to a jet engine when the hole accelerates or grows. Analysis of the jetting effect enables us to explain quantitatively why hole velocities vary the way they do.

Interplay of collisional and turbulent transport processes.

X. Garbet, N. Bouzat, S. Breton, P. Donnel, C. Ehrlacher, D. Estève,
G. Dif-Pradalier, P. Ghendrih, V. Grandgirard, G. Latu, Y. Sarazin
CEA, IRFM, F-13108 Saint Paul-lez-Durance, France

Transport in magnetized plasmas is a question of utmost importance as it controls the confinement properties, and therefore the performances of fusion devices. Fluxes are traditionally separated in two contributions related to collisional and turbulent processes. Collisional transport is amplified by geometry effect in toroidal fusion devices. It is then called neoclassical transport. Neoclassical and turbulent transport are often calculated separately, and added up. This procedure is based on an argument of scale separation. Neoclassical transport is related to large wavelength poloidal asymmetries. Turbulence is characterized by much smaller spatial scales. This clear spatial separation is usually considered as providing a firm ground for treating separately turbulent and neoclassical transport processes.

However this rationale is questionable. One reason is that turbulence is known to generate large scale flows, which exhibit poloidal asymmetries, and therefore potentially affect collisional transport. Turbulence is also responsible for scattering in the velocity space, which may play a role similar to collisional scattering, and thus modify some neoclassical results. Conversely, collisions damp large scale shear flows, which back react on turbulence. Hence interplay is possible, and indeed several examples of interaction have been found recently. The present review lists these examples, and aims at clarifying certain critical points. Implications for pending issues such as transport barriers will be discussed.

Integration of Kinetic Effects in Multi-Fluid Global Models: Theory and Simulation

A. Bhattacharjee[1], K. Germaschewski[2], A. Hakim[1], J. Ng[1] and L. Wang[2]

[1] Department of Astrophysical Sciences and Princeton Plasma Physics Laboratory, Princeton University, Princeton, NJ 08540, USA
[2] Space Science Center, University of New Hampshire, Durham, NH 03824, USA

Since fully kinetic global electromagnetic simulations of laboratory, space, and astrophysical plasmas with realistic plasma parameters and system size remain beyond the capability of present petascale or even planned exascale computers over the next 10 years, there has been significant interest in developing extended multi-fluid equations that incorporate kinetic effects through closure relations. Asymptotic perturbation expansions generally rely on small Knudsen numbers for their rigorous validity (be it Chapman-Enskog or Grad's 13-moment approach). However, in weakly collisional or collisionless plasmas, which are often the realm of space and astrophysical objects, these expansions tend to break down.

We have introduced an extensible multi-fluid moment model in the context of collisionless magnetic reconnection. This model evolves full Maxwell equations along with moments of the Vlasov equation for each species in the plasma. Effects like finite particle inertia and pressure tensor that break field lines are self-consistently included in the model without the need to invoke a generalized Ohm's law. At different levels of truncation---5, 10, and 13 moments---we obtain an increasingly detailed description of reconnection dynamics. Whereas the 5-moment model can be shown to be formally equivalent to Hall MHD (in the limit of vanishing electron inertia and infinite speed of light), it neglects heat flux, which is essential in obtaining results that are in reasonable agreement with the results of fully kinetic simulations. For collisionless plasmas, we have tested the efficacy of a local variant of Hammett-Perkins closure, and the results of our multi-fluid model are shown to be quite encouraging.

This approach of integrating kinetic effects in global simulations is not without its mathematical subtleties. Depending on the physical problem, "more" can sometimes be "less", because the fluid equations can change character, especially in the regime of large heat flux where instabilities that are artifacts of the truncation of the asymptotic expansion appear in the theory. The mitigation strategies for such instabilities are a subject of current research. Implications of these developments for global simulations of the heliosphere will be discussed.

This research is supported by the NASA-NSF Collaboration for Space Weather.

Nonlinear hybrid simulations of precessional Fishbone instability

M. Faganello[1], M. Idouakass[1], H. L. Berk[2], X. Garbet[3], S. Benkadda[1]

[1] Aix Marseille University, CNRS, PIIM UMR 7345, 13397 Marseille, France
[2] Institute for Fusion Studies, University of Texas, USA
[3] CEA, IRFM, 13115, St Paul lès Durance, France

The precessional Fishbone instability results from the interplay between energetic particles trapped in a toroidal magnetic configuration and the bulk of the plasma [1]. This electromagnetic mode is characterized by bursts of activity and frequency down-chirping and can cause enhanced transport and losses of energetic particles, being them alpha-particles in next-future fusion devices or heated particles in present Tokamaks [2]. The model adopted for its description is reduced to its simplest form, assuming a reduced MagnetoHydroDynamic description for the bulk plasma and a two-dimensional phase-space evolution (gyro and bounce averaged) for deeply trapped energetic particles [3]. Numerical simulations elucidates the complex non-linear dynamics that leads to the frequency chirping and to the outward radial motion of particles. Special care is given in presenting the peculiar Hamiltonian dynamics of particles in a Tokamaks and their unusual canonical coordinates.

References

[1] L. Chen et al., *Phys. Rev. Lett.* **52**, 1122 (1984)

[2] K. McGuire et al., *Phys. Rev. Lett.* **50**, 891 (1983)

[3] A. Ödblom et al., *Phys. of Plasmas* **9**, 155 (2002)

A quasi-neutral kinetic model for collisionless plasma

E. Camporeale[1], F. Deluzet[2], C. Tronci[3]

[1] Center for Mathematics and Computer Science (CWI), Amsterdam, The Netherlands
[2] Université de Toulouse, Toulouse, France
[3] University of Surrey, Guildford, United Kingdom

We present a new simplified kinetic model that treats all species kinetically, but neglects radiation effects by assuming charge neutrality directly in the Maxwell-Vlasov system. Therefore, electrostatic Langmuir waves are exactly factored out. The new model generalizes all collisionless neutral plasma models presented in the literature in the last few decades. We present linear theory results, comparing the new model with the hybrid (electron fluid and ion kinetic) and the gyrokinetic models. Moreover, we will discuss preliminary results on nonlinear simulations and their numerical implementation.

References

[1] C. Tronci and E. Camporeale (2015). Neutral Vlasov kinetic theory of magnetized plasmas. *Phys. Plasmas*, 22(2), 020704

Neutron star magnetospheres and winds

J. Pétri

Observatoire astronomique de Strasbourg, Université de Strasbourg,
CNRS, UMR 7550, 11 rue de l'université, F-67000 Strasbourg, France.

Neutron stars are fascinating astrophysical objects immersed in strong gravitational and electromagnetic fields of the order $B \approx 10^{5-8}$ T, at the edge of our current theories. These stars manifest themselves mostly as pulsars, emitting a timely very stable and regular electromagnetic signal with periods between $P \approx$1 ms – 1 s. Even though discovered almost fifty years ago, they still remain mysterious compact objects. In this review, we summarize the most fundamental theoretical aspects of pulsar magnetospheres and winds. A global but still rather qualitative picture emerges slowly thanks to recent advances in numerical simulations. However considerations about their magnetosphere remain speculative. For instance the exact composition of the magnetospheric plasma is not yet known. Is it filled with a mixture of leptons $e^{\pm}$, or does it contain a non negligible fraction of protons and/or ions? Actually, is it almost entirely filled or empty? Answers to these questions will strongly direct the description of the magnetosphere to seemingly contradictory results leading sometimes to inconsistencies. Nevertheless, account are given to the latest developments in simulations of pulsar magnetospheres, from the basic force-free approximation [2] or in the ideal MHD regime [4] to more detailed two-fluid and PIC approaches including radiation reaction [1] and general-relativistic effects [3]. In any case, neutron star electrodynamics remains challenging for theoreticians as well as for people performing computer simulations because of the extraordinary large span in space and time scales involved in such stars. Indeed a typical ratio between the cyclotron frequency ω_B and the stellar rotation frequency Ω is

$$\frac{\omega_B}{\Omega} = \frac{e\,B}{m\,\Omega} \approx 10^{16-19}. \tag{1}$$

Moreover the ratio between neutron star radius R and Larmor radius r_B is also large

$$\frac{R}{r_B} = \frac{R\,\omega_B}{c} = \frac{\omega_B}{\Omega}\,\frac{R}{r_{\rm L}} \approx 10^{15}\,\frac{R}{r_{\rm L}} \tag{2}$$

where $r_{\rm L} = c/\Omega \approx 10 - 10.000\,R$ is the light-cylinder radius, i.e. another important length scale indicating the transition between the static quasi-stationary and the wave zone.

References

[1] B. Cerutti, A. A. Philippov, and A. Spitkovsky. Modelling high-energy pulsar light curves from first principles. MNRAS, 457:2401–2414, April 2016.

[2] J. Pétri. The pulsar force-free magnetosphere linked to its striped wind: time-dependent pseudo-spectral simulations. MNRAS, 424:605–619, July 2012.

[3] J. Pétri. General-relativistic force-free pulsar magnetospheres. MNRAS, 455:3779–3805, February 2016.

[4] A. Tchekhovskoy, A. Spitkovsky, and J. G. Li. Time-dependent 3D magnetohydrodynamic pulsar magnetospheres: oblique rotators. MNRAS, 435:L1–L5, August 2013.

Driving beam mode analysis in the longitudinal self-consistent plasma wake field mechanism

T. Akhter[1,4], D. Terzani[1,4], R. Fedele[1,4], S. De Nicola[2,4], D. Jovanović[3,4]

[1] Università di Napoli Federico II, Napoli, Italy
[2] CNR-SPIN, Napoli, Italy
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We carry out an analysis of the beam modes that are originated by perturbing the 'beam-plasma' system in the purely longitudinal case, when the beam is experiencing the self-consistent plasma wake field interaction with the surrounding plasma. This is done by considering the pair of perturbed Vlasov-Poisson-type equations. In Fourier space, the latter is reduced to a Landau-type dispersion relation for the beam modes. We first analyze the monochromatic beam case, where the existence of a purely growing mode is shown and a simple stability criterion is formulated. Then, by taking into account a distribution function with finite width, the Landau approach leads to obtain both the dispersion relation and an expression for the imaginary part of the frequency, showing the stable or unstable character of the beam modes.

Extended hydrodynamical models for plasmas

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We propose an extended hydrodynamical model for plasmas, based the moments of a particle distribution function $f(\mathbf{x}, \mathbf{v}, t)$ which satisfies the Fokker-Planck-Landau (FPL) transport equation,

$$\frac{\partial f}{\partial t} + v_i \frac{\partial f}{\partial x_i} + F_i \frac{\partial f}{\partial v_i} = \mathcal{C}[f] := \frac{\partial}{\partial v_i} \int_{\mathbb{R}^3} U_{ij}(\mathbf{v} - \mathbf{v}') \left[f' \frac{\partial f}{\partial v_j} - f \frac{\partial f'}{\partial v_j} \right] \mathrm{d}\mathbf{v}'. \tag{1}$$

Here, $\mathbf{F}$ is the force term, $U_{ij}(\mathbf{u}) = U_0 u^3 (u^2 \delta_{ij} - u_i u_j)$, $u = |\mathbf{u}|$, with $U_0 > 0$, and the prime denotes evaluation at $\mathbf{v}'$, as in $f' = f(\mathbf{x}, \mathbf{v}', t)$.

The equations for the moments $M_{i_1 i_2 \cdots i_k} = \int_{\mathbb{R}^3} f v_{i_1} v_{i_2} \cdots v_{i_k} \, \mathrm{d}\mathbf{v}$ can be obtained by multiplying Eq. 1 by $v_{i_1} v_{i_2} \cdots v_{i_k}$ and integrating over $\mathbb{R}^3$:

$$\frac{\partial}{\partial t} M_{i_1 i_2 \cdots i_k} + \frac{\partial}{\partial x_r} M_{r i_1 i_2 \cdots i_k} - k F_{(i_1} M_{i_2 \cdots i_k)} = Q_{i_1 i_2 \cdots i_k}, \quad k = 0, 1, \ldots, n, \tag{2}$$

where the brackets denote symmetrization and $Q_{i_1 i_2 \cdots i_k} = \int_{\mathbb{R}^3} \mathcal{C}[f] v_{i_1} v_{i_2} \cdots v_{i_k} \, \mathrm{d}\mathbf{v}$.

Next, we introduce the mean component $\mathbf{u}$ and the random component $\mathbf{c}$ of the particle velocity $\mathbf{v}$, by $u_i = \frac{M_i}{M}$, $v_i = u_i + c_i$. The internal moments are defined by $\hat{M}_{i_1 i_2 \cdots i_r} = \int_{\mathbb{R}^3} f c_{i_1} c_{i_2} \cdots c_{i_r} \, \mathrm{d}\mathbf{v}$. In particular, we have $\hat{M} = M$, $\hat{M}_i = 0$. The internal moments are used as state variables together with $\mathbf{u}$. In Eq. 2 there appear extra unknowns, for which we determine constitutive relations by means of the maximum entropy principle [1]. Thus, the spurious quantities can be evaluated by using a distribution function which maximizes the entropy of the system while maintaining the state variables, namely $f_{ME} = \exp(\sum_{k=0}^{n} \lambda_{i_1 \cdots i_k} c_{i_1} \cdots c_{i_k})$.

The maximum entropy distribution function depends on Lagrangian multipliers $\lambda_{i_1 \cdots i_k}$, which have to be expressed in terms of the state variables by inverting the constraints

$$\int_{\mathbb{R}^3} \exp\left(\sum_{l=0}^{n} \lambda_{j_1 \cdots j_k} c_{j_1} \cdots c_{j_l} \right) c_{i_1} c_{i_2} \cdots c_{i_k} \, \mathrm{d}\mathbf{c} = \hat{M}_{i_1 i_2 \cdots i_k}. \tag{3}$$

We will concentrate on the 13-moment system [2], which considers the weights $1, v_i, v_i v_j$, for which we will show some preliminary results. Related models which make use of the maximum entropy principle are available in literature, e.g. [3], but they use a modified collision operator or partial moments with respect to angular variables. Although apparently complicated, the symmetrizable hyperbolic system Eqs. 2-3 is viable for efficient numerical simulations.

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Low-beta collisionless equilibria for the Force-Free Harris Sheet

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We present discussion and analysis of the physical properties of new exact collisionless equilibria for a 1D nonlinear force-free current sheet (Force-Free Harris Sheet). The solution allows any value of the plasma beta (β_{pl}), and crucially below unity, which other nonlinear force-free collisionless equilibria [1, 2, 3, 5] can not. The distribution function (DF) involves infinite series of Hermite Polynomials in the canonical momenta, of which the important mathematical properties of convergence, non-negativity and boundedness have recently been proven [6].

Despite the fact that the DF derived in [4] has been analytically proven to be convergent for all values of β_{pl}, we have not found it simple to attain numerical convergence for very low values of β_{pl}. The lowest value obtained for this DF is $\beta_{pl} = 0.85$.

In the effort to model equilibria with lower values of β_{pl}, we calculate DFs for the same macroscopic equilibrium (the FFHS) with a new gauge for the vector potential [6]. Numerical results are presented for this equilibrium with $\beta_{pl} = 0.05$.

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One-dimensional self-consistent kinetic models as Vlasov equation solutions

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In charged particle beam physics the self-consistent kinetic models are proved to be very useful for the particle beam behavior description [1]. Such models are often used for analytical prediction of the particle ensemble dynamics as well as they are often included into the simulation programs. In the models the method of the construction of the specific kinetic distribution function dependent on the particle motion integrals is usually realized to describe the intense charged particle flux. As a solution of the Vlasov equation such distribution function allows to obtain the self-consistent equations for the beam boundary or envelope.

Here one-dimensional models as the solutions of the Vlasov equation are described, corresponding to the particle ensembles in two cases: one dimensional flux, characterized by the sharp front, and the sheet continuous beam, characterized by single coordinate direction of the particle oscillations in the beam cross-section.

In first case the distribution function may look as:

$$f = \frac{\kappa\sigma(1-I)}{\sqrt{1-I}}, \tag{1}$$

where I is the invariant, σ – the Heaviside function, κ – the normalization constant. The corresponding beam envelope equation represents the wide particle flux front motion and may be used for analytical investigation of the charged particle bunch formation [2].

