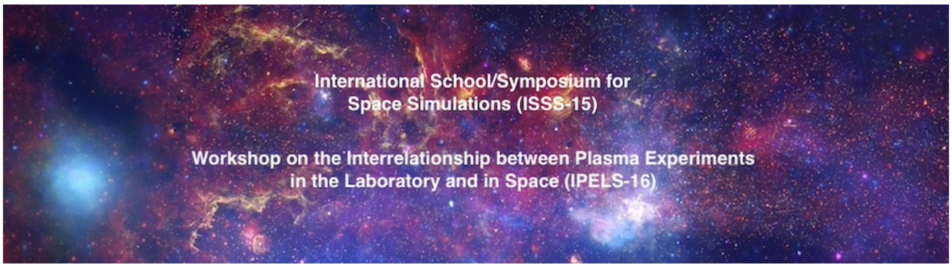
ISSS-15 + IPELS-16

Thursday, August 1, 2024 - Friday, August 9, 2024

IPP Garching, Germany



Report of Abstracts

IPELS poster / 107

Laboratory Study of Alfvén Wave Steepening

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Alfvénic fluctuations - fluctuations with magnetic-field and velocity fluctuations perpendicular to the background magnetic field which are proportional to each other - are thought to be ubiquitous in magnetized astrophysical plasma environments and are observed across scales in our own solar wind. Recent theoretical work by Mallet et al [1] proposes a mechanism by which small-scale, oblique Alfvén waves undergo a one-dimensional nonlinear steepening process only at dispersive length scale smaller than the ion inertial length (e.g. when one or more of k⊥ρs, k⊥de, or k∥di becomes significant). This work presents the first laboratory tests of this steepening model, comparing predictions for the amplitude of the harmonic of a driven wave to experimental measurements from the Large Plasma Device (LAPD). These tests span highly inertial (vA ≫ vth,e) to highly kinetic (vA ≪ vth,e) conditions at low β to provide insight into turbulence in environments like the solar corona, where the usual counterpropagating Alfvén wave interactions may be suppressed.

[1] Mallet, Alfred, et al. "Nonlinear dynamics of small-scale Alfvén waves." Physics of Plasmas 30.11 (2023).

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AHKASH: a new Hybrid particle-in-cell code for simulations of astrophysical collisionless plasma

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I will describe Astrophysical Hybrid-Kinetic simulations with the flASH code (AHKASH) - a new Hybrid particle-in-cell (PIC) module developed within the framework of the multi-physics code FLASH. Our new second-order accurate hybrid PIC method uses the Boris particle integrator and a predictor-predictor-corrector algorithm for advancing the Hybrid-kinetic equations. It also employs the constraint transport method to ensure that magnetic fields are divergence-free. We employ the cloud-in-cell stencil for interpolation operations between particles and the computational grid and have implemented a δf method to study instabilities in collisionless plasmas. I will present code tests for standard physical problems such as the motion of a charged particle in the presence of magnetic fields, propagation of Alfv'en and whistler waves, and Landau damping of ion-acoustic waves. We introduce turbulence driving, modelled using the Ornstein-Uhlenbeck process, in the new Hybrid PIC code. To investigate steady-state turbulence with a fixed Mach number, it is important to maintain isothermal conditions, and we introduce a novel cooling method for PIC codes to achieve this. I will present tests of the cooling method and demonstrate the importance of using it when turbulence is introduced in a collisionless plasma. Additionally, I will discuss the numerical convergence of turbulence driving experiments with varying grid and particle resolutions and test the computational scalability, the hybrid precision method, and the efficiency of the new code.

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1D Vlasov-Poisson simulations of linear and solitary ion acoustic waves close to the Sun: Parker Solar Probe observations

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The correlation between linear and nonlinear ion acoustic waves (IAWs); i.e. solitary waves, observed in the vicinity to the Sun is still an open question. These electrostatic structures have a high electric field and are regularly spaced (Mozer et al. 2021; Graham et al. 2021). We study the onset of the ion acoustic instability in a parameter regime compatible with these observations. In the presence of two resonant counter-streaming ion populations, ion-acoustic instabilities may develop (Gary & Omidi 1987). We check with kinetic linear theory analysis that the system is unstable due to IA instability. We then verify our results with 1D VlasovPoisson simulations. Our main results are the following: 1) we do observe ion acoustic instability in a regime
compatible with the Mozer and Graham observations 2) we observe the production of a chain of ion holes which produce, in the frame of the core distribution, signatures compatible with the high-frequency bursts
recorded in observations.

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Bridging the gap between fluid and kinetic simulations

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Space plasma simulations are typically categorized into fluid and kinetic models, which are employed for modeling macroscopic and microscopic phenomena, respectively. Fluid models consider only lower-order moments (usually up to the second order), whereas kinetic models have degrees of freedom that are more than one order of magnitude larger. This introduces a significant gap between the two different approaches both in terms of physics and computational requirement, making it difficult to investigate the coupling between different scales. To bridge this gap, we propose a novel kinetic closure that incorpolates the cyclotron resonance effect into a fluid model. It adopts the same strategy as the Hammett-Perkins closure for Landau damping but applies it to electromagnetic flucuations for a fluid species with a pressure tensor that includes off-diagonal components. Although the model is based on linear theory, nonlinear simulations of temperature anisotropy instabilities demonstrate that it is capable of describing quasi-linear isotropization and saturation in the nonlinear phase. We show that inclusion of the off-diagonal components of the pressure tensor is crucial for reproducing qualitatively correct nonlinear behavior. The proposed approach may be an important step toward an intermediate model between fluid and kinetic models.

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Accelerating Fusion Plasma Collision Operator Solves with Portable Batched Iterative Solvers on GPUs

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High fidelity numerical simulations are necessary to drive design choices for future fusion devices, e.g. the ITER tokamak. XGC is a gyrokinetic Particle-in-Cell (PIC) application optimized for modeling the edge region plasma. The Coulomb collision operator is one of the more computationally expensive components of XGC. It requires linear solutions for a large number of small matrices with an identical sparsity pattern. These are still performed on the CPU, a major bottleneck given that exascale-class machines have over 95% of their compute performance on the GPUs. As the collision operator matrices are sparse, well-conditioned, and of medium size, batched iterative solvers utilizing sparse data structures are an attractive option. We showcase the acceleration of XGC with an integration of the Ginkgo batched iterative solvers with realistic test cases from ITER and DIII-D. We present results obtained from three platforms: NVIDIA A100 GPUs (NERSC Perlmutter), AMD MI250X GPUs (OLCF Frontier) and Intel Data Center Max 1550 GPUs (ALCF Aurora) and show the reduction in time provided by the Ginkgo solver compared with the LAPACK CPU solver. We present a weak scaling study to almost full-scale on the NVIDIA platform. The results show that Ginkgo's batched sparse iterative solvers enable efficient utilization of the GPU for this problem. The performance portability of Ginkgo in conjunction with Kokkos (used within XGC as the heterogeneous programming model) allows seamless execution on exascale-oriented heterogeneous architectures.

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Energetic electron tail production from binary encounters of discrete electrons and ions in a sub-Dreicer electric field

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During transient instabilities in a 2 eV, highly collisional MHD-driven plasma jet experiment, evidence of a 6 keV electron tail was observed via x-ray measurements. The cause for this unexpected high energy tail is explored using numerical simulations of the Rutherford scattering of a large number of electrons and ions in the presence of a uniform electric field that is abruptly turned on as in the experiment. When the only active processes are Rutherford scattering and acceleration by the electric field, contrary to the classical Fokker–Planck theory of plasma resistivity, it is found that no steady state develops, and instead, the particle kinetic energy increases continuously. However, when a power loss mechanism is introduced mimicking atomic line radiation, a near steady state can develop and, in this case, an energetic electron tail similar to that observed in the experiment can develop. The reasons underlying this behavior are analyzed, and it is shown that an important consideration is that Rutherford scattering is dominated by the cumulative effect of grazing collisions, whereas atomic line radiation requires an approximately direct rather than a grazing collision.

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Investigating sources of pulsar coherent radio emissions by particle-in-cell kinetic simulations

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Coherent radio waves from pulsars bring information about relativistic extremely-magnetized pair plasmas in neutron star magnetospheres because the waves originate at plasma kinetic scales. Though various radio emission mechanisms have been proposed in the last decades for their interpretation, many lack the inclusion of self-consistent wave–wave and particle–wave interactions, emission power, spectrum, polarization properties, and directivity that are necessary for interpreting the observations. Hence, particle-in-cell kinetic simulations that self-consistently include the necessary effects are an excellent tool for the plasma and radio emission diagnostics.