Another case is related with the sheet particle ensemble which may be shaped both artificially in special slit structures and in space during the beam propagation in complicated electromagnetic field. The corresponding kinetic distribution function may look as:

$$f = \kappa\sigma(1-I), \tag{2}$$

where I is invariant, which corresponds, for instance, to the Gaussian distribution function in coordinate space, κ – the constant of normalization, σ - the Heaviside function [3]. The beam envelope obtained with the help of such function describes the particle ensemble evolution with time, caused by both ensemble statistical temperature and self-consistent electromagnetic fields.

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Self-consistent time-dependent model for the description of magnetized charged particle beam

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Magnetized charged particle beams may be described in the frame of Vlasov theory. In practically important cases the beam pulse duration is essentially less than specific time between the particle collisions, so the beam dynamics is determined by both the external fields and self-consistent electromagnetic fields. The model is proposed to describe such a beam propagating in external magnetic field.

Assuming the linear character of the fields affecting the particles, one can buid the invariant as a function of the particle linear motion integrals [1]. The kinetic distribution function dependent on such invariant automatically satisfies the Vlasov equation.

We suppose that such invariant may include the bilinear integrals of the motion, so the term dependent on the coupling particle transverse coordinates and the velocities could be emphasized [2], in the case of the particles of the beam affected by the arbitrary magnetic field :

$$I = \frac{(u^{\cdot} x - u x^{\cdot})^2}{\varepsilon_x^2} + \frac{(v^{\cdot} y - v y^{\cdot})^2}{\varepsilon_y^2} + \frac{x^2}{u^2} + \frac{y^2}{v^2} + C_0 (x^{\cdot} y - x y^{\cdot}) \qquad (1)$$

It may be shown, that the last term in (1) corresponds to the mean angular momentum of the particle, so the distribution function $f = \kappa\delta(I-1)$ will correspond to the magnetized beam.

From the Vlasov equation one can easy obtain the differential equations for the beam root-mean-square radii. Solving the Cauchy problem for the equations analitically or numerically, one can obtain full description of the dynamics of the magnetized charged particle beam with elliptical cross-section. The model developed may be used for the beam behavior prediction in different devices as well as in the case of beam propagation in space near the objects having the own strong magnetic field. The beam parameter time evolution must be taken into account while the experiment providing and interpretating, because the magnetic fields change the beam phase characteristics essentially.

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Secondary fast reconnecting instability in the sawtooth crash

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We summarize the results recently discussed in Ref.[1]. We consider magnetic reconnection in thin current sheets when microscopic scales (e.g electron inertia) comparable to kinetic ones become important. For simplicity, we consider a fluid, "cold", reduced MHD model with both resistive and electron inertia effects. When the current sheet is produced by a primary instability of the internal kink type, the analysis of secondary instabilities indicates that reconnection proceeds on a time scale much shorter than the primary instability characteristic time. The quantitative estimations of this analysis seem to agree with the numerical results obtained [2] in the purely resistive regime of the internal kink instability in a cylindrical tokamak. In the case of a sawtooth crash, non-collisional physics becomes important above a value of the Lundquist number which scales like $S \sim (R/d_e)^{12/5}$, in terms of the tokamak major radius R and of the electron skin depth d_e. This value is commonly achieved in present day devices. As collisionality is further reduced, the characteristic rate increases, approaching Alfvénic values when the primary instability approaches the collisionless regime.

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Relaxation of weakly collisional one-component plasmas: Vlasov-Fokker-Planck vs Multi-particle collision simulations

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We study the dynamical relaxation and the onset of anomalous diffusion in 1D and 2D one-component plasmas embedded in a static neutralizing background. We consider systems in which the contribution of the Coulomb two body collisions (although smaller than mean-field effects) is non negligible using two different numerical approaches, an Eulerian Vlasov-Fokker-Planck solver [1] and a Particle-Mesh N-body code in which particle collisions are implemented via the so-called multi-particle collision method [2].

In the first case we numerically integrate via a finite difference solver the Vlasov-Fokker-Planck equation for the phase-space distribution function $f(\mathbf{r}, \mathbf{v})$

$$\frac{\partial f}{\partial t} - \mathbf{v} \cdot \nabla_{\mathbf{r}} f + \frac{q}{m} \mathbf{E} \cdot \nabla_{\mathbf{v}} f = \nabla_{\mathbf{v}} \cdot [\nu(\mathbf{r}, \mathbf{v}) \nabla_{\mathbf{v}} f] \,, \tag{1}$$

where $\mathbf{E}$ is the self-consistent electrostatic field and $\nu(\mathbf{r}, \mathbf{v})$ is the velocity diffusion coefficient [3], accounting for the collisions. In the second case, in the line of previous work [4, 5], we introduce a cell dependent stochastic collision term in the otherwise collisionless $N-$body dynamics, ensuring the local conservation of energy and momentum.

We find [5, 6], that with the second scheme we are able to control the crossover between ambipolar (normal) and anomalous diffusion in numerical simulations with a smaller number of free parameters. Moreover, we observe the relaxation of water-bag initial conditions with the two approaches leads to qualitatively different end-products, owing to the intrinsic differences between particle-based and single-particle phase-space distribution models.

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The semi-Lagrangian discontinuous Galerkin method for the solution of the Vlasov equation

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Due to the high dimensionality of the phase space, particle methods are often employed to compute a numerical approximation to the Vlasov equation. However, in a number of physical problems it is advantageous to directly discretize the Vlasov equation in phase space (the so-called Eulerian approach).

In this context semi-Lagrangian methods, which follow the characteristics backward in time, are usually the method of choice. This is due to the fact that they do not suffer from a Courant-Friedrichs-Lewy (CFL) condition. Note, however, that the feet of the characteristics starting at a given grid point not necessarily coincide with the numerical grid. Thus, some interpolation procedure has to be employed. Most commonly this is done using cubic splines.

In this talk, we introduce and discuss the properties of the more recently developed semi-Lagrangian discontinuous Galerkin methods. These methods are considered an attractive alternative to more traditional approaches as, similar to spline interpolation, they are conservative and limit numerical diffusion. However, contrary to spline interpolation, the resulting numerical schemes are completely local. This makes them ideally suited for parallelization on large clusters (which is significantly more challenging for spline or Fourier based methods). We show numerical simulations that demonstrate that our dimension independent implementation scales to at least 10^4 cores on the Vienna Scientific Cluster. Furthermore, we present long time integration results that emphasize the good conservation properties of the semi-Lagrangian discontinuous Galerkin method and discuss how filamentation filtration can be included as part of this algorithm.

This talk is based on [1, 2, 3, 4, 5, 6].

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Destabilization of 2D magnetic current sheets by resonance with bouncing electrons - a new theory

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In the general context of understanding the possible destabilization of the magnetotail before a substorm, we propose a kinetic model for electromagnetic instabilities in resonant interaction with trapped bouncing electrons. The geometry is clearly 2D and uses Harris sheet profile. Fruit et al.[1] already used this model to investigate the possibilities of electrostatic instabilities. Tur et al.[2] generalizes the model for full electromagnetic perturbations. Starting with a modified Harris sheet as equilibrium state, the linearized Vlasov equation is solved for electromagnetic fluctuations with period of the order of the electron bounce period (a few seconds). The particle motion is restricted to its first Fourier component along the magnetic field and this allows the complete time integration of the non local perturbed distribution functions. The dispersion relation for electromagnetic modes is finally obtained through the quasineutrality condition and Ampere's law for the current density.

The present contribution will focus on the main results of the electrostatic theory that may apply to the near-Earth environment (8-12 R_E) where β is rather low. It is showed that inclusion of bouncing electron motion enhances strongly the growth rate of the classical drift wave instability. Thus, this model could potentially explain the generation of strong parallel electric fields in the ionosphere and the formation of aurora beads with wavelength of a few hundreds of km.

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A kinetic model for ions in the magnetic presheath

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In order to better understand the mechanisms underlying plasma exhaust, nonlinear fluid codes are used to simulate the plasma in the Scrape Off Layer (SOL). These require appropriate boundary conditions at the wall, which have been derived so far, in the form of constraints on the moments of the ion and electron distribution functions, by use of fluid equations [1]. However, it is widely agreed that a kinetic treatment of the boundary layer is necessary, because its characteristic lengths are comparable to or smaller than the ion mean free path.

We develop a gyrokinetic model for ions valid in the plasma-wall boundary layer known as the magnetic presheath [2], at a distance of order the ion gyroradius from the wall. This analytical model exploits the properties of single particle motion in a magnetic presheath with a grazing angle magnetic field [3]. It retains orbit distortions caused by the strong electric field variations to lowest order in the expansion parameters, while averaging over the orbit phase. Most attempts at modelling the boundary layer use either fluid equations, Particle-In-Cell (PIC) simulations and, more rarely, numerical solutions to the Vlasov equation using Eulerian codes [4]. Very few attempts consist of fully analytical and completely kinetic treatments of the magnetic presheath. We hope that the gyrokinetic framework that we develop will simplify the computation of numerical kinetic solutions of the ion density and electrostatic potential in the magnetic presheath, while at the same time providing a starting point into further analytical calculations that can give useful and relatively simple results. As an example of such a calculation, we will apply this model to find the form of the electrostatic potential and ion density in the region of the magnetic presheath closest to the wall, working under the assumption of collisionless ions. The distribution function in this region cannot be treated as a lowest order gyroaverage of closed orbits, because most ions are travelling along open trajectories that end up at the wall.

This work is a building block of a kinetic model of the whole boundary layer, which will include a purely collisional drift kinetic layer at lengths much larger than the ion gyroradius from the wall. The moments of the distribution function entering the collisional layer will provide the boundary conditions to the fluid codes used to simulate the Scrape-Off Layer.

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Quasineutrality limit of the Vlasov-Poisson system

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My PhD work focuses on the mathematical study of the Vlasov-Poisson system and the regularity of its solutions. This system is a combination between a non-linear hyperbolic system with a non-linear elliptic equation.

It is a classical kinetic model in plasma physics and describes the behavior of ions and electrons in a plasma. More precisely, we are interested in the quasineutral limit of this system, i. e. the limit when the Debye length tends to zero. Physically, it means that, locally, the charge of the ions must compensate exactly the charge of the electrons, hence the name quasineutral limit.

Already existing results concern the case of adiabatic electrons or frozen ions. My job is to try to extend these results in the case of two species (ions and electrons) without such hypotheses. To begin, we study the one-dimensional formal Vlasov-Poisson limit system for two species. We concentrate on the stationary case and we try to find some properties on the characteristics. Alongside, we also study the approach $\epsilon \to 0$ of the classical Vlasov-Poisson system.

Field-aligned interpolation in semi-Lagrangian methods for gyrokinetics

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In magnetic fusion devices like Tokamaks and Stellarators, the gradient of the solution along a magnetic field line is typically much smaller than along a perpendicular direction. This observation should be taken into account for more efficient simulations. To this end, many gyrokinetic codes employ field-aligned coordinates, but this approach has a few drawbacks: 1) a non-conformal correction is needed after one turn, either in the poloidal or toroidal direction; 2) field-aligned coordinates become singular when approaching the separatrix in a divertor configuration; and 3) the resulting numerical grid is highly inhomogeneous. A very promising alternative, which is flexible in regard to the choice of coordinates, was introduced in [1], and an equivalent approach in [2]. The main idea is to compute the derivatives locally along the field lines, getting the needed values for finite differences by interpolation to the intersection points of a field line with the poloidal planes. As shown in [3], the same approach can be extended to semi-Lagrangian schemes.

This work is devoted to the study of field-aligned interpolation in semi-Lagrangian codes, with special emphasis on the numerical analysis, verification and benchmarking. In toroidal geometry, field-aligned interpolation consists of a 1D interpolation along the field line, combined with 2D interpolations on the poloidal planes (at the intersections with the field line). In the case of 2D constant advection, we prove unconditional stability and give error estimates which highlight the advantages of the method. We then solve the gyrokinetic Vlasov equation, using the ion temperature gradient (ITG) instability as a test-case, both in cylindrical (screw-pinch) and toroidal (circular Tokamak) geometries. In the first case, the algorithm is implemented in Selalib [4], and the numerical simulations provide linear growth rates in accordance with the linear dispersion analysis. In the second case, the algorithm is implemented in the Gysela code [5], and benchmarked against the standard (not aligned) scheme. We conclude that field-aligned interpolation leads to considerable memory savings for the same level of accuracy; the execution time is comparable to the standard approach, but the implementation in the code can be further optimized.

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Evolution of spherical, self-gravitating collisionless systems in phase-space

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We study numerically the fine phase-space structure of spherically symmetric self-gravitating collisionless fluids with initial power-law density profiles and Gaussian velocities distributions. Simulations are run with a spherical semi-Lagrangian Vlasov solver, a N-body shell code as well as a standard N-body tree-code (hence not preserving spherical symmetry), which allows for a comparison of various numerical methods. In all the simulations, the system first experiences, as expected, a quiescent mixing phase, during which it displays a smooth spiral structure in phase-space. The properties of this spiral agree well with predictions from self-similar collapse when either inertial force dominates (small radius) or gravitational force dominates (large radius). After the mixing phase, the system reaches a quasi-stationary regime. At this point, we study in details the properties of the phase-space distribution as a function of energy and angular momentum. Fitting simple functional forms allows us to understand in details the behaviour of the system in different regimes, in particular the presence of a core or a cusp in the projected density, and to relate the results to existing models in the literature.

Plasma Waves as a Benchmark Problem

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Collisionless plasmas admit a large number of wave phenomena. Their properties depend on parameters such as temperature, background magnetic field and the composition of the plasma. They exist in different components of the electromagnetic fields and can be described by their direction of propagation, polarization, frequency, and damping rate all, of which can depend strongly on the wavelength. Analytic descriptions of these properties are widely available in the literature, but differ strongly in their complexity and the inclusion of finite temperature effects and corrections due to heavy ions.

A major part of current research however is not performed analytically, but using simulation codes for the numerical description of plasma properties. Simulation codes that include a self-consistent description of particles and fields also admit the existence of wave modes. The properties of these modes depend on the description that was chosen and the numerical implementation.

Given that the properties of the wave depend on the description of the particles, electromagnetic fields and their interplay implies that wave properties can be used to test a large fraction of the code against known behavior of the physical system.

For a few wave modes this talk will start with the well known cold plasma dispersion relations before extending the theoretical description with finite temperature corrections and will then quickly go to numeric solutions of the dielectric tensor.

It will then compare those descriptions with the results from a Particle-in-Cell code (covering the range from fully electromagnetic over the Darwin approximation to the electrostatic limit), a hybrid code with and without electron inertia and a Vlasov-hybrid code.

The talk intends to explain a well posed test problem and to encourage users of other codes to perform the same tests with their code.

Vlasov Hybrid Simulation (VHS) method: recurrence effect and nonlinear phenomenon

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A method to simulate collisionless plasma based on Vlasov Poisson set of equations is presented. Vlasov Hybrid Simulation (VHS) following phase points trajectories [1, 2] includes a method intensively focused on retaining the positivity of distribution function, so in each time step, velocity and position of so called *phase points* are being pushed while the distribution function values of them stay untouched.

This method have been proven to overcome the unphysical effect of *recurrence effect*, which exists in almost all the other Vlasov simulation methods [3]. By randomizing the initial sampling of the phase space the recurrence effect can be removed from the simulation while the behavior of the physical system stays the same in the linear regime. Other method for removing this effect suggests adding opportune collisionality term to the Vlasov equation. Recently it is shown that this approach can result in great divergence in the nonlinear regime of the long-run simulations [4]. Here the nonlinear behavior of VHS method under both regular sampling (which produces recurrence effect) and randomized sampling (which removes the recurrence effect) is discussed in details for two different scenarios including long time behavior of nonlinear Landau damping (compared to Manfredi's results [6]) and bump-on-tail instability.

Furthermore the existence of filamentation [5] and entropy conservation under these both circumstances are studied. It is shown that filamentation stays unaffected in random sampling however the entropy conservation is slightly improved.

Multicomponent version of the method is developed [7] and the effect of removing recurrence effect on nonlinear phenomenon in multicomponent plasmas is briefly addressed. The intricacy of the multicomponent plasmas demonstrates that the recurrence effect can be removed without any trace on physical behavior in both linear and nonlinear regimes.