Most of pulsar radio waves are probably produced by pair cascades in their polar cap regions by quantum-electrodynamic pair cascades. We carried out PIC simulations that included the relativistic and pair creation in polar caps, magnetospheric currents, and curvature radiative losses of plasma particles. We studied a range of magnetic dipole inclination angles and magnetospheric currents to reveal how radio emissions can operate for various structures of pulsar magnetospheres.

We found that the pair creation events produce intensive Poynting flux originating in an electric gap region close to the star surface. The Poynting flux escapes the polar cap along open field lines where the plasma density is low, and the flux may propagate without significant absorption. Our results indicate that no energy conversion process from particles to waves is necessary for the pulsar coherent radio emissions.
The pulsar emission is directly produced by electromagnetic waves that escape the oscillating gap. Moreover, the produced pulsar radio beam does not have a cone structure; instead, the radiation mostly escapes along those open magnetic field lines in which no pair creation occurs.

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Space and Laboratory Experiments Using Plasma Waves to Detect Satellites in Low Earth Orbit

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The number of satellites launched into low Earth orbit (LEO) is increasing at an exponential rate. Launches support deployment of multi-satellite constellations for many applications. In situ experiments with the Canadian Swarm-E Satellite have been conducted to better locate the positions of satellites and space debris for prevention of collisions.
Currently, there are about 27,000 known space objects and over 100 million of unknown pieces of space debris. Collision avoidance requires precise knowledge of the positions for all space objects. New techniques are being developed to detect the small, < 10 cm, objects by the plasma waves they generate in space. The bases for this technique is that all space objects in orbit around the Earth (1) pass through a magnetized plasma, (2) become electrically charged, and thus (3) produce detectable plasma waves [1]. The University of Alaska is working with the University of Calgary to find space debris and satellites moving through these irregularities and can excite plasma emissions such as whistler, compressional Alfven, or lower hybrid waves. Orbital kinetic energy is the source of lower hybrid waves which is converted into an electromagnetic plasma oscillation when a charged space object encounters a field aligned irregularity (FAI). Such whistlers propagate undamped at around 9000 km/s from the source regions and can be detected at ranges of several earth-radii. Laboratory Experiments are being developed using the plasma chambers and lasers to accelerate particles through plasma targets simulating wave generation by charged objects in space. The signature of space objects identified with orbit-driven waves is analyzed with Plasma Dispersion and Poynting Vector theory to determine the angle, range, and physical characteristics of small size space debris.

[1] P.A. Bernhardt, R.L Scott, A Howarth, George. J. Morales (2023) Observations of Plasma Waves Generated by Charged Space Objects, Phys. Plasmas 30, 092106, https://doi.org/10.1063/5.0155454

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Electrostatic waves and electron holes in PIC simulations of the Earth's bow shock

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Collisionless low Mach number shocks are abundant in astrophysical and space plasma environments, exhibiting complex wave activity and wave-particle interactions. In this paper, we present 2D Particle-in-Cell simulations of quasi-perpendicular nonrelativistic (Vsh=(5500-22000) km/s) low Mach number shocks, with a specific focus on studying electrostatic waves in the shock ramp and the precursor regions. In these shocks, an ion-scale oblique whistler wave creates two hot counter-streaming electron beams, which drive unstable electron acoustic waves (EAWs) that can turn into electrostatic solitary waves (ESWs) at the late stage of their evolution. By conducting simulations with periodic boundaries, we show that EAW properties agree with linear dispersion analysis. The characteristics of ESWs in shock simulations, including their wavelength and amplitude, depend on the shock velocity. When extrapolated to shocks with realistic velocities (Vsh=300 km/s), the ESW wavelength is reduced to one tenth of the electron skin depth and the ESW amplitude is anticipated to surpass that of the quasi-static electric field by up to a factor of 140. These theoretical predictions may explain a discrepancy, between PIC and satellite measurements, in the relative amplitude of high- and low-frequency electric field fluctuations.

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Exploring the structure of AGN Jet recollimation shocks: Insights from 2D and 3D RMHD Simulations

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Despite significant strides in numerical and theoretical understanding, the active galactic nucleus (AGN) jet structure is still an open question. Relativistic magnetohydrodynamical (RMHD) simulations are indispensable tools for probing the dynamics and emission of these astrophysical sources. Recent attention has shifted towards investigating instabilities downstream of recollimation shocks, mainly through 3D simulations, revealing their complex dynamics and impact on jet structures. Furthermore, turbulence downstream of strong recollimation shocks facilitates particle acceleration to higher energies, potentially explaining extreme phenomena observed in high-energy peaked blazars. However, the suppression of instabilities by intense magnetic fields remains a topic of ongoing research, with implications for understanding sources like extreme blazars. This work explores various instabilities downstream of recollimation shocks in AGN jets. We employ preliminary high-resolution MHD 2D and 3D simulations to pave the way for comprehensive RMHD simulations

using the PLUTO code. Our results aim to elucidate the spectral energy distribution, intensity, and polarization of non-thermal emission, contributing to a deeper understanding of AGN jet dynamics.

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Overview of the Basic Plasma Science Facility

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Co-authors: Gurleen Bal [1]; Jia Han [1]; Josh Larson [1]; Mel Abler [2]; Pat Pribyl [1]; Phil Travis [1]; Shreekrishna Tripathi [1]; Stephen Vincena [2]; Walter Gekelman [1]

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The Basic Plasma Science Facility (BaPSF) at UCLA is a collaborative research facility for studies of fundamental processes in magnetized plasmas, supported by US DOE and NSF. The centerpiece of the facility is the Large Plasma Device (LAPD), a 20m long, magnetized linear plasma device. The LAPD is used to study a number of fundamental processes, including: collisionless shocks; dispersion and damping of kinetic and inertial Alfv\'{e}n waves; turbulence and transport; flux ropes and 3D reconnection; and interactions of energetic ions and electrons with plasma waves. An overview of research using the facility will be given, followed by a more detailed discussion of recent studies of the physics of ion cyclotron range of frequencies (ICRF) waves, including generation of RF sheaths and scattering/mode conversion on turbulent structures in LAPD.

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Hybrid particle simulations of mirror instabilities and waves

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Mirror waves are widely observed in space plasma environments. The mirror instability may occur in anisotropic plasmas where the perpendicular temperature exceeds the parallel temperature. An important characteristic of mirror waves is the anticorrelation between plasma density and magnetic field perturbations. Moreover, recent observations have indicated an anticorrelation between temperature and magnetic field perturbations. The linear mixed kinetic-MHD theory may quantitatively describe the phase relations of the observed mirror waves in the terrestrial magnetosheath (Hau and Chang 2020; Hau et al. 2021). In this study, we investigate the time evolution of proton mirror instability based on hybrid particle simulation model for 20 sets of initial plasma beta values. Our findings have shown that the observed mirror events in terms of phase relationships can be quantitatively reproduced by nonlinear simulation results. The statistical analyses indicate that the saturated phase relations are consistent with the theoretical predictions.

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Strongly Non-linear Alfvén Wave Interactions in a Laboratory Experiment

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Alfvénic turbulence is pervasive in the solar wind and thought to be common in space and astrophysical plasmas. The solar wind has allowed us to learn much about this turbulence, however, there are many open questions about how it works and shapes these systems. Lab experiments provide a controlled environment to test the basic physics of such turbulence. Here, we present an experiment on the Large Plasma Device at UCLA, in which interacting low-frequency Alfvén waves at small $k_\perp \rho_s$ are studied. We show that both counter-propagating and co-propagating waves result in a spectrum of new modes generated by their non-linear interaction. Estimated strength parameters, the wave frequencies involved, and their amplitude dependence on the initial waves, indicate the interaction to be in the strong regime - that applicable to space/astrophysical systems. The co-propagating waves produce a comparable spectrum to the counter-propagating ones, indicating a non-MHD interaction. We discuss a new nonlinearity, that scales with $k_\perp d_i$, which may be responsible, and may also be important for understanding unexplained features of the solar wind. We test this with 3D hybrid simulations, showing a good match to the theory. We also demonstrate energy transfer to higher $k_\perp$ through the non-linear interactions, indicative the processes that may be involved in the Alfvénic turbulence in the solar wind. This series of experiments also allows other aspects of strong Alfvénic turbulence to be studied, such as residual energy, and kinetic range interactions, which will also be presented at this meeting.