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Spurious entropy production in numerical simulations of Vlasov turbulence

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For a wide range of astrophysical and laboratory plasma phenomena, collisions are negligible. Then, the evolution of the particle distribution in phase-space is usually described by the Vlasov equation. Accurate numerical simulation of such systems requires careful treatment of conserved physical quantities (e.g. mass, energy, or entropy).The numerical treatment of kinetic nonlinearities such as particle trapping is particularly challenging. Indeed, trapping involves the filamentation of phase-space, whereby an initially smooth particle distribution is mixed by the particle motion into finer and finer structures. Phase-space filaments eventually become smaller than the numerical grid size. Then information is inevitably lost, which breaks the conservation of entropy. This problem is well-known for Vlasov codes [1], but the impact on physics of interest, i.e. the evolution of coarse-grained observables, is unknown.

In overcoming the numerical issues associated with phase-space filamentation, one can distinguish three classes of approach. The first approach is to add a collision operator to the model [2, 3], even if the collision frequency has to be artificially increased to overcome the issues. The second approach is to add artificial damping [4] or filters [5] (Fourier codes belong to this class). The third approach is to simply let numerical discretization dissipate the smallest scales and coarse-grain average the distribution function in an uncontrolled manner. For all three classes of approach, however, a concern is that arbitrary choices may impact the physics of interest.

In this work, we report a systematic spurious entropy production, of 15% of the initial entropy, when the quasi-steady state of ion-acoustic turbulence is reached, regardless of the numerical treatment [6]. Indeed, the issue is not limited to Vlasov codes. The same error is found for fundamentally different types of simulation, i.e. Vlasov (semi-Lagrangian) and particle-in-cell (PIC), different schemes and different choices of grid sizes. Furthermore, the error is relatively insensitive to parameters of the physical system. As expected, a collision operator with velocity diffusion resolves the issue, but surprisingly, only if the collision frequency is artificially increased to values so large that it dominates the long-time evolution.

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Transform method for numerical solution to the Vlasov equation

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In the recent years transform methods became again more popular in the field of numerical physics for solution to the Vlasov equation. They were originally introduced in the pioneering work of G. Knorr [1], where the Fourier transform was used for the solution of 1D Vlasov-Poisson system in the both spatial and velocity coordinate. However, our approach is based on the use of Hermite transform in the velocity coordinate while the Fourier transform is employed in the spatial coordinate. This method was proposed and studied in the following paper by T. P. Armstrong [2]. This technique is suitable especially for modelling of Gaussian-like distribution functions. The essential truncation of the Hermite expansion is the main limiting factor of this method, because there is usualy a tendency to develop fine structures on the distribution function during the phase space evlution, which requires extension of Hermite expansion to achieve good stability and accuracy of the computation. In other case, the nonphysical information is generated at the boundary of the truncated matrix, which keeps spreading inside the matrix and damage the computational run. Various techniques have been developed to slow down the propagation of this kind of numerical error and prolong the evolution time accessible by the computation. As example let us mention the case when a proper collision term is added on the right hand side of the Vlasov equation, e.g. [3], or when a spectral filter is applied before each time step for the Hermite spectrum [4]. Good results were achieved by employing the Fokker-Planck electron-ion collision term, where the collisions are added to the model in the natural way and therefore no non-physical entropy growth is experienced. Moreover, other advantage of this method is its suitability for the use on modern parallel computer facilities. Resulting set of the first order differential equation forms tridiagonal matrix, which significantly reduces communication demands when the set is solved on more processors.

The goal of this contribution is to present our implementation of the Fourier-Hermite transform method and to study numerical stabilization by using above mentioned techniques on the simple 1D Vlasov-Poisson system. This approach is then succesfuly employed for the Vlasov-Maxwell system and used for the study of the laser intensity dependence of the reflectivity of the stimulated Raman scattering in the fusion relevant plasmas, whose results are also presented.

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Synthetic diagnostic of Doppler Back-Scattering mesurements on the Tore Supra Plasma #TS45511 with a dedicated GYSELA non-linear gyrokinetic simulation

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The GYSELA non-linear gyrokinetic simulation #TS45511 has been dedicated to the study of the Tore Supra shot #TS45511, with simulation parameters chosen as close as possible to the experimental background profiles and heating sources. Recently, the radial "$\mathbf{E} \times \mathbf{B}$ staircase" structure of fluctuations has been shown in good agreement between the GYSELA simulation and experimental results obtained by means of Fast-Sweeping Reflectometry [1]. We present here a complementary study of the same Tore Supra plasma, where a synthetic diagnostic of Doppler Back-Scattering (DBS) is applied onto the numerical plasma resolved with GYSELA. DBS technique allows to access to the electron density fluctuations spectrum along the binormal wave vector, as well as to the associated velocity of fluctuations and its time evolution [2, 3].

The synthetic diagnostic used here has been validated for edge plasma turbulence studies, with the fluid code TOKAM [4]. The first results with the GYSELA datas will be presented, giving the first comparisons between turbulent spectra and binormal velocities of the fluctuations in the core plasma of Tore Supra. The time evolution of these velocities should allow to complete previous studies and characterizations of Geodesic Acoustic Modes in the Tore Supra #TS45511 plasma [5]. Finally, the degree of poloidal anisotropy of the perpendicular velocity will be discussed.

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Predator Prey Dynamics in Magnetized Fusion Plasmas

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Predator-Prey systems are a useful fundamental paradigm for the study of various dynamical systems [1, 2]. More specifically, such models have been shown very relevant for the study of turbulence in magnetized plasmas [3]. In such plasmas, the competition between micro-turbulence at small scales and large scale flows, *ie* Zonal Flows, lead to a predator-prey behavior, where the Zonal Flows developping only non-linearly act as a predator for the micro-scale turbulence. Predator-Prey oscillations have been observed on various machines [4].

We will present here how Predator-Prey oscillations can be recovered in a large variety of magnetized plasmas and reveal to be a common paradigm in magnetized plasma turbulence. A simple Lotka-Volterra [1, 2] model will be shown to reproduce well experimental measurements as well as gyrokinetic simulations [5]. Such simple model will also be shown, when coupled to a transport model, to reproduce interestingly the L-H transition in Tokamaks [7, 6]. Finally, recent observations of Predator-Prey interactions in the ToriX machine at LPP will be presented.

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Broadband Simulation of VLF chorus generation by the method of Kinetic Phase Point Trajectories

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We employ a methodology for the simulation of collision free plasma termed *Vlasov Hybrid Simulation (VHS)* [1],[2], also referred to as the *Kinetic Phase Point Trajectory Method* [3],[4]. Within the simulation phase space box, simulation particle trajectories are followed forwards continuously in time. From Liouville's theorem distribution function F will be known (the initial value Fo) at the phase points occupied by the particles. At each time step F is ***interpolated*** from the particles onto a phase space grid, from which integration over velocity space readily furnishes the plasma charge/current field, enabling the wavefield to be updated and particle trajectories to be advanced. Particles may be added or removed from the phase fluid at will, and in particular inserted at the boundary if phase fluid flows into the simulation box. Simulation particles only carry the information F, and are not associated with any phase volume.

The method is very straightforward ,easy to program, robust against filamentation, gives good resolution of distribution function and does not diffuse F. Boundary conditions on F are easily applied. The interpolation operation is realised with a simple bilinear finite element scheme, and very much relies on the fact that particles DO NOT bunch in phase space and density of simulation particles in phase space remains constant.

The main application here is a 1 3/2D EM code to simulate the generation of VLF chorus and triggered VLF emissions. This is due to the non linear interaction between VLF waves with k//B and cyclotron resonant electrons in the parabolic field inhomogeneity in the equatorial region. Dynamics is characterised by phase trapping of electrons such that they remain in resonance with the wavefield for long distances ~6000kms. which makes VHS particularly appropriate as trajectories are followed right through the phase box. The phase box is confined in dimension Vz to a region about local cyclotron resonance. The new broadband VHS code has simulated successive chorus elements, rising and falling tones as well as hooks, and also resonant sideband generation. A demonstrator 1D VHS code for beam excitation of electrostatic waves has also been developed which is both fast and efficient. Results convincingly demonstrate excellent distribution function resolution.

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Full particle orbit effects in integrable and chaotic magnetic fields

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We numerically study on full orbits of a charged particle motions [1] in the cylindrical magnetic field without any kinds of reduction such as guiding center or gyro-kinetic ones. The back ground field consists of non-zero static magnetic field with periodic boundary condition and null electric field. The magnetic field is given by a vector potential $\boldsymbol{A} = \boldsymbol{A}_0(r) + \epsilon \boldsymbol{A}_1(r, \theta, z)$, where

$$\boldsymbol{A}_0(r) = -\frac{B_0 r}{2}\boldsymbol{e}_\theta - F(r)\boldsymbol{e}_z, \quad \boldsymbol{A}_1(r,\theta,z) = \sum_{m,n} \hat{A}_1^{mn}(r)\cos\left(m\theta - nz/R_{\mathrm{per}}\right)\boldsymbol{e}_z,$$

and where (r, θ, z) is cylindrical coordinates, B_0 strength of magnetic field, ϵ a small parameter, and $\boldsymbol{e}_i$ a base unit vector for $i = r, \theta, z$. The function $F(r)$ is determined by the safety factor $q(r)$ as $F(r) = B_0 \int^r \frac{r'}{q(r')}\mathrm{d}r'$.

We firstly look into the chaotic motion of a particle in the integrable field with one mode perturbation. For some q-profile and initial conditions, we numerically examine non-existence of the third integral of motion even though the magnetic field line is integrable. This fact indicates that there is no global invariant associated with a magnetic momentum, which is assumed in a global gyro-kinetic reduction.

By adding the perturbation with several modes to the magnetic field, the field line becomes chaotic. By tuning q-profile and ϵ, we find the internal transport barriers (ITB) foliated by the regular tori [3]. We then look at the charged particle motion in a chaotic magnetic field line, and compare it with the magnetic field line profile, to answer a problem: Do magnetic ITBs act as barriers for the particles? We check the topology of trajectory for a particle with several initial conditions determined by the kinetic energy and initial pitch angle between velocity and magnetic field. We find that the high energy or large pitch angle creates transport barrier for the particles, even though the magnetic ITB does not exist. On the one side, we also find that it is possible that the particle with small pitch angle and with some ranges of kinetic energy destroys the magnetic ITB. This ITB works as a filter to confine the particles rather than the barrier.

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Hamiltonian fluid reduction of the drift-kinetic equation

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Solving kinetic equations used in plasma physics is a challenging task due to the high complexity of both their analysis and computation. Here we investigate fluid models derived from kinetic equations. These models have a lower numerical cost and are usually more tangible than their kinetic counterpart as they describe the time evolution of physical quantities such as density, fluid velocity, pressure, etc. However, all the fluid moments are dynamically coupled such that there is a need for a closure of the resulting infinite hierarchy of fluid equations, which can be based on various physical assumptions.

Here, we present a strategy for building fluid models from kinetic equations while preserving their Hamiltonian structure. This ensures that the reduction does not introduce any non-physical dissipation. Starting with the drift-kinetic equation, we derive a fluid model for the first three moments of the distribution function (density, fluid velocity and pressure). We show that the associated closure is equivalent to the one given by the water-bag distribution. We discuss the associated conserved quantities, which can be used to check the validity of numerical simulations, and establish a link with those of the parent drift-kinetic equation.

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Coherent structures in continuously RF-excited trapped plasmas

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Magnetized non-neutral plasmas are a well-known example of collective system where the diocotron (Kelvin-Helmholtz) instability dominates the dynamics of the flow, giving rise to a turbulent evolution and formation of coherent structures. The typical example is a single-species (electron) plasma confined in a Penning-Malmberg trap.

With respect to the studies usually performed on this kind of system, the electron plasma may have a substantial degree of neutralization when it is generated by means of a radio-frequency (RF) drive leading to residual-gas ionization [1, 2], and is subject to a destabilization mechanism known as ion instability [3, 4]. The dynamics is inherently non-linear due to the interplay of several factors taking place over an extended time span, i.e. continuous RF excitation, collisions, ion and electron production and loss. The evolution may be characterized by the formation of coherent structures and non-axisymmetric final states that show unexpected robustness properties against common sources of instability [5, 6].

Experimental results are presented and compared to simulations performed with a two-dimensional Particle-In-Cell code [7] showing the influence of a confined ion fraction on the accretion of long-lived vortices, a phenomenon that turns out to be enhanced when a balance of the confined particle number is assumed on the basis of continuous particle replenishment due to the RF excitation [8].

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Pressure-tensor description for Weibel type instabilities

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Weibel-type instabilities [1], [2] are a well-known family of instabilities in plasma physics. They are involved in many problems [3] : (un-)magnetised plasmas, (non-)relativistic ones. They appear in the laser-plasma interaction context (fast ignition scenario in inertial fusion, secondary instabilities following the growth of the Raman instability), and in astrophysics (relativistic jets, supernovae, magnetosphere). These instabilities are velocity space anisotropy driven and generate long-lasting magnetic fields. Then, they are good candidates to explain the origin of the cosmological magnetic field.

The initial anisotropy can be related to temperature [1], a quite common situation in weakly collisional and/or magnetised plasmas. In this case, we speak about « pure Weibel instability » in the non-magnetised case, and about Whistler instability in the magnetised one. The anisotropy can also be due to counter-streaming beams (current filamentation instability or streaming-Weibel instability) as shown by Fried [2]. A complete description of these phenomena requires the use of the kinetic theory. However, Fried's interpretation of the Weibel instability in terms of counter-streaming beams implicitly suggests that, maybe, it is possible to provide a fluid interpretation to some aspects of the Weibel-like instabilities. Basu [4] was the first to use the pressure tensor in order to recover the strong anisotropy limit of the kinetic pure Weibel instability dispersion relation.

We extend Basu's analysis to a system of counter-streaming beams by discussing the potentiality the model has to describe the linear coupling between Weibel instability and CFI and the qualitative role played by symmetry and pressure effects in the coupling between transverse (i.e. "electromagnetic") and longitudinal (i.e. "electrostatic") features of these linear modes. The importance of the heat flux tensor is also discussed.

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Effects of density holes in the excitation of Langmuir waves via bump-on-tail instability in space plasmas

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Space plasmas are the archetype of collisonless plasmas where high velocity electron beams (due to e.g. eruptions in the solar corona or propagating shock waves) can drive various plasma instabilities.

In situ observations of electrostatic waves (in particular Langmuir waves) in the interplanetary medium are puzzling and rise several questions with particular emphasis on the role played by density perturbations and large density holes in the development of plasma instabilities. To test the role of such density holes on the development of the bump-on-tail instability, we have performed 1D-1V and 2D-2V Vlasov simulations (in the electrostatic limit). We show how the presence of a density hole can serve as a seed for the instability, and thus control the location of Langmuir wavepackets.

The relationship between the wave amplitude and the characteristics of the density hole is also described, showing how the electron beam may select specific holes to generate enhanced Langmuir wavepackets.

A Vlasov model for wave scattering

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Ion acoustic wave scatterimg experiments in the past have utilized field probes and have been analyzed assuming that there is a single, frequency dependent, reflection coefficient. We start from a Vlasov description, and describe reflection in terms of the CVK spectrum. We utilize the appropriate Morrison transform [1] for ion waves with the electron density described by a Boltzmann factor and with the assumption of quasineutrality. With these approximations, there is no need to use a Fourier transform either in space or time before applying the Morrison transform.

In the transform domain, an ion acoustic wave is observed to be a packet of CVK amplitudes g(u) narrowly centered on the ion acoustic speed $u \sim C_s$. The variety of results for ion acoustic scattering may be caused by the fact that one is scattering an entire spectrum g(u) -> g'(u) rather than a single mode at each frequency.

Experiments are performed in a magnitized and singly-ionized Argon gas discharge. Ion acoustic waves are excited at frequencies below the ion cyclotron frequency where wave behavior tends to be 1-dimensional parallel to the magnetic field of 1kG. The ion distribution function parallel to the magnetic field is measured using laser-induced fluorescence on Argon ion metastable states. The fluorescence light is collected using movable periscopes and photons are counted with a dwell-time of 1 microsecond. A Morrison transform is applied to the data by means of a digital implementation of a Hilbert transform [2]. The plasma density is low enough (10^9 cm^{-3}) so that the plasma is weakly collisional. Preliminary results will be presented.

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Electromagnetic reduced fluid models for collisionless plasmas with pressure anisotropies

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In this contribution we present the derivation of two reduced fluid models for collisionless plasmas accounting for pressure anisotropies as well as magnetic perturbations both parallel and perpendicular to the direction of a strong mean field. The models are derived starting from a simplified version of the gyrokinetic equations adopted in Ref. [1] and then considering two asymptotic limits of the resulting gyrofluid equations. The first model assumes cold ions, negligible electron inertia, and is valid for scales much larger than the electron Larmor radius. When expressed in terms of particle moments it provides a generalization of Hall reduced magnetohydrodynamics [2] accounting also for anisotropic electron pressure dynamics. The second model also neglects electron inertia as well as finite electron Larmor radius effects but does not assume cold ions and is valid for length scales intermediate between the electron and ion Larmor radius. In terms of particle fluid moments this model provides a way to extend, beyond the isothermal closure, the two-field model adopted in Ref. [3] to investigate kinetic Alfvén wave turbulence. Energy conservation laws of the two models will be discussed. An alternative derivation of the models, which considers a two-fluid model [4] as starting point, will also be presented and strategies for closure relations will be suggested.

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Study of Chirp Driven Vlasov-Poisson Systems

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The understanding the dynamics of collision-less plasma is the subject of extensive fundamental research. It has wide range of applications - for example, from interplanetary environments to laboratory plasma systems. Kinetic effects such as wave-particle resonant interactions, provide efficient mechanisms that transfer energy from fluctuations to the plasma (and vice versa), which can lead to damping effects, instabilities, nonlinear particle trapping and several interesting nonlinear coherent structures. Such structures may form as a final state of a initial value problem [1, 2] or as a consequence of an external drive in a bounded plasmas [3].

In the present work, using 1D model, we consider an unbounded 1D Vlasov-Poisson Plasma driven by an external electric field for a range of amplitudes, frequencies and wave-numbers. It is found that, in an unbounded plasma modelled using periodic boundary conditions, for values of external drive amplitude much smaller than or comparable to the linear limit, surprisingly large amplitude coherent structures in phase space are seen provided, the drive frequency is chirped[4]. A rich variety of steady state coherent solutions are obtained numerically for a range of drive parameter conditions. This and other details will be presented.

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Hybrid kinetic-MHD models

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Many physical contexts involve the interplay of different phenomena at different scales. The corresponding description requires the use of multi-physics models, whose mathematical formulation poses several challenges. In plasma physics, the interaction of energetic particles (obeying kinetic theory) with a fluid bulk (obeying magnetohydrodynamics) requires formulating hybrid kinetic-MHD models, which are often obtained by making assumptions on the equations of motion [2]. As a consequence, fundamental properties such as energy balance may be lost in the approximation [6]. The use of Hamiltonian/Lagrangian symmetry techniques is shown here [3, 4] to provide a unifying framework for coupling nonlinear kinetic and fluid theories in a consistent way, thereby leading to new hybrid plasma models. Special emphasis is given to the linear stability of Alfvén waves, for which it is shown that a spurious instability appears in previous hybrid models. This instability is removed in the new equations of motion. The case of gyro-averaged kinetics is also discussed [5], along with the role of a correction term in the magnetization current [1].

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Tuesday, May 31st 2016

F. Pegoraro 9:00 – 9:30
S. Cowley 9:30 – 10:00
D. Del Sarto 10:00 – 10:20
COFFEE BREAK 10:20 – 10:50
P. Morrison 10:50 – 11:20
M Strumik 11:20 – 11:40
L. Friedland 11:40 – 12:10
LUNCH 12:10 – 15:00
A. Schekochihin 15:00 – 15:30
B. Dorland 15:30 – 16:00
R. Fedele 16:00 – 16:20
COFFEE BREAK 16:20 – 16:50
T. Carter 16:50 – 17:20
O. Pezzi 17:20 – 17:40
F. Pucci 17:40 – 18:00
J. Hurst 18:00 – 18:20
DINNER 20:00

A subject of renewed appeal

F. Pegoraro

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The recent announcement of the detection of a gravitational wave event, and the debate that followed on whether or not it was, or should have been, accompanied by an electromagnetic signal, is likely to bring renewed interest to the field of the interaction of an electromagnetic plasma with a time varying gravitational field.

Such an interaction can take place in the superstrong field of a system of compact gravitational objects surrounded by a relativistic plasma: for this case there is ample recent literature, mostly within a general relativistic magnetohydrodynamic theory. It can also take place in the field of a gravitational wave, for which there is a string of papers dating back [1]at least from the ` 70s. These papers are mainly aimed at studying the conversion of gravitational waves into electromagnetic or longitudinal plasma waves from the point of view of the gravitational waves damping and/or detection, or even possibly of their generation under laboratory conditions. On the contrary, in the astrophysical community interest has been focussed mainly on discrete processes, such as photon-graviton conversion and viceversa, more than on collective processes in plasmas.

There is an enormous imbalance in strength between electromagnetic and gravitational interactions. Thus it would appear natural to think that, if the huge objects that are supposed to be involved in the collapse that generated the gravitational waves are in contact with, or through their ultrastrong fields can interact with, an electromagnetic medium a fraction of the energy released must take the form of electromagnetic energy. A possible conversion mechanism can be identified by observing that, while the gravitational fields per se tend to make all matter move (free fall) along the geodesics of the deformed space geometry independently of matter being charged or not, they can induce charge and current separation in the presence of electromagnetic fields.

The focus within the present meeting will be on the possible effects of oscillatory gravitational fields on a Vlasov plasma. In my talk I will present a somewhat schematic review of the literature on this subject (mostly linear theory in the search for resonances plus parametric conversion) and will try to discuss possible regimes of physical interest and identify effects where the gravitational-electromagnetic coupling in a plasma may play an observationally significant role. A goal of this rather exploratory presentation is to see whether the tools that have been recently developed in the context of purely electromagnetic plasmas can be put to use in order to study kinetic plasma phenomena induced by fast oscillating, strong gravitational fields such as those that can be expected to occur not too far from the source of the recent gravitational wave event.

[1] Earlier in the ` 60s in the context of the direct interaction between gravitational and electromagnetic fields not including the plasma contribution.

When is a plasma a fluid?

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The Chapman-Enskog procedure for obtaining the fluid (Braginsky) equations for a plasma has a long history. It is usually supposed that this procedure is valid when the mean free path, λ_{mfp}, is small compared to the typical scale length over which the plasma varies, L. In fact $\epsilon = \lambda_{mfp}/L \ll 1$ is *not* the correct criteria. The Chapman-Enskog distribution function can be unstable to small collisionless scale modes which invalidate the calculation of the transport coefficients. For example Weibel instabilities will be excited in unmagnetised plasmas when $1 \gg \epsilon^{3/2} \gg \delta = c/(\omega_p L)$. Magnetised plasmas have similar criteria for the excitation of firehose and mirror instabilities.[1] Plasmas in these regimes with small scale instabilities are expected to be common in astrophysics – for example in galaxy clusters $\epsilon \sim 0.1 - 0.01$ and $\delta \sim 10^{-12}$. I will discuss how we treat such regimes and the prospects for macroscopic fluid equations with transport terms that capture the effects of the small scale turbulence.

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Anisotropy in fluid models with full pressure tensor dynamics

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Information about the details of the distribution function marks the difference between kinetic and fluid models. In general, the closure condition on the highest moment of the Vlasov equation that is retained in the fluid description, fixes the quantity of details of the distribution function that survive in the fluid modeling. With a typical polytropic-type closure only the width of the distribution function is known (corresponding to an isotropic pressure or "temperature"), besides its integral over the velocity coordinate (fluid density) and its "barycenter" in the velocity space (fluid velocity). Instead, when a full pressure tensor evolution replaces polytropic-type closures, information about the quadrupole moment of the distribution function is retained in a fluid model, too [1,2]. Here we discuss some features and consequences of this "extended fluid/reduced kinetic" modeling, which, besides making it possible to study some kinetic phenomena numerically at a reduced computational cost, allows us to identify some processes whose physical interpretation may appear less evident within a kinetic analysis. An example is provided by a mechanism that generates both non-gyrotropic and gyrotropic anisotropy induced by a sheared, fluid velocity field [2]. Another example is offered by the relationship between finite temperature effects and the coupling of longitudinal (i.e. electrostatic) and transverse (i.e. electromagnetic) features in the current filamentation instability [3].

Here we discuss the results presented in some recent works that are related: to the normal modes that propagate perpendicularly to a background magnetic field in a plasma with mass-less, cold electrons and anisotropic ions [1]; to the generation of pressure agyrotropy from a sheared velocity field [2]; to the existence of anisotropic fluid equilibria in presence of sheared velocity fields [4]; and to the possibility to describe Weibel-type instabilities by considering fluid anisotropic electrons in a non-evolving ion background [3].

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The Vlasov-Poisson Inverse Problem

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Given temporal behavior of the electric field, I will use the tools developed in [1, 2] to address the question of what one can say about the set of initial distribution functions that produces such behavior in the Vlasov-Poisson system.

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Physical mechanisms of regulation of pressure anisotropy in collisionless turbulent plasmas within MHD-CGL regime

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Dynamics of weakly collisional plasmas may lead to thermal pressure anisotropies that are driven by velocity shear, plasma expansion/compression or temperature gradients. The pressure anisotropies can provide free energy for the growth of micro-scale instabilities, like the mirror or firehose instabilities, that are commonly believed to constrain the pressure anisotropy if appropriate thresholds are exceeded. We discuss an alternative mechanism of regulation of the pressure anisotropy that works in the absence of micro-scale fluctuations produced by the instabilities. The mechanism is particularly relevant for turbulent collisionless plasmas, where velocity fluctuations naturally produce pressure anisotropies and for sufficiently large level of anisotropy further evolution of velocity fluctuations becomes strongly constrained by forces related to anisotropic stress tensor. Using the MHD-CGL (also known as double-adiabatic) approximation we demonstrate that in high-β regime the pressure anisotropy constraints scale like $|p_\perp/p_\parallel - 1| \propto \beta^{-1}$ as implied by state equations and momentum/energy transport in the system. We present results of three-dimensional numerical simulations that illustrate the analytical results. Possible role of pressure balance and magnetic relaxation processes is also discussed in the context of pressure anisotropy distribution measured by Wind spacecraft in turbulent solar wind. We demonstrate connections between constraints on the pressure anisotropy and amplification of the magnetic field by small-scale dynamo process in turbulent collisionless plasmas.

Adiabatic resonance dynamics in phase space

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The dynamics of passage and capture into resonance of a distribution of particles in phase space driven by a chirped frequency perturbation is discussed. The resonant capture in this case involves crossing of separatrix by individual particles and, therefore, the adiabatic theorem cannot be used in studying this problem no matter how slow is the variation of the driving frequency. It will be shown that if instead of analyzing complicated single particle dynamics in passage through resonance, one considers the slow evolution of a whole distribution of initial conditions in phase space, the adiabaticity and phase space incompressibility arguments yield a solution to the resonant capture probability problem. We will illustrate this approach in the case of an ensemble of charged particles driven by a chirped frequency wave passing through the Cherenkov resonances with the velocity distribution of the particles.

Suppression of phase mixing in drift-kinetic plasma turbulence

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W. Dorland[2], A. Kanekar[2] and G. W. Hammett[3]

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Transfer of free energy from large to small velocity-space scales by phase mixing leads to Landau damping in a linear plasma. In a turbulent drift-kinetic plasma, this transfer is statistically nearly canceled by an inverse transfer from small to large velocity-space scales due to “anti-phase-mixing” modes excited by a stochastic form of plasma echo. Fluid moments (density, velocity, temperature) are thus approximately energetically isolated from the higher moments of the distribution function, so phase mixing is ineffective as a dissipation mechanism when the plasma collisionality is small. In this talk, I will outline a scaling theory of drift-kinetic plasma turbulence in a 4D phase space [1] and show numerical evidence that lends some support to its conclusions, as summarised above [2].

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Echoes in collisionless plasma turbulence

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In a collisionless, magnetized plasma, particles can stream quickly along magnetic-field lines, leading to phase mixing of their distribution function and consequently to strong damping of any density perturbations. This is known as Landau damping, and in appropriate regimes, also as Barnes damping. It is one of the most fundamental physical phenomena that make plasma different from a conventional fluid. Nevertheless, broad power-law spectra of density fluctuations are found in many astrophysical plasmas, most vividly in the solar wind. Elsewhere in Nature, such spectra are normally associated with fluid turbulence, where energy cannot be dissipated in the inertial scale range and is therefore cascaded from large scales to small.

It is shown here, by means of drift-kinetic direct numerical simulations, that the density cascade in a collisionless plasma is undamped because the phase mixing that in a linear system would give rise to Landau damping is strongly suppressed on average by the stochastic plasma echo effect, arising due to nonlinear advection of the particle distribution by the turbulent motions of the plasma and giving rise to "anti-phase-mixing" that compensates for the phase mixing in the inertial range. Besides resolving the long-standing (if perhaps not always fully appreciated) puzzle of the density fluctuations in the solar wind, these results suggest a fundamental conceptual shift for understanding kinetic plasma turbulence generally: rather than being a system where Landau damping plays the role of dissipation, a collisionless plasma is essentially dissipation-less except at very small scales.

Self-consistent plasma wake field dynamics of a charged-particle beam: Vlasov versus quantum-like approaches

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The self-consistent evolution of a relativistic charged-particle beam while interacting with a plasma is presented in both classical and quantum-like domains. This is done by taking into account the plasma wake field mechanism driven by a long beam in a magnetized plasma. A comparison between the virial description provided by the Vlasov-Poisson-type system of equations and the one provided by the Schrödinger-Poisson-type system of equations is carried out.

Observation of an Alfvén wave parametric instability in a laboratory plasma

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The LArge Plasma Device (LAPD) at UCLA is a 17 m long, 60 cm diameter magnetized plasma column with typical plasma parameters $n_e \sim 1 \times 10^{12}\mathrm{cm}^{-3}$, $T_e \sim 5\mathrm{eV}$, and $B \sim 1\mathrm{kG}$. Studies of the nonlinear properties of Alfvén waves have been performed using LAPD; in these experiments, two launched Alfvén waves nonlinearly interact to drive: a nonresonant mode [1], a drift wave [2], an acoustic mode [3, 4], or an Alfvén wave [5]. In new experiments, a shear Alfvén wave parametric instability is observed for the first time in the laboratory [6]. When a single finite ω/Ω_i kinetic Alfvén wave (KAW) is launched in the Large Plasma Device above a threshold amplitude, three daughter modes are produced. These daughter modes have frequencies and parallel wave numbers that are consistent with co-propagating KAW sidebands and a low frequency nonresonant mode. The observed process is parametric in nature, with the frequency of the daughter modes varying as a function of pump wave amplitude. The daughter modes are spatially localized on a gradient of the pump wave magnetic field amplitude in the plane perpendicular to the background field, suggesting that perpendicular nonlinear forces (and therefore $k_\perp$ of the pump wave) play an important role in the instability process. Despite this, modulational instability theory with $k_\perp$ = 0 has several features in common with the observed nonresonant mode and Alfvén wave sidebands.

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Collisions of two Alfvénic wave packets: beyond the Moffatt-Parker problem

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The problem of two colliding and counter-propagating Alfvénic wave packets has been investigated in detail since the late Seventies. In particular Moffatt [1] and Parker [2] showed that, in the framework of the incompressible magnetohydrodynamics (MHD), nonlinear interactions can develop only during the overlapping of the two packets.

Here we describe a similar problem in the framework of the kinetic physics. The collision of two quasi-Alfvénic packets has been analyzed by means of MHD, Hall-MHD and kinetic simulations performed with two different hybrid codes: a PIC code [3] and a Vlasov-Maxwell code [4]. Due to the huge computational cost, only a 2D-3V phase space is allowed (two dimensions in the physical space, three dimensions in the velocity space).

Preliminary results suggest that, as well as in the MHD case, the most relevant nonlinear effects occur during the overlapping of the two packets. For both the PIC and Vlasov cases, strong temperature anisotropies are present during the evolution of the wave packets. Moreover, due to the absence of numerical noise, Vlasov simulations show that the collision of the counter-propagating solitary waves produces a significant beam in the velocity distribution functions [5], which, instead, cannot be appreciated in PIC simulations.

We remark that, beyond the interest of studying a well-known MHD problem in the realm of the kinetic physics, our results allows also to compare different numerical codes.

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From Alfvén waves to kinetic Alfvén waves in an inhomogeneous equilibrium structure.