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Electron Dynamics throughout the Solar System

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Electron-scale physics is often the key ingredient that helps to disentangle complex plasma measurements. In this talk, I highlight the synergies between in-situ observations, simulation models and laboratory experiments, characterizing the role that localized plasma processes can have in regulating the large-scale dynamics and evolution of a macroscopic system. I focus on modeling the kinetic interaction of bodies immersed in plasma using different numerical approaches. I investigate (a) dust and tiny magnets exposed to a laboratory plasma, (b) the charging of spacecraft, such as the Parker Solar Probe, and instruments deployed on regolith surfaces, and (c) the plasma interaction with outgassing comets, such as 67P, lunar magnetic anomalies, such as the Reiner Gamma region, and planetary magnetospheres, such as Mercury. To conclude, this talk provides an overview of a set of state-of-the-art tools that are continuously pushing forward our understanding of fundamental planetary processes across multiple Solar System bodies. If you have a problem, if no one else can help, maybe you can try a fully kinetic model?

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Structure and acceleration processes of electrons in astrophysical shock environment using PIC simulation

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The objective of this project is to investigate shocks through Particle-In-Cell (PIC) simulations, particularly focusing on intermediate Mach. By delving into the transition between low and high Mach number instabilities, we aim to gain valuable insights into shock dynamics and electron behavior. Through experimentation and analysis, we hope to improve our understanding of shocks and electron dynamics, thereby making significant contributions to the field of astrophysical research. This study is the first step in a project to investigate the structure and electron acceleration in planetary and astrophysical shocks using PIC simulations. A first simulation has been conducted for a High Mach number configuration, which implies the generation of Weibel instability and the formation of a filamentary structure for electron. The transition between Whistler and Weibel instabilities is also discussed.

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Cosmic Rays and Magnetic Fields in the Local Universe

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Investigations of E×B velocity shear-driven waves and the significance of ambipolar electric fields in the laboratory and magnetotail

Author: Ami DuBois[1]

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Ambipolar electric fields are often observed in compressed plasma layers throughout the near-Earth space environment and have been shown to be important for plasma flows, wave generation, broadband turbulence, and dissipation mechanisms. When an ambipolar electric field self-consistently forms perpendicular to a background magnetic field, E×B velocity shear is generated. Shear-driven instabilities in the lower hybrid frequency range arise in a shear layer of width less than an ion gyro-diameter in which electrons are magnetized but the ions are effectively unmagnetized due to gyro averaging effects. These are called the electron-ion hybrid (EIH) instability. The EIH instability recently has been shown to play an important role in plasma dynamics occurring in compressed magnetotail current sheets.

The electrostatic EIH instability has been extensively studied in the laboratory in order to document the wave characteristics and understand the effects of electric fields, density gradients, and neutral

collisions. New spatially resolved spectral measurements in the Space Physics Simulation Chamber at the Naval Research Laboratory show that electromagnetic EIH waves are broadly distributed in frequency and wavenumber. Azimuthal mode numbers up to m=5 have been resolved, with observations of two bands in the dispersion relation. The lower band has a frequency much less than the electron cyclotron frequency (Ωce) with a positive group velocity and azimuthal and radial components. The higher band has a frequency of approximately 0.7Ωce with a negative group velocity and a purely azimuthal component. The empirical parallel and transverse dispersion relation of the waves is extracted and compared to theoretical calculations. These laboratory experiments are critical to understanding how the EIH instability driven turbulence interacts with the background plasma flow and gradient profiles, and how anomalous dissipation mechanisms (i.e. resistivity and viscosity) arise.

Knowledge of the turbulence characteristics gained from laboratory experiments is being applied to observations of compressed current sheets in the magnetotail to help understand the role of the EIH instability in the current sheet development toward magnetic reconnection. Using NASA's Magnetospheric Multiscale (MMS) mission data, electrostatic lower hybrid waves are observed to be localized to a region with a strong transverse ambipolar electric field located at the center of a compressed gyro-scale current sheet with a strong guide field in the magnetotail. The waves were found to be driven by electron E×B velocity shear. The terms in the generalized Ohm's Law are estimated directly from MMS data, and analysis shows that the wave effects (resistivity, viscosity, and diffusion) and pressure anisotropy effects were comparable. It was also found that the quasi-static electric field gradient generates a non-gyrotropic electron distribution function, which theoretical arguments suggest is an indicator of the possibility for magnetic reconnection to occur. These results stress the importance of the ambipolar electric field in gyro-scale current sheets and in reconnection physics.

This work is supported by the Naval Research Laboratory Base Program.