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One view of the solar wind turbulence is that the observed highly anisotropic fluctuations at spatial scales near the proton inertial length may be considered as kinetic Alfvén waves (KAWs). In the present work, we study a model where an initial Alfvén wave propagates inside an equilibrium structure which is inhomogeneous in the direction perpendicular to the equilibrium magnetic field. We employ numerical simulations, using both a Hall-magnetohydrodynamic (HMHD) and a Hybrid Vlasov-Maxwell (HVM) model for linear and non linear pertubation, respectively. Linear HMHD results show that in all the considered cases the time evolution leads to the formation of kinetic Alfvén waves within the inhomogeneity regions, which are identified by a comparison with analytical linear theory results [1]. Non linear HVM results show the generation of temperature anisotropy with respect to the local magnetic field and the production of field-aligned proton beams. The regions where the proton-distribution function highly departs from thermal equilibrium are located inside the shear layers, where the KAWs are excited [2]. These results could be relevant both in the solar corona and in large-scale structures of the solar wind, where Alfvénic fluctuations are present along with large-scale inhomogeneities.

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Vlasov equation with spin effects

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The coupling between the electronic dynamics and the spin degrees of freedom in nanometric objects has stimulated a great deal of interest, both theoretical and experimental, over the last few decades. In this work, we derive a four-component Vlasov equation for a system composed of spin-1/2 fermions (typically electrons) [1]. The orbital part of the motion is classical, whereas the spin degrees of freedom are treated in a completely quantum-mechanical way. The Zeeman and spin-orbit interactions are included in an self-consistent way.

The Vlasov equations for the four-component distribution functions $f_0(\boldsymbol{r}, \boldsymbol{v}, t)$ and $f_i(\boldsymbol{r}, \boldsymbol{v}, t)$, where $i = x, y, z$, read as follows:

$$\frac{\partial f_0}{\partial t} + \boldsymbol{v} \cdot \nabla f_0 - \frac{e}{m} (\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}) \cdot \nabla_{\boldsymbol{v}} f_0 + \frac{\mu_B}{2mc^2} (\boldsymbol{E} \times \nabla)_i f_i - \frac{\mu_B}{m} \nabla \left[B_i - \frac{1}{2c^2} (\boldsymbol{v} \times \boldsymbol{E})_i \right] \cdot \nabla_{\boldsymbol{v}} f_i$$
$$- \frac{\mu_B e}{2m^2c^2} [\boldsymbol{E} \times (\boldsymbol{B} \times \nabla_{\boldsymbol{v}})]_i f_i = 0, \tag{1}$$
$$\frac{\partial f_i}{\partial t} + \boldsymbol{v} \cdot \nabla f_i - \frac{e}{m} (\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}) \cdot \nabla_{\boldsymbol{v}} f_i + \frac{\mu_B}{2mc^2} (\boldsymbol{E} \times \nabla)_i f_0 - \frac{\mu_B}{m} \nabla \left[B_i - \frac{1}{2c^2} (\boldsymbol{v} \times \boldsymbol{E})_i \right] \cdot \nabla_{\boldsymbol{v}} f_0$$
$$- \frac{\mu_B e}{2m^2c^2} [\boldsymbol{E} \times (\boldsymbol{B} \times \nabla_{\boldsymbol{v}})]_i f_0 - \frac{2\mu_B}{\hbar} \left\{ \left[\boldsymbol{B} - \frac{1}{2c^2} (\boldsymbol{v} \times \boldsymbol{E}) \right] \times \boldsymbol{f} \right\}_i = 0. \tag{2}$$

The component f_0 is related to the density of particles in the phase space and f_i is related to the density of magnetization along the i axis. In other words, f_0 represents the probability to find an electron at one point of the phase space at a given time, while f_i represents the probability to have a spin-polarization probability in the direction i for this electron. The electric and magnetic fields are either internal, i.e. generated by the particles themselves, or external (for instance, an electromagnetic pulse).

We apply this model to ferromagnetic films (particularly nickel) to study the nonlinear dynamics of charges and spins after a short (femtosecond) laser pulse excitation. The distinction is made between itinerant magnetism (carried by the electronic spins) and localized magnetism (carried by the fixed ions). The former is described by the above four-component Vlasov equations (1)-(2), whereas the latter obeys a Landau-Lifshitz equation for the ion magnetization. Both types of magnetization carriers interact with each other through the exchange interaction.

In this work, we focus on the influence of the film surfaces on the magnetic properties of the system. After the initial laser pulse, both charge and spin currents are excited in the film. However, the charge currents are quickly damped away by Landau damping. In contrast, the spin currents persist in the ferromagnetic film for much longer times.

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Wednesday, June 1st 2016

P. Henri 9:00 – 9:30
T. Passot 9:30 – 10:00
S. Cerri 10:00 – 10:20
COFFEE BREAK 10:20 – 10:50
F. Rincon 10:50 – 11:20
M. Kunz 11:20 – 11:40
N. Loureiro 11:40– 12:10
LUNCH 12:10 – 15:00
B. Eliasson 15:00 - 15:30
E. Sonnendrucker 15:30 - 16:00
COFFEE BREAK 16:00 – 16:30
POSTER SESSION 2 16:30 – 18:30
DINNER 20:00

The plasma environment of a comet, witnessed by the ESA's Rosetta space mission

P. Henri[1], on behalf of the Rosetta Plasma Consortium

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Launched in 2004, the ESA's Rosetta spacecraft [1] reached its target comet, 67P/Churyumov-Gerasimenko, in summer 2014, while it was still at more than 3 A.U. from the Sun. From then, Rosetta surveyed the cometary surface and its close environment (gas, dust and plasma) at distances ranging from 10 to 1500 km from the comet nucleus. In summer 2015, a year after Rosetta's arrival, Churyumov-Gerasimenko reached its perihelion, at 1.2 AU from the Sun, and the maximum of the cometary activity has been observed. Its distance to the Sun has increased since then, until the end of mission planned in September 2016.

Since Rosetta's arrival, the different plasma sensors of the Rosetta Plasma Consortium [2] has been continuously monitoring the close plasma environment of comet Churyumov-Gerasimenko: its structure, evolution and dynamics, as well as its varying interaction with the solar wind. A key aspect of the Rosetta mission is that the spacecraft has been following comet Churyumov-Gerasimenko during its journey from large to close distances from the Sun, so that Rosetta has witnessed large variations in the comet outgassing. This has enabled to observe a variety of different plasma conditions: from the collisionless to the (plasma-neutral) collisional regimes.

The ionisation of the expanding cometary atmosphere first builds up an ionosphere embedded in the solar wind [3]. The mass loading of the solar wind [4] is at the origin of solar wind-comet interaction [5], through the formation of an induced magnetosphere [6], the deflection of the solar wind and the picking-up of new-born cometary ions [7]. As the comet gets closer to the Sun, the surrounding neutral density increases and the plasma eventually becomes collisional through gas-plasma interactions, until the solar wind magnetic field is expelled to form a diamagnetic cavity around the comet [8].

After a summary of the key aspects of the Rosetta mission and an introduction on the cometary plasma and its interaction with the solar wind, I will review our current understanding of the plasma environment around comet Churyumov-Gerasimenko through the results obtained so far by the Rosetta Plasma Consortium (RPC), by combining the in situ observations obtained from the different RPC sensors.

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Sub-ion-scale magnetic spectra in kinetic Alfvén wave turbulence: phenomenology and FLR-Landau fluid simulations

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A phenomenological model for the perpendicular magnetic spectrum of Kinetic Alfvén waves (KAWs) in the Solar Wind is presented [1], that extends previous analyses [2, 3]. The main result concerns the non-universal character of the so-called dissipation range spectrum, where the power law index appears to depend on the critical balance parameter measuring the ratio of the nonlinear to the linear wave propagation characteristic time scales. For plasma beta of order unity and equal ion and electron temperatures, the model predicts a range of spectral exponents consistent with solar wind and magnetosphere observations [4]. Landau damping plays a crucial role, not only in providing an exponential decay of the spectrum at the electron scale, but also in allowing for a modification of the spectral exponent. The above predictions are succesfully tested with direct numerical simulations of the FLR-Landau fluid model [5, 6] where two parameters are varied: the propagation direction and the amplitude of the randomly driven KAWs, thus permitting to control the nonlinearity parameter. The influence of the beta parameter is also briefly described.

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Forced hybrid-kinetic turbulence in 2D3V

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A frontier problem in plasma physics and among the hot topics in space plasma research, is the understanding of the kinetic processes at play in plasma turbulence. In this context, the solar wind (SW) plasma is mostly found in a turbulent state [1], thus representing an ideal natural laboratory for the study of collisionless plasma dynamics. Here we investigate the properties of turbulence from the end of the magnetohydrodynamic (MHD) casdade to scales well below the ion gyroradius (i.e., the so-called "dissipation" or "dispersion" range) by means of unprecedented high-resolution simulations of forced hybrid-kinetic turbulence in a 2D3V phase-space (two real-space and three velocity-space dimensions). Different values of the plasma beta parameter typical of the SW are investigated. Several properties of turbulence at small-scales emerging from the simulations are analyzed: these include spectral features, turbulent reconnection (and the formation of coherent structures), and temperature anisotropy generation. Even within the limitations of the hybrid approach in 2D3V, a reasonable agreement with SW observations [2, 3, 4] and with theory [6, 7, 8] is found. An analysis on the type of turbulent fluctuations at small scales [9] is provided and the effect of the drive is discussed. Finally, we draw possible implications and questions related to SW turbulence which arise from this study.

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Turbulent dynamo in a collisionless plasma

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While magnetic field amplification in magnetohydrodynamic fluids has been thoroughly studied over the last fourty years, the dynamo effect in weakly collisional plasmas has comparatively received little attention, in spite of its potential relevance for high energy astrophysics and cosmology. Fully kinetic numerical simulations of the Vlasov equation in a six-dimensional phase space necessary to answer this question have until recently remained beyond computational capabilities. I will present the first simulations of a turbulent dynamo in a stochastically-driven non-relativistic flow of collisionless plasma, and describe the main properties of this dynamo in regimes that can be probed with current computational means. The results notably suggest that this dynamo self-accelerates and becomes entangled with kinetic instabilities as magnetization increases. I will finally discuss the potential implications of these results for cosmic magnetogenesis and cluster magnetic fields, and future directions of research on this problem.

Hybrid-Kinetic Turbulence in Space and Astrophysical Plasmas

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Many space and astrophysical plasmas are so hot and diffuse that the collisional mean free path is larger than the system size. In this talk, we focus on two such systems: the solar wind and low-luminosity accretion flows onto black holes. In both cases, we study turbulence, transport, and dissipation by employing the hybrid-kinetic particle-in-cell code, *Pegasus* [1].

To study kinetic solar-wind turbulence, we stir ß ~ 1 plasma Alfvénically at large scales and follow the development of a critically balanced turbulent cascade to small scales in 6D phase space, paying particular attention to kinetic-scale features in the magnetic-energy and density power spectra and to the anisotropic heating of ions. Regarding the latter: while Alfvén-wave turbulence is now known to play an important, perhaps dominant, role in the heating of the solar wind, much less understood is the fact that protons in low-beta fast-wind streams are heated in such a way that thermal motions perpendicular to the mean magnetic field are much more rapid than thermal motions along it. Our simulations, the first 6D kinetic simulations to capture driven steady-state Alfvénic turbulence, provide a means of self-consistently assessing the efficacy of stochastic perpendicular heating and its ability to explain the observed ion temperature anisotropy.

We also show results from the first 6D kinetic simulations of magnetorotational turbulence. The interplay between turbulence, angular-momentum transport, and Larmor-scale instabilities (firehose, mirror) is studied in the local shearing-box approximation. Pressure anisotropies develop during the growth of the kinetic magnetorotational instability and subsequently drive firehose and mirror instabilities, which regulate the anisotropy and thereby the “viscous” transport of angular momentum. A movie will be shown of the first kinetic study of magnetorotational dynamo.

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Magnetic Field Generation via the Biermann Battery and the Interplay with the Weibel Instability

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The Biermann battery is a well-known mechanism for the generation of magnetic fields in initially unmagnetized plasmas. Its essential ingredients are non-aligned electron density and temperature gradients, as may arise in astrophysical shocks and in plasmas generated in intense laser-solid interactions.

The combination of weak (initially zero) magnetization with low collisionality, as may occur in situations of both astrophysical and laboratory interest, undermines the adoption of simplified plasma descriptions, and forces one to instead analyze the Biermann battery in the framework provided by the Vlasov plus Maxwell system of equations.

We have recently performed the the first *ab initio* (PIC) numerical investigations of magnetic field generation via the Biermann battery [1, 2] in collisionless plasmas. For small systems, we verify the basic picture expected from a simple, fluid-type analysis of the Biermann battery: the generation of a system-size (L) magnetic field whose magnitude, measured in terms of the plasma $\beta = 8\pi p/B^2$, scales as L^2. However, for larger system sizes, we find that the Biermann battery is superseded by the Weibel instability, resulting in much stronger $\beta \sim 10$, but small scale ($kd_e \sim 0.1$), magnetic fields. These results suggest that magnetic field generation scenarios may need to be revisited: the problem of explaining the observed cosmological magnetic fields may lie less in a discrepancy about their magnitude (given that the Weibel-generated fields are strong), and more in accounting for how to turn electron skin-depth-size fields into large-scale ones.

An additional finding from these numerical investigations are power-law spectra for the magnetic and electric energy at scales below the electron Larmor radius, in agreement with predictions from gyrokinetic theory [3].

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Vlasov simulation study of electron acceleration by large amplitude electron Bernstein waves

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We present a Vlasov simulation study [1] of the nonlinear coupling between upper hybrid waves and electron Bernstein waves in a magnetized plasma. When injected along the magnetic field, an ordinary mode wave can be mode converted to large-amplitude upper hybrid waves trapped in field-aligned plasma density cavities, or striations. The trapped large amplitude upper hybrid wave can decay to a secondary upper hybrid wave and a lower hybrid wave, or to a short wavelength electron Bernstein waves and either a lower hybrid wave or a different branch of electron Bernstein waves. Large amplitude Bernstein waves can significantly heat the electrons via quasilinear or stochastic processes. A Fourier method in velocity space [2, 3] is used to carry out Vlasov simulations of the induced plasma turbulence in one spatial and two velocity dimensions. The study has relevance to ionospheric heating experiments at the HAARP facility [4], where there are observations of descending ionospheric layers attributed to high-energy electrons ionizing the neutral gas.

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A mixed variable gyrokinetic model for electromagnetic gyrokinetic simulations

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The gyrokinetic reduction of the Vlasov-Maxwell equations consists in a sequence of changes of variables aiming at removing the fast angular variable representing the rotation of the particles around the magnetic field lines. This has the advantage for numerical simulations of reducing the phase space dimension by one variable and also of removing the fast gyration time scale. There are two natural formulations: one called the symplectic formulation is based on the parallel velocity and the other is based on the canonical parallel momentum and called hamiltonian [1]. Both have major drawbacks for a numerical Particle In Cell simulations, which are enhanced for MHD modes. The symplectic formulation contains $\partial_t A$ terms in the equations of motion of the gyrocenters, which necessitates an implicit discretisation for stability and the hamiltonian formulation introduces a large skin term in the parallel Ampere equation, which cancels with the large adiabatic part of the current computed as a Monte Carlo estimate, which is noisy. This needs a very well tuned control variate for a sufficiently accurate computation [2]. An alternative approach, based on a new variable intermediate between the canonical parallel momentum and velocity has been introduced recently in [3, 4]. This can be interpreted as a integrating factor method, for the integration of the gyrocenter equations of motion of either the symplectic or the hamiltonian formulation and enables to get rid of the numerical issues of either of the original formulations. This simple algorithm enables to take a much larger time step in all cases and larger by more than an order of magnitude for MHD modes [5]. The so-called mixed formulation can be directly derived from the original electromagnetic particle Lagrangian using Lie transforms as the original gyrokinetic equations and cast in a Field theoretic Lagrangian of the same form as the one obtained in [6]. This enables in particular to derive and exact conserved energy and total canonical angular momentum using a Noether theorem. This is in particular very useful for the verification and analysis of the resulting Particle in Cell code.

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A Vlasov-Hybrid code with Hermite expansion of the distribution function

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A Vlasov-hybrid algorithm and code implementation is here presented. The distribution function is expanded in series of Hermite functions.[1][2]. Thanks to the properties of the latters it is possible to project the Vlasov equation to find an equation for each coefficient of the expansion. These coefficients are advanced in time using a CAM algorithm with splitting method for the Vlasov operator. [3] The latter is subdivided in space advancement operator Λ_x and velocity advancement Λ_v operator. The former is treated explicitely due to the coupling between all the cells given by the spatial derivaty, while the latter is treated implicitely with a GMRES solver. The current is advanced with a temporal ODE derived taking moments of the Vlasov equation.

A 1D3V code is here implemented and tested. The code can be used to study low growth rate instabilities which are very sensitive to the initial noise due to the particle positioning in traditional PIC-hybrid codes, such us temperature anisotropy instabilities (e.g. proton cyclotron instability, proton firehose instability).

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A Vlasov-Ampére solver for the simulation of unmagnetized collisionless plasmas with open boundary conditions

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The propagation of electrostatic waves in inhomogeneous, collisionless and unmagnetized plasmas has been investigated through a Eulerian Vlasov-Ampére solver in $1D$-$1V$ phase space geometry (one dimension in physical space and one dimension in velocity space), with open boundary conditions in the spatial domain. The numerical algorithm is based on a finite difference upwind scheme to solve the Vlasov equation and on an Adam-Bashforth multi-step scheme to advance the electric field. The well-known time splitting method has been employed [1]. For the spatial boundary conditions, on the downwind border (outgoing flux) the characteristic method is applied, while for the upwind border (ingoing flux) the assumption of plasma at thermal equilibrium outside the box is considered.

In linear regime, we tested the numerical solution against that obtained by means of a Vlasov-Poisson solver: in particular, reflection and transmission of a Langmuir wave across a plasma inhomogeneity has been investigated. For the nonlinear case, we focused on the propagation of the so-called Electron Acoustic Waves (EAW) in inhomogeneous plasmas, in order to investigate the transmission of these fluctuations across a density gradient. The EAWs are electrostatic fluctuations with a dispersion relation of the acoustic form and phase speed around the electron thermal velocity [2, 3, 4]. As predicted by kinetic theory, this kind of fluctuations are strongly Landau damped [5] unless they are sustained by a population of trapped electrons. In the Vlasov-Ampére simulations, the excitation of the EAWs has been produced by applying on the plasma initially at equilibrium a spatially localized external driver electric field to create the trapped electron population.

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Multiple current sheet systems: Energy release and turbulence

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In the outer heliosphere, beyond the termination shock, we can expect the heliospheric current sheet to form a region of closely-packed, thin current sheets. These structures may be subject to an ion-kinetic tearing instability, and hence generate magnetic islands and hot populations of ions associated with magnetic reconnection. Reconnection processes in this environment have important implications for local particle transport, for particle acceleration at reconnection sites, and for the generation of turbulence. We study this complex environment by means of three- dimensional hybrid simulations over long time scales, in order to capture the evolution of the system from linear growth of the tearing instability at early times, to a developed turbulent state at late times. Simulations are conducted using both force-free and Harris current sheet equilibria, with varying plasma beta, guide field angle, and parallel shear. We discuss the evolution of the magnetic topology, and how changes in the initial conditions affect reconnection rates, particle acceleration, cross-boundary transport and magnetic spectra. We also examine the effect of including an energetic population of newly-born interstellar H+ pick-up ions. Finally, we examine the turbulent end state in the simulations, in order to investigate the multiple current sheet system as a general scenario for driving turbulence.

Energizations of protons in the Earth's magnetotail by magnetic fluctuations moving in a new class of self-consistent Vlasov equilibria

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In our previous work [1] we develop Vlasov solutions for a current sheet model which allow to regulate the level of plasma temperature and density inhomogeneities across the sheet. These models generalize the classical Harris current sheet via including two-temperature current-carrying plasma populations (both ions and electrons) and the background plasma not contributing to the current density. The parameters of these plasma populations allow regulating contributions of plasma density and temperature to the pressure balance. A brief comparison with spacecraft observations demonstrates the model applicability for describing the Earth magnetotail current sheet. We also develop a two dimensional (2D) generalization of the proposed model. The interesting effect found for 2D models is the nonmonotonous profile (along the current sheet) of the magnetic field component perpendicular to the current sheet. These equilibrium configurations can be used to study the ions energization in the Earth's magnetotail by applying the model developed by Perri et al. [2], in which the energization of protons is due to interaction with time-depended electromagnetic fluctuations. Indeed protons with energies up to 100 keV are observed in the magnetotail [3], but the mechanism that can energize particles in this region is not fully understood. The main idea of the model [2] is to reproduce the combined effect of the steady state electric field E_{0y} and of moving magnetic islands. The protons interact with such fluctuations undergoing a second order Fermi-process and can reach energies up to 100 keV. We study the influence of different magnetic profiles $B_x(z)$ obtained by the above self consistent model developed in [1] on the particle dynamics.

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Simulated response of top-hat electrostatic analysers: importance of phase-space resolution

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We use a numerical code which reproduces the angular/energy response of a typical electrostatic analyzer of top-hat type [1] starting from velocity distribution functions (VDFs) generated by numerical simulations. The simulations are based on the Hybrid Vlasov-Maxwell numerical algorithm which integrates the Vlasov equation for the ion distribution function in phase space, while the electrons are treated as a fluid [2]. Virtual satellite launched through the simulation box measures the particle VDFs. Such VDFs are moved from the simulation Cartesian grid to energy-angular coordinates to mimic the response of a real electrostatic sensor in the solar wind. Different energy-angular resolutions of the analyser are used in order to study the importance of the phase-space resolution for a space plasma experiment meant to investigate kinetic plasma regime.

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High-resolution hybrid simulations of the ion-scale spectral break of solar wind turbulence from low to high plasma beta

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We investigate the properties of the ion-scale spectra break of solar wind turbulence by means of two-dimensional high-resolution hybrid particle-in-cell simulations. We impose an initial ambient magnetic field perpendicular to the simulation box and we add a spectrum of in-plane, large-scale, magnetic and kinetic fluctuations. We perform a set of simulations with different values of the plasma beta, β, distributed over three orders of magnitude, from 0.01 to 10. In all cases, once turbulence is fully developed, the power spectrum of magnetic fluctuations follows a power law with a spectral index of $-5/3$ in the inertial range. In the sub-ion range we observe another power law with a spectral index varying with β (from around -3.6 for small values to around -2.9 for large ones). The two ranges are separated by a spectral break around ion scales. We identify the length scale at which such break occurs, which is found to be proportional to the ion inertial length, d_i, for $\beta \ll 1$ and to the ion gyroradius, $\rho_i = d_i\sqrt{\beta_\perp}$, for $\beta \gg 1$, i.e., to the larger between the two scales in both regimes. For intermediate cases, i.e., $\beta \sim 1$, a combination of the two scales is involved. We infer an empiric relation for the dependency of the spectral break on β that is able to approximate the scaling over the whole range of values. We compare our results with solar wind observations and suggest possible explanations for such behavior.

PIC simulations of the MagnetoRotational instability in electron-positron plasmas

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The magnetorotational instability (MRI) is a crucial mechanism of angular momentum transport in a variety of astrophysical accretion disks. Accretion disks are ubiquitous in astrophysics and play a fundamental role in areas as diverse as planet formation, gamma-ray bursts, and accretion onto supermassive black holes in the centers of galaxies. The MRI has been widely studied using MHD model [1] and MHD simulations. According to these results, the MRI has become an essential ingredient in our understanding of astrophysical fluids in a state of differential rotation. As a result of its action, strong turbulence develops in situation where a conducting fluid whose rotation rate decreases away from the rotation axis is immersed in magnetic field. The turbulent magnetic stress it creates is the most likely source of angular momentum transport in accretion disks. The joint action of turbulence and differential rotation can drive a dynamo capable of maintaining the magnetic energy at a few percent of the fluid internal energy. However, in many cases the MHD approach is not directly applicable. When the timescale for electron and ion Coulomb collisions is longer than the inflow time in the disk, the plasma is macroscopically collisionless and MHD breaks down.This is the case of the limit of weak magnetic field, i.e., as the ratio of the ion cyclotron frequency to orbital frequency becomes small.

Leveraging on the recent addition of the shearing co-moving frames equations of motion and Maxwell's equations modules in our PIC code OSIRIS 3.0, we intend to present our recent results of the analysis of MRI in electron-positron plasma in the limit of weak magnetic field. We will recall the theoretical 1D linear model of Krolik et Zweibel [2] that describes the behavior of MRI in the limit of weak magnetic field and use it to support our simulation results. Moving to 2D simulations, the analysis of MRI via PIC code permits to investigate also how MRI, in particular its non linear behavior, will act in comparison with other Kinetic instabilities, like firehose and mirror instabilities [3], looking for their influence of the turbulent regime triggered by MRI.

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Velocity diffusion of beam particles accelerated by Langmuir turbulence in solar wind plasmas

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Particle diffusion in velocity space is studied on the basis of 1D simulations of Langmuir turbulence generated by electron beams in solar wind plasmas where the presence of ambient random density fluctuations affects the character of diffusion of the beam particles.

The simulation results are provided by a numerical code based on a Hamiltonian model where the self-consistent resonant interactions between beam electrons and Langmuir waves are described in a plasma involving density fluctuations, for conditions relevant to solar type III observations at 1 AU [1-3]. Using the Zakharov's equations with an additional term representing the electron beam, the model takes into account strong preexisting and randomly varying density inhomogeneities and includes the low frequency plasma response.

The use of such a method provides several advantages compared to the kinetic Vlasov-Poisson approach [4]. The most important here are the possibility to model more easily plasma inhomogeneities and to investigate physical processes connected with the dynamics of individual particles over very long periods of time. Indeed, using a large amount of particle trajectories calculated with a great accuracy and over long times and analyzing them with statistical algorithms [5], the diffusion coefficients of particles in wave packets are estimated, as well as their relation to the waves' intensities and spectra and their dependence on the average level of background plasma density fluctuations. Results are compared with analytical solutions provided by the quasilinear theory of weak turbulence.

It is shown that, in the case of Langmuir turbulence in plasmas with random density fluctuations, simulation results provide coefficients of velocity diffusion which agree well with the analytical predictions of the quasilinear theory of weak turbulence. Nevertheless some noticeable quantitative differences exist, especially at the velocities lying in the phase velocity range of the short waves, where the main part of the wave energy is concentrated. The dependences of the velocity distribution of the beam particles accelerated due to Langmuir wave scattering on the density inhomogeneities on the parameters of the beam and the ambient plasma are discussed on the basis of the distribution of the diffusion coefficients in velocity space.

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Self-generating and autonomous production of relativistic electrons in planetary radiation belts

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The last ten years have shown what could potentially be described as a paradigm shift in our understanding of relativistic electron production in planetary radiation belts. The observation that wave-particle interactions might dominate the transport properties of relativistic electrons (Green & Kivelson 2004; Chen et al. 2007; Reeves et al. 2013), followed a few years later by the discovery of large-amplitude ($\delta E \geq 100$ mV/m), obliquely propagating $\theta_{kB} \geq 40$, quasi-monochromatic whistlers (Cattell et al. 2008, 2012; Cully et al. 2008; Kellogg et al. 2010, 2011; Breneman et al. 2011, 2012; Kersten et al. 2011; Wilson et al. 2011; Agapitov et al. 2014; Artemyev et al. 2015), and the more recent discovery of nonlinear electronic structures (Kellogg et al. 2010; Mozer et al. 2013, 2014; Malaspina et al. 2014), have irremediably altered our comprehension of radiation belts. Using theoretical arguments and numerical estimates, we present a relationship between nonlinear electrostatic modes and large-amplitude whistlers in the dynamics of planetary radiation belts and their role in a self-generating and autonomous mechanism for the production of relativistic electrons ($E > 100$ keV) from thermal levels ($E \simeq 100$ eV). The enhancement of electrons to relativistic levels can occur on kinetic timescales proportional to several electron bounce periods ($\tau \simeq 10 - 100$s), which is much faster than previously inferred by quasi-linear ($\tau \simeq 1$ hour) and large-scale diffusion ($\tau \simeq 1$ day) transport models.

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The structure of magnetic field discontinuities at sub-proton scales in the solar wind

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Using high resolution Cluster observations and a multi-dimensional intermittency technique, we show that magnetic discontinuities in the turbulent solar wind are connected through spatial scales from proton down to electron scales. Approaching small scales, a current fragmentation process arises, producing, in some cases, Harris-like layers. These observations are consistent with a scenario where many current layers develop in turbulence, and where the outflow of reconnection events are characterized by complex sub-proton networks of secondary islands, in a self-similar way.

Study of nonlinear effects in turbulent plasma: from fluid to kinetic modeling

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Turbulence is a highly nonlinear process that can be observed from simple fluids to plasmas, with compelling evidence in space plasmas observations, as well as in laboratory devices. In all the cases the dynamics can be fundamentally described as a cascade of energy through different scales: the energy injection is at scales comparable to the system size (large scale), then the energy cascades self-consistently towards smaller and smaller scales, until to the much smaller kinetic scales where dissipation processes can occur. Nowadays numerical simulations represent an indispensable tool for plasma diagnostics and a comparison between different plasma models is crucial to distinguish among fluid and non-fluid processes [1, 2]. Here, we discuss the comparison between compressible Hall MHD and hybrid Vlasov-Maxwell simulations, in a two-dimensional geometry and in decaying regime, starting with the same initial conditions. Preliminary results reveal a very similar behavior for the evolution of the turbulent activity. One of the main differences seems to be the compressibility, which is higher in the Hall MHD simulation. On the other hand, in the hybrid-Vlasov simulations, different effects, such as temperature anisotropy, heat flux and beam generations, appear in the proton distribution function. These kinetic effects have been statistically analyzed in the velocity space [3, 4, 5, 6, 7].

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Collisional relaxation of fine velocity structures in plasmas

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In a weakly collisional plasma, such as the solar wind, collisions are usually considered far too weak to produce any significant effect on the plasma dynamics [1]. However, the estimation of collisionality is often based on the restrictive assumption that the particle velocity distribution function (VDF) shape is close to Maxwellian [2]. On the other hand, *in situ* spacecraft measurements in the solar wind [3], as well as kinetic numerical experiments [4], indicate that marked non-Maxwellian features develop in the three-dimensional VDFs, (temperature anisotropies, generation of particle beams, ring-like modulations etc.) as a result of the kinetic turbulent cascade of energy towards short spatial scales. Therefore, since collisional effects are proportional to the velocity gradients of the VDF, the collisionless hypothesis may fail locally in velocity space.

Here, the existence of several characteristic times during the collisional relaxation of fine velocity structures is investigated by means of Eulerian numerical simulations of a spatially homogeneous force-free weakly collisional plasma. The effect of smoothing out velocity gradients on the evolution of global quantities, such as temperature and entropy, is discussed, suggesting that plasma collisionality can increase locally due to the velocity space deformation of the particle velocity distribution.

In particular, by means of Eulerian simulations of collisional relaxation of a spatially homogeneous force-free plasma, in which collisions among particles of the same species are modeled through the complete Landau operator, we show that the system entropy growth occurs over several time scales, inversely proportional to the steepness of the velocity gradients in the VDF. We report clear evidences that fine velocity structures are dissipated by collisions in a time much shorter than global non-Maxwellian features, like, for example, temperature anisotropies. Moreover we indicate that, if small-scale structures in the VDF are artificially smoothed out by fitting the VDF with some analytical model as, for example, the bi-Maxwellian one, the physics related to small scale structures (entropy growth, existence of many characteristic times) is definitively lost.

These results support the idea that high-resolution measurements of the particle velocity distributions are crucial for an accurate description of weakly collisional systems, such as the solar wind, in order to answer relevant scientific questions, related, for example, to particle heating and energization. Future space missions, planned to increase both energy and angular resolution for the measurements of the particle VDFs, will provide insights for understanding these processes.

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Collisional effects in weakly collisional plasmas: nonlinear electrostatic waves and recurrence phenomena

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The initial state recurrence in numerical simulations of the Vlasov-Poisson system is a well-known phenomenon [1]. Here, by means of Vlasov-Poisson simulations in a 1D–1V phase space, we analyze the effect on recurrence of artificial collisions modeled through the Lenard-Bernstein operator [2]. By decomposing the linear Vlasov-Pisson system in the Fourier-Hermite space, the recurrence problem is investigated in the linear regime of the damping of a Langmuir wave and of the onset of the bump-on-tail instability. The analysis is then confirmed and extended to the nonlinear regime through an Eulerian collisional Vlasov-Poisson code.