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Magnetic reconnection plasma thruster

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We have recently introduced a new concept for rocket thrusters that exploit the mechanism behind solar flares, where magnetic energy is converted to kinetic energy through the process of magnetic reconnection. Inspired by the studies of fundamental processes in helicity injection experiments in NSTX, computer simulations (in both single and two-fluid extended MHD models) were used for the first time to demonstrate that a particular configuration of electric and magnetic fields can both create plasma and accelerate it by continuously producing plasmoids (plasma enclosed by magnetic fields that are detached from the externally applied fields) through spontaneous fast magnetic reconnection. Due to an Alfvenic outflow from the reconnection site, its thrust is proportional to the square of the magnetic field strength and does not ideally depend on the mass of the ion species of the plasma, giving flexibility in the choice of propellant gas [Journal of Plasma Physics, 86(6), 2020]. Our calculations of thrust and exhaust velocity are performed via state-of-the-art extended MHD simulations with a realistic coil configuration. Variable unidirectional high exhaust ion velocities, as well as quasi-steady large net thrust, are directly demonstrated in the simulations. These results support the fast reconnection base magnetic reconnection thruster (MRT) concept. New computational results, as well as our system design to build a plasmoid-mediated MRT will be presented. Operational thruster regimes based on magnetic reconnection phase diagram will also be discussed. This work has been supported by DOE at PPPL.

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Examining Wave Instabilities from a Global PIC Model of the Earth's Magnetosphere

Author: Nicole Echterling[1]

Co-authors: David Schriver ; Giovanni Lapenta ; Liutauras Rusaitas ; Mostafa El Alaoui ; Ray Walker

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A 3D implicit particle-in-cell (PIC) simulation has been used to model the Earth's magnetosphere to investigate the development of the ring current when electron kinetics are included. Initialized with starting conditions from a global magnetohydrodynamic (MHD) simulation, the computational burden for modeling the entire magnetosphere using a PIC code is reduced and allows the system to evolve self-consistently including the effects of both ion and electron kinetics. The inclusion of both species'kinetics has been shown to enhance particle energization and alter local features of the magnetosphere's boundaries. The sharpening of the bow shock, magnetopause, and current sheet increases wave activity near these boundaries. This work examines electron velocity distributions taken from the global model. Anisotropic distributions from the global simulation are first examined using the WHAMP linear dispersion solver to determine kinetic instabilities and the linear wave growth produced by such distributions. A local, high-resolution 2.5D electromagnetic PIC simulation is then initialized with the anisotropic electron velocity distributions to examine the ensuing nonlinear wave-particle interactions. Of particular interest is the pitch-angle scattering of electrons into the loss cone by waves that contribute to the loss of electrons from the magnetosphere through precipitation into the Earth's atmosphere.

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Kinetic Properties of the Reconnection Electron Diffusion Region, Explored Through Theory and Experiment

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During magnetic reconnection in collisionless plasma strong electron jets often emanate from the electron diffusion region (EDR). Given the results of the influential Sweet-Parker reconnection model (derived for a collisional plasma), it is commonly assumed that these electron jets are driven by the reconnection electric field. In contrast, kinetic models and simulations have suggested that the jets are driven by anisotropic electron pressure which primarily form in the reconnection inflow regions. In particular, a new reduced kinetic theory will be presented [1,2], which details how the pressure anisotropy couples to the electron Speiser orbits of the EDR. This 1D model is derived in the adiabatic limit of a vanishing small reconnection rate, yet it largely accounts for the structures of all essential electron fluid quantities across the EDR, including the electron jet formation. The theory will be discussed in the context of fully kinetic simulations, laboratory experiments as well as MMS spacecraft observations from Earth's magnetotail.

[1] Egedal J, "On a plasma sheath with a small normal magnetic field separating regions of oppositely directed magnetic field"(2023), Phys. Plasmas, 30(11).
[2] Egedal J, "The Adiabatic 1D Kinetic Equilibrium of the Electron Diffusion Region During Anti-Parallel Magnetic Reconnection"(2024), Geophy. Res. Lett., 51(10).

Plenary / 58

Field inference with information field theory

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In many scientific, industrial, and economical applications, knowledge of fields, quantities that vary as a function of position, is essential.
Inferring a physical field from data, however, is an ill posed problem, as the finite data can not alone constrain the infinite number of degrees of freedom of a function over continuous space. Domain knowledge has to regularize the set of possible solutions. Usually significant uncertainties remain and need to be quantified. This can be done via information field theory (IFT), which is a mathematical formulation of probabilistic field inference. IFT is related to modern AI/ML methodologies like generative models, however, it does not require training, despite being self-adaptive, as domain knowledge is systematically used. Here, the basic concepts of IFT and its numerical implementation are introduced and some of its recent application to astrophysical datasets are presented that probe space plasma in various environments and ways ranging from gamma ray astronomy over Galactic tomography to black hole filming.