It is found that, despite being routinely used, an artificial collisionality is not a viable way of preventing recurrence in numerical simulations without compromising the kinetic nature of the solution [3]. Moreover, it is shown how numerical effects associated to the generation of fine velocity scales can modify the physical features of the system evolution even in nonlinear regime. This means that filamentation-like phenomena, usually associated with low amplitude fluctuations contexts, can play a role even in nonlinear regime.

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Slow electrostatic fluctuations generated by beam-plasma interactions

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The excitation of electrostatic waves due to the interaction of a relative low density and cold electron beam with a collisionless unmagnetized plasma have been investigated numerically. Analytical predictions of the existence of these fluctuations in linear regime dates back to the late sixties [5] and these electrostatic waves have been named "beam modes". Here we investigate both analytically and numerically the range of parameters where the excitation of these waves is successful, based on the use of a numerical solver of the electrostatic Vlasov dispersion relation and Eulerian Vlasov solvers both with periodic and open boundary conditions in the spatial domain. In particular, we investigated the possibility of exciting beam modes with phase speed v_ϕ close to the electron thermal velocity. [3] Kinetic theory predicts the existence of the so-called electron acoustic waves (EAWs), which are electrostatic fluctuations with a dispersion relation of the acoustic form and phase speed around the electron thermal velocity v_{th}. For a monotonically decreasing Maxwellian velocity distribution, the EAWs are heavily Landau damped [4] in linear regime. However, it is possible to turn off the Landau damping by creating a population of trapped electrons, this flattening the velocity distribution around v_ϕ. This can been accomplished by applying an external driver electric field spatially and temporally resonant with the EAWs [2, 1].

Alternatively to the use of the driver field, it is possible to excite electrostatic wave at low phase speed by introducing a beam of electrons of low density and temperature with a velocity drift v_d around the phase speed of the EAW. In this case, the initial Maxwellian distribution function is slightly modified by the presence of the beam and a small bump appears around the velocity drift of the beam. The presence of the beam not only turns off Landau damping but changes the slope of the distribution function, and can, therefore, generate unstable beam modes.

By using a kinetic linear solver, the roots of the dispersion relation have been computed for various values of v_d for a beam with a Maxwellian distribution function in velocity. Unstable modes are recovered in this case: in particular, the maximum value of the rate of wave amplification is obtained for $v_d = 1.9\ v_{th}$. An Eulerian code for the resolution of the Vlasov-Poisson system has been used to simulate the interaction between the beam and the plasma and to analyze the excitation of beam modes in linear and nonlinear regime.

Finally, an Eulerian Vlasov-Ampère solver with open boundary conditions in the spatial domain has been employed to simulate the excitation of beam modes due to the propagation of a low density and cold electron beam in an initially homogeneous background plasma.

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Plasma turbulence in the Earth's magnetosheath in the range of kinetic scales (according to Spectr-R data)

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The Earth's magnetosheath is the turbulent region in front of the magnetopause and bounded with the bow shock. Thus the magnetosheath serves as a natural laboratory to study plasma turbulence developing between two boundaries. To date only magnetic field fluctuations in the magnetosheath have been explored in the vicinity of ion and electron scales due to the lack of plasma measurements with high enough time resolution. Such measurements with time resolution of 0.031 s are now available on board Spectr-R spacecraft. This data lets us to study turbulence cascade of plasma fluctuations with frequencies up to 10 Hz.

We present statistical study of magnetosheath plasma fluctuations in frequency range 0.001 to 10 Hz. The study deals with two quantities: ion flux value and its direction. We consider fluctuations spectra shape and indexes together with power spectral density and probability distribution functions of the plasma fluctuations. We present and discuss dependencies of spectral indexes on various plasma parameters. We also demonstrate a spacecraft passing through the magnetosheath from one boundary to another and changes of the turbulence characteristics during it.

Nonstationary character of solar wind turbulence and the role of filament like structures in its formation

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High-resolution ion flux measurements of BMSW device onboard the SPECTR-R spacecraft are used for the analysis of the properties of the permanently present significant variations in the solar wind up to the scale of ~ 10 Hz. We show that forms of the spectra of such fluctuations as a rule do not correspond to spectra described by stationary models of turbulence. In this study we analyze the characteristics and the diversity of spectra of ion flux fluctuations and their PDFs (probability distribution functions) in the frequency range (10^{-2} to 10 Hz). The analysis of high order structure functions allows us to select the intervals with high level of intermittency and to determine the conditions of its formation. We produce the comparison of statistical characteristics of small scale solar wind ion flux fluctuations with the predictions of various statistical models of turbulence. The log-Poison model was selected as the best for the description of the experiment data set. The parameterization of scaling of experiment structure functions, provided with this model, demonstrate the dominant contribution of filament like current structures in the formation of the turbulent regions in the solar wind. We discuss the role of the geometry of such current structures in the observed properties of turbulence.

Electron Plasma Instabilities in the non-linear stage of the magnetised Kelvin-Helmoholtz instability

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Using a full kinetic PIC simulation [1], we study the non thermal effects produced during the nonlinear regime of the Kelvin Helmholtz (KH) instability in a magnetized plasma. The analysis of the electron and ion distribution functions reveal that electron distributions are very anisotropic and non-symmetric (much more than ions.) These effects, concentrated in local patterns, have been found to be correlated to shears. For the electrons, these features correspond to strong anisotropy, non-gyrotropy and the production of energetic beams.

The above mechanisms can be crucial for the understanding of mixing processes, heating, and particle acceleration mechanisms in turbulent plasmas.

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Explosive particle dispersion in plasma turbulence

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Particle dynamics are investigated in plasma turbulence, using self-consistent kinetic simulations, in two dimensions. In steady state, the trajectories of single protons and proton-pairs are studied, at different values of plasma β (ratio between kinetic and magnetic pressure). For single-particle displacements, results are consistent with fluids and magnetic field line dynamics, where particles undergo normal diffusion for very long times, with higher β's being more diffusive. In an intermediate time range, with separations lying in the inertial range, particles experience an explosive dispersion in time, consistent with the Richardson prediction. These results are relevant for astrophysical and laboratory plasmas, where turbulence is crucial for heating, mixing and acceleration processes.

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The dynamical Evolution of the Particles in Earth's Radiation Belts

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In this research, we have analyzed the distributions and evolutions of energetic particles in the inner geomagnetosphere, carried out the theoretical and numerical analysis on the mechanisms of dynamic evolutions of the Earth's radiation belts under external disturbances. This work has investigated analytically the stable distribution of outer belt energetic particles originated from plasma sheet injections driven by the convection electric field. Furthermore, we have developed our numerical model based on Fokker-Planck equation for the dynamic evolutions of radiation belt particles, analyzed the sources and global distributions of outer belt particles and their evolutions under external disturbance. This numerical model can yield the global evolution of the energetic ions of the ring current during storms, storm Dst index, flux of the energetic neutral atoms produced by charge exchange, as well as the current density of the ring current. One case study for the 25 Aug 2005 storm event is made, and the results are in agreement with the observations.

Kinetic effects in multi-component solar wind turbulence: hybrid Vlasov-Maxwell simulations

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Spacecraft measurements generally reveal that the electromagnetic field fluctuations in the solar wind are in a state of fully developed turbulence and both cross-scale couplings and strong modifications of the particle distribution function are involved [1, 2]. The general picture of astrophysical turbulence becomes more complicated because of the multi-component nature of the solar wind. The interplanetary medium, although predominantly constituted of protons, is also made up of a finite amount of alpha particles, together with a few percents of heavier ions. Several observations [3, 4, 5, 6, 7, 8] have shown that heavier ions are heated and accelerated preferentially as compared to protons. Here, hybrid Vlasov-Maxwell simulations are used to investigate the role of kinetic effects in a two-dimensional turbulent multi-ion plasma, composed of protons, alpha particles, and fluid electrons [9, 10, 11]. Thank to a relatively high resolution in the velocity space, we are able to characterize the nature of the deformation of the ion distribution functions and to identify the spatial region which are the sites of kinetic activity, with particular attention to the differential heating. We also discuss the dependence of the observed properties of non-Maxwellian features on plasma parameters like the plasma beta.

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Intermittency of the distribution functions in gyrokinetic plasma turbulence

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Turbulence in space plasma occurs over a wide range of scales. While large scale dynamics can be captured by fluid approximations, turbulence studies on scales comparable to the ion gyroradius and smaller require a kinetic description. Regardless of the scales of interest and the formalisms used for their representation, turbulence can be identified as an intermittent energy exchange between scales.

Intermittency represents a measure for the departure of turbulence from self-similarity (i.e. scale invariance of the dynamics). From the perspective of the real space, turbulence is associated with the development of localized coherent structures, such as eddies, filaments and sheets, which possess high energy densities. As the energy at small scales ends up being contained in a few energetic structures, intermittency can be seen as the tendency of small scales to be less volume filling than larger scales. In wave space, intermittency manifests itself as an increase in the nonlocality of the energetic exchanges between scales [1, 2].

For kinetic turbulence and its rigorous gyrokinetic (GK) limit found in strongly magnetized plasmas [3], distribution functions represent now the dynamical quantities of interest and the total measure of turbulent fluctuations is given by the free energy. As the nonlinear dynamics occur in phase space, obtaining information related to the intermittency of the distribution functions provides much needed insight into the kinetic (velocity based) impact on real space structure formation. This has strong implications in the generation of current sheets and heating structures and becomes relevant in the context of solar wind heating studies [4].

We will present for the first time results related directly to the intermittency of the distribution functions, obtained from large simulations of GK turbulence [2]. The ions and electrons are shown to have a different spatially intermittent behavior. We will compare this to the intermittency of the magnetic field and discuss the impact of velocity fluctuations on the generation of field structures. The implication for the electromagnetic dissipation and plasma heating is discussed.

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Linear stability analysis of the self-consistent transverse wake field interaction between the driving beam and the surrounding plasma

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We carry out a linear stability analysis within the context of the self-consistent transverse plasma wake field interaction. This is done by considering the transverse dynamics experienced by a relativistic charged particle beam travelling through a warm, magnetized plasma, where the external magnetic field is oriented along the beam propagation direction. We show that the spatiotemporal evolution of the system is governed by the Vlasov-Poisson-type pair of equations that, in the linear approximation, gives the Landau-type dispersion relation. Stability criteria are then established for both beam-plasma modes.

Simulations of electron acceleration at and downstream of quasi-perpendicular shock

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Energetic electrons play an important role in many astrophysical environments, and are commonly observed in space plasmas. For example, shock accelerated electrons, and the electron super-halo of the solar wind, are both examples of system where a significant electron population can be accelerated out of the thermal distributions (up to 2 - 20 keV [1]). Our understanding of the mechanisms responsible for such particle acceleration processes is still incomplete. In a collisionless plasma, the single-particle dynamics of electron and protons (ions) have very different typical scales. Particularly, if one is interested in electron acceleration via turbulence and/or shocks, both the proton and the electron scales must be resolved: this yields to serious computational problems. Therefore, we confront the problem of electron acceleration using a combination of hybrid Particle-in-Cell and test particle simulations. The electric and magnetic fields, in which the test particle electrons are followed, are obtained from 2D PIC simulations. Test particle method is used to follow electron trajectories using fields spatially and temporally interpolated from the hybrid plasma simulation. A range of different injection energies for quasi-perpendicular shocks is studied. The test particle electrons must be released with an initial energy high enough so that they do not affect the large scale electromagnetic fields[2]: an initial value of about 1 keV is used. In order to solve the equations of motion for the electrons we use a 4th order scheme with appropriate conservation properties [3][4], performing a bicubic spline interpolation for the fields and using an adaptive timestep. The electrons are released (1) in the upstream region, right before the shock front, (2) in the downstream region, right after the shock front. The downstream region of a shock is characterized by a turbulent nature so it can be used as an example of where turbulent acceleration possibly occurs.

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Electrostatic waves in a weakly collisional plasma: analytical and numerical study

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The damping of electrostatic waves in a non-collisional plasma was explained by Landau in [1]. In numerical simulations one encounters numerical recurrence, a phenomenon due to discretization in phase space. This happens because of the advection term in Vlasov equation, responsible of creating finer and finer scales in velocity space.

In this work a numerical algorithm to evaluate Landau damping in a weakly collisional plasma is presented. In the non-collisional case the distribution function evolves according to the Vlasov equation. For the collisional case a Lenard-Bernstein collisional operator is implemented [2]. This collisional operator is very simple in nature, in fact the collision frequency, ν, is constant and independent from velocity. The distribution function is expanded in Fourier basis functions for the spatial part, and in Hermite basis functions for the velocity part [3]. The time integration is performed using a fourth order Adams-Bashforth scheme.

It is shown that, in the non-collisional case, Landau damping is recovered, while in the weakly collisional case, the damping is modified due to the collisional term that tends to bring the system back to the equilibrium state. In particular, choosing a proper value for the collision frequency, it is possible to change the damping rate and avoid numerical recurrence [4], [5]. Moreover, using LB operator, the Landau-damped solutions become eigenmodes of the system [6]. Finally, it is not possible to observe the distribution function in phase space, owing to problems in the reconstruction of the function after the decomposition in Hermite space. The latter remains an unresolved problem in the code, probably due to the fact that high order Hermite functions are not able to converge in the window frame.

The code is benchmarked against an Eulerian code.

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Particle-in-Cell Simulations of Collisionless Magnetic Reconnection with a Non-Uniform Guide Field

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Results are presented of a first study of collisionless magnetic reconnection starting from a recently found exact nonlinear force-free Vlasov-Maxwell equilibrium. The initial state has a Harris sheet magnetic field profile in one direction and a non-uniform guide field in a second direction, resulting in a spatially constant magnetic field strength as well as a constant initial plasma density and plasma pressure. It is found that the reconnection process initially resembles guide field reconnection, but that a gradual transition to anti-parallel reconnection happens as the system evolves. The time evolution of a number of plasma parameters is investigated, and the results are compared with simulations starting from a Harris sheet equilibrium and a Harris sheet plus constant guide field equilibrium.

A fractional kinetic Parker equation for the transport and acceleration of energetic particles in space plasmas

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The acceleration and transport of energetic particles in space plasmas and, on larger scales, of cosmic rays, can be described by the so-called Parker equation, which is a kinetic equation comprising diffusion terms both on coordinate space and on momentum space. In the last years, it has been found that energetic particle transport in space can be anomalous, for instance superdiffusive rather than normal diffusive. Here, we extend the Parker equation to the case of anomalous diffusion, introducing fractional derivatives in space, which are one of the tools used to describe anomalous transport. We consider the case of steady-state solutions upstream and downstream of a planar shock, and obtain an estimate of the particle acceleration time at shocks, which is in agreement with the expression obtained by Perri and Zimbardo [1], in the case of superdiffusion. We also recover the break length for the scale invariant solutions considered by Litvinenko and Effenberger [2] and by Perri et al. [3]. Using a Fourier transform in space, we can obtain an analytical solution of the fractional Parker equation which gives, in the relevant limits, a power law profile for the energetic particle intensity upstream of the shock.

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Thursday, June 2nd 2016

A. Vaivads 9:00 – 9:30
A. Retinò 9:30 – 10:00
L. Matteini 10:00 – 10:20
COFFEE BREAK 10:20 – 10:50
B. Matthaeus 10:50 – 11:20
P. Hellinger 11:20 – 11:40
S. Servidio 11:40– 12:10
LUNCH 12:10 – 15:00
G. Lapenta 15:00 – 15:30
P. Veltri 15:30 – 16:00
D. Perrone 16:00 – 16:20
COFFEE BREAK 16:20 – 16:50
G. Howes 16:50 – 17:20
K. Klein 17:20 – 17:40
Y. Maneva 17:40 – 18:00
THOR APERITIF 19:00
DINNER 20:00

Turbulence Heating Observer – Thor

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[4] Institute of Atmospheric Physics, Prague, Czech Republic,
[5] Universita della Calabria, Italy,
[6] Imperial College London, United Kingdom,
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[10] Space Research Institute/Austrian Academy of Sciences, Austria,
[11] University of Turku, Finland,

Turbulence Heating ObserveR (THOR) is a candidate mission to be launched by ESA in 2026. The downselection will be made spring 2017 and currently THOR is undergoing mission and payload study phase. THOR would be the first mission ever flown in space fully dedicated to study plasma turbulent fluctuations and associated kinetic processes leading to plasma energization. THOR will achieve this by making detailed in situ measurements of the closest available dilute and turbulent magnetized plasmas in the near-Earth space at unprecedented temporal and spatial resolution. Here we present the results of the ongoing mission study particularly focusing on the mission concept, payload capabilities and payload operation.

http://thor.irfu.se/

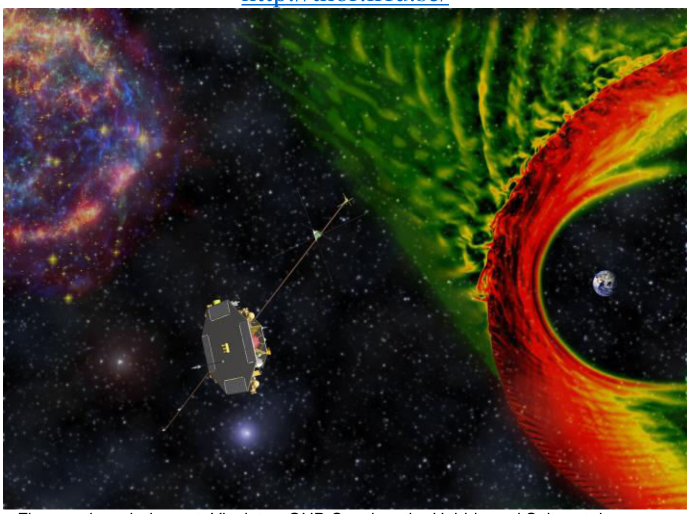

Figure acknowledgment: Vlasiator, OHB-Sweden, the Hubble and Spitzer telescopes, the Chandra X-ray Observatory, M. Palmroth, W. Puccio.

Exploring turbulent energy dissipation and particle energization in space plasmas: the science of THOR mission

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The visible Universe is permeated by hot magnetized plasmas which are in most cases in a turbulent state. Turbulent plasmas are found in active galactic nuclei, supernova remnants, the intergalactic and interstellar medium, as well as in the solar corona, the solar wind and the Earth's magnetosphere. They can also be found in laboratory devices such as e.g. tokamaks. Our comprehension of the plasma Universe is largely based on measurements of electromagnetic radiation, such as light or X-rays, which originate from particles that are heated and accelerated as a result of energy dissipation in turbulence. Therefore, it is of key importance to understand how plasma is energized by turbulent fluctuations. Most of the energy dissipation occurs at kinetic scales, where plasma no longer behaves as a fluid and the properties of individual plasma species (electrons, protons and heavier ions) become important. THOR (Turbulent Heating ObserveR) is a space mission currently in Study Phase as candidate for M-class mission within the Cosmic Vision program of the European Space Agency. The scientific theme of the THOR mission is turbulent energy dissipation and particle energization in space plasmas, which ties in with ESA's Cosmic Vision science. Specifically, the THOR mission aims to address fundamental questions such as how plasma is heated and particles are accelerated by turbulent fluctuations at kinetic scales, how energy is partitioned among different plasma components and how dissipation operates in different regimes of turbulence. To achieve this goal, THOR will make in situ measurements with unprecedented resolution in specific regions in near-Earth space: the pristine solar wind, the Earth's bow shock and interplanetary shocks, and the compressed solar wind regions downstream of shocks. These regions are selected because of their different turbulence properties, and reflect similar astrophysical environments. Here we present the science of THOR mission and we discuss implications of THOR observations for space, astrophysical and laboratory turbulent plasmas

Probing turbulence from MHD to kinetic scales in space plasmas: electric and magnetic field spectra in Earth's magnetosheath

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Using Cluster measurements in Earth's magnetosheath we investigate the transition of plasma turbulence from fluid to kinetic scales. Simultaneous spectra of magnetic and electric fields from MHD to electron scales are presented for the first time. While the two spectra have approximatively similar behavior in the fluid-MHD regime, they show different trends beyond ion scales. As the magnetic field spectrum steepens at sub-ion scales, the electric field spectrum is characterized by a shallower power law reaching electron scales. Such an evolution is consistent with Vlasov theoretical expectations, assuming that the turbulence is dominated by highly oblique k-vectors and that between ion and electron scales the electric field is governed by the non-ideal terms in the generalized Ohm's law. This leads to a predicted linear increase of the electric-to-magnetic ratio in the turbulent fluctuations, consistent with observations discussed here. These findings are at present restricted to magnetosheath plasma due to observational limitations, however, thanks to the much higher resolution proposed for instruments on board THOR, it will be possible to test and confirm them also in interplanetary space in the future.

Turbulence from MHD to Vlasov and beyond

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Turbulence, complex nonlinear dynamical behavior, is widely believed to be well-described by magnetohydrodynamics (MHD) at large spatial scales and low frequencies. As spatial and temporal scales approach the lengths and timescales that are characteristic of plasma behavior, one expects to see the onset of distinctive plasma dynamics. For a low collisionality plasma such as the solar wind, solar corona, or magnetosphere, a description in terms of the Vlasov-Maxwell, or the Vlasov-Maxwell-Boltzmann system of equations, becomes appropriate. For turbulence one expects multi-scale behavior, and even nonlocal-in-scale behavior. Consequently the nontrivial question arises as to whether the familiar properties of fluid and MHD turbulence can be observed in the kinetic plasma case, and if so, for what conditions? Do the paradigms that we expect from hydrodynamics and MHD remain valid? Do detailed dynamical effects occur in plasmas in the same way as they do in MHD? Here we address some of these questions, and summarize some of the progress that has been made in recent years in understanding these issues, which are of great significance in space and astrophysical plasmas. Topics we address include : (i) effects of system size, equivalent to the question of effective Reynolds numbers [1] ; (ii) control of the cascade by large scales, and von Karman energy decay [2] ; (iii) the emergence of coherent structures and the generation of intermittency [3]; and (iv) the role of coherent structures, especially current and vorticity structures, in dissipation [4], and their relation to the distribution of energy between protons and electrons [2,5,6]. Finally we remark on the distribution and concentration of work done on particles by the fields, viewed as a surrogate for dissipation [7]. This leads to a suggestion that a useful way to view both MHD and plasma turbulence is through scale-filtered equations [e.g., 8]. Such an approach may lead to a more unified perspective on turbulence across scales from MHD to the electron kinetic scales.

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Fire hose instabilities in the expanding solar wind

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Using two-dimensional hybrid expanding box simulations we investigate properties of fire hose instabilities in the solar wind. We compare results of two simulations of a homogeneous electron-proton plasma system, one with the radial interplanetary magnetic field (IMF) [1] and one with the oblique Parker IMF. Effects of turbulent fluctuations on the development of fire hose instabilities will be also discussed [2].

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Vlasov simulations of plasma turbulence

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Non-thermal plasma processes and turbulence represent two main features of the solar wind, suggesting that these phenomena need to be investigated with nonlinear plasma models. Hybrid Vlasov-Maxwell (HVM) simulations are presented, establishing a link between kinetic effects and turbulence. Using a five-dimensional geometry (2D in space and 3D in the velocity space), it is found that kinetic effects (or non-fluid effects) manifest through the deformation of the proton velocity distribution function (DF), with patterns of non-Maxwellian features being concentrated near regions of strong magnetic gradients [1]. Results have been confirmed by recent 6D Vlasov simulations. The simulations are directly compared to spacecraft observations, where usually proton temperature anisotropy is observed. Both simulations and solar wind data suggest that temperature anisotropy is not only associated to magnetic intermittent events, but also with gradient-type structures in the flow and in the density [2]. This connection between kinetic features and turbulence open a new path on the study of processes such as heating, particle acceleration, and temperature-anisotropy, being also crucial for upcoming solar wind missions.

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Modelling Astrophysical Plasmas with Particles: Conservation of Energy and Acceleration mechanisms.

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Everybody knows that modelling plasmas with particles suffers from one problem: noise. Noise is another word for discretization error. PIC has a stochastic truncation error while phase-space grid-based Vlasov codes have a deterministic smooth discretization error. However, what is perhaps less widely known is that the real trouble with noise is that it leads to a non conservation of energy. The particles are discrete agents and every time step they radiate noise in terms of numerical high frequency electromagnetic waves. If left unchecked this tendency heats the plasmas over time.

This effect is troubling in more than one sense: energy conservation is a cardinal rule in physics. First, going from Newton to Einstein to Shroedinger, one thing remained true: energy (and its equivalent in mass) is conserved. Not in PIC simulations it is not. Second, having a spurious extra source of energy can drive unphysical phenomena while having artificial cooling can quench processes. Rigorous analysis done in the early days od PIC development give the user secure guidance to avoid this problem, but at the cose of having to resolve scales of the order of the Debye lenght.

The implicit method removes this constraint[1]. The implicit method conserves energy exactly, as rigorously as in the physical system. But at a cost: the need for a Newton iteration of the governing non-linear equations[2]. This cost is offset by removing the need to resolve the Debye length. Focusing in particular to the moment implicit formulation [1], large grid spacing and time steps can be used because noise is reduced by the moment averaging and energy is conserved exactly.

We present here a completely new approach: an explicit energy conserving Particle in Cell method [3]. The method is revolutionary: it allows to conserve energy, to eliminate the adverse role of noise, to eliminate the finite grid instability and to study large domains with full kinetic description.

We consider especially the case of particle energization and turbulence in the solar wind. The solar wind is cold, only a few eV. This is much less than the typical keV of the magnetosphere where PIC is usually applied. PIC has a real hard time modeling the solar wind, such cold plasmas with small Debye length are subject to finite grid instability and noise-driven heating. The new method completely eliminates the problem, at a cost comparable to the standard explicit PIC method. The approach remains explicit, remains simple, does not need any Newton iteration.

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Electrostatic Turbulence generated by Solar Wind nonlinear Energy Cascade

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Using hybrid VlasovMaxwell simulations we have investigated the dynamics of the solar-wind plasma in the tail of the MHD nonlinear cascade, where the energy injected in large-scale slab-type Alfvenic fluctuations is transferred toward short spatial scale lengths, across the proton skin depth. In particular we have shown that a significant level of electrostatic activity can be generated at wavelengths smaller than the proton inertial scale and propagating in the longitudinal direction with respect to the ambient magnetic field.

A careful study of the generation process of these electrostatic fluctuations in terms of the electron-to-proton temperature ratio T_e/T_p has allowed to furnish a clear evidence that even in the case of cold electrons, i. e. T_e of the order of T_p (an appropriate condition for solar-wind plasmas), the resonant interaction of protons with large-scale left-hand polarized ion-cyclotron waves is responsible for the excitation of short-scale electrostatic fluctuations with an acoustic dispersion relation.

Through our numerical results we also suggest a physical mechanism to explain the observation of beams of accelerated particles along the direction of the ambient magnetic field for both protons and alpha particles. This mechanism is found to be more efficient for protons than for alpha particles, in agreement with recent solar-wind data analyses.

Kinetic effects in solar wind using kinetic Vlasov simulation and Cluster data

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Turbulence represents one of the most spectacular and unsolved problem in plasma physics, where cross-scale couplings and kinetic effects are present. The energy, injected at large scales, progressively decays towards smaller scales, where kinetic effects dominate the plasma dynamics (heating, particle acceleration and so on). 'In situ' measurements revel that kinetic effects control solar-wind dynamics [1, 2]. In this scenario, the use of both kinetic numerical simulations and spacecraft measurements becomes crucial. Here, hybrid Vlasov-Maxwell simulations are used to investigate the structures that contribute to the local anisotropy observed in the solar wind. As the level of turbulence increases, smaller and smaller scale structures (current sheets, vortices and so on) are produced and larger and larger values of temperature anisotropy are reached [3, 4, 5, 6]. The same behavior has been recovered in Cluster data, by using wavelet technique and multi-satellite analyses, close to the ion spectral break in the solar wind turbulent cascade. Different kind of coherent structures have been detected (from soliton-like one-dimensional structures to current sheet- or wave-like two-dimensional structures), that have a strong wave-vector anisotropy in the perpendicular direction with respect to the local magnetic field and typical scales around ion characteristic scales [7]. Thanks to the synergy between observational data and massive kinetic simulations, a robust theoretical support for the interpretation of satellite data on the turbulent behavior of solar-wind plasma could help to address important questions about the nature of turbulent fluctuations in solar wind turbulence.

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Using Field-Particle Correlations to Diagnose the Collisionless Damping of Plasma Turbulence

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Plasma turbulence occurs ubiquitously throughout the heliosphere, yet our understanding of how turbulence governs energy transport and plasma heating remains incomplete, constituting a grand challenge problem in heliophysics. Specifically, we have yet to determine definitively the kinetic physical mechanisms responsible for the damping of the turbulent electromagnetic and plasma flow fluctuations in the weakly collisional solar wind and the ultimate conversion of their energy into plasma heat, or some other form of particle energization. In weakly collisional heliospheric plasmas, such as the solar corona and solar wind, damping of the turbulent fluctuations occurs due to collisionless interactions between the electromagnetic fields and the individual plasma particles. A particular challenge in diagnosing this energy transfer is that spacecraft measurements are typically limited to a single point in space. Here we present an innovative field-particle correlation technique that can be used with single-point measurements to estimate the energization of the plasma particles due to the damping of the electromagnetic fields, providing vital new information about this how energy transfer is distributed as a function of particle velocity. The basic concept of this technique is illustrated using the simplified case the collisionless damping of electrostatic fluctuations in a 1D-1V Vlasov-Poisson plasma. This technique has the promise to transform our ability to diagnose the kinetic plasma physical mechanisms responsible for not only the damping of turbulence, but also the energy conversion in both collisionless magnetic reconnection and particle acceleration.

Secular Field-Particle Energy Transfer in a Turbulent, Gyrokinetic System

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Measuring the transfer of energy from electromagnetic fluctuations to particle distributions is a necessary step for fully characterizing dissipation for a broad class of plasma systems. Motivated by the form of the field-particle interaction term in the Vlasov Equation, a correlation technique has been proposed to measure this secular transfer of energy, and has been applied to the 1D-1V electrostatic system[1]. We extend that work to the case of the fully turbulent 3D-2V electromagnetic gyrokinetic system[2]. The changes to the correlation necessitated by the additional complexity of the gyrokinetic system are described. Results from nonlinear simulations using the AstroGK code[3] are presented and serve as illustrations of the expected velocity space signature of the field-particle energy transfer. Even in the presence of strong turbulence, the secular transfer of energy can be isolated, and is accessible in single point measurements of the type made in a variety of experimental settings, including solar wind spacecraft observations.

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Generation of temperature anisotropies and anisotropic turbulence via wave-particle interactions in drifting proton-alpha plasmas

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The power spectra of magnetic fluctuations in the solar wind typically follow a turbulent power law dependence with respect to the observed frequencies and wave-numbers. The background magnetic field often influences the plasma properties, setting a preferential direction for plasma heating and acceleration. At the same time the evolution of the solar wind turbulence at the ions and electron scales in return is influenced by the plasma properties through micro-instabilities and wave-particle interactions. The solar wind plasma temperature and the solar wind turbulence at ion and electron scales simultaneously show anisotropic features, with different temperature and fluctuation power in parallel and perpendicular direction with respect to the orientation of the background magnetic field. The ratio between the power of the magnetic field fluctuations in parallel and perpendicular direction at the ion scales may vary with the heliospheric distance and depends on various parameters, such as the plasma compressibility, wave properties and the non-thermal plasma features, such as temperature anisotropies and relative drift speeds. In this work we have performed 2.5D hybrid simulations to study the importance of relative drifts and a gradual solar wind expansion in a multi-species plasma, consisting of fluid electrons, kinetic (particle-in-cell) protons and a drifting population of He ++ ions. At the beginning of the simulations we impose a turbulent spectrum of paralllel propagating Alfvén-cyclotron waves, co-existing with the drifting multi-species plasma. In the course of nonlinear evolution of the system we observe substaintial anisotropic cascade of the magnetic field power spectra towards perpendicular wave numbers. The nature of the anisotropic turbulent cascade depends on the differential streaming between the different ion populations and is affected by the solar wind expansion. In the case of sub-Alfvénic differential streaming the perpendicular wave power is enhanced and the anisotropic cascade is shifted towards smaller wave numbers.

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