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Energy partition in collisionless shocks

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Collisionless shocks are among the most fundamental nonlinear processes in plasmas. Generated by violent interactions of supersonic plasma flows with the interstellar medium or planetary magnetospheres, collisionless shocks are inferred to heat the plasma, amplify magnetic fields, and accelerate electrons and protons to highly relativistic speeds. However, the exact mechanisms that control energy partition in these shocks remain a mystery, in particular in high Mach number regimes. I will discuss recent progress in using the combination of fully kinetic simulations and laser-driven laboratory experiments to study energy partition in high-Mach number collisionless shocks. I will focus on the results on magnetic field amplification, plasma heating and particle acceleration, and discuss how experimental measurements are helping benchmark models of the shock microphysics.

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Recent results and future plans for space and astrophysical plasma studies at the Wisconsin Plasma Physics Laboratory

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This talk will be a review of the principle space and astrophysical plasma relevant experiments undertaken at Wisconsin Plasma Physics Laboratory (WiPPL) since the last IPELS meeting. WiPPL is a collaborative user facility, operating the Big Red Ball (BRB) and the Madison Symmetric Torus (MST) out of the Physics Department at the University of Wisconsin, hosting users from around the world. I will give highlights on experiments on magnetic reconnection in the TREX configuration on the BRB, plasma self-organization in tokamak plasmas in MST, runway electron generation of Whistler waves and relaxation, perpendicular and parallel shocks using pulsed power on BRB, and

studies of flow domimnated plasmas in the geometry of the Parker Spiral and in Couette flow. I will end with new directions that might be taken on the Wisconsin HTS Axisymmetric Mirror, whose supersonic exhaust through a DeLaval-like magnetic nozzle may offer a path to a collisionless, highly anisotropic expanding plasma like the solar wind.

Plenary / 105

It's Not Easy Being Green: Quantitative Modeling of Aurora-like Picket Fence Emissions Driven by Local Ionospheric Parallel Electric Fields

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The 'picket fence' is a captivating visual phenomenon characterized by vibrant green streaks in the subauroral sky, often appearing below a rare purpleish-white arc called STEVE (Strong Thermal Emission Velocity Enhancement). Recent studies suggest that, despite its aurora-like appearance, the picket fence may be driven NOT by magnetospheric particle precipitation but instead by local ionospheric electric fields parallel to Earth's magnetic field. We investigated this hypothesis by quantitatively comparing observed picket fence spectra with emissions generated in a kinetic model driven by parallel electric fields in a realistic neutral atmosphere. We find that sufficiently large parallel electric fields can reproduce the observed ratio of N_2^+ first positive to oxygen green line emissions, without producing N_2^+ first negative emissions, reproducing the unique emission spectrum of the picket fence. At a typical picket fence altitude of 110 km, parallel electric fields between 40 and 70 Td (~80 to 150 mV/m at 110 km) result in calculated spectral features consistent with observed ones, providing a benchmark for future observational and modeling studies. Additionally, we review studies which have identified similar features to the picket fence in the aurora, suggesting that a similar mechanism may be at work there. Since visible and ultraviolet auroral emissions are increasingly used to infer magnetospheric activity, it is important to better understand and quantify potential sources of emission beyond particle precipitation. Furthermore, this work highlights how, when combined with modeling, detailed spectroscopic observations prove a powerful tool for diagnosing and disentangling new ionospheric physical processes.

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Kinetic Simulations of Collisionless Shock Formation in the Dark Sector

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Historically, dark matter searches have primarily focused on hunting for effects from two-to-two scattering. However, given that the visible universe is primarily composed of plasmas governed by collective effects, there is great potential to explore similar effects in the dark sector. Recent semi-analytic work has shown that new areas of parameter space for dark U(1) and millicharged models can be probed through the observation of collisionless shock formation in astrophysical dark plasmas, a nonlinear process that requires simulation. Here, I will show results from simulating such warm, non-relativistic pair plasmas within the Smilei framework, a fully-kinetic particle-in-cell plasma physics simulation suite.

Plenary / 130

Going beyond MHD: New Developments in Space Environment Modeling

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A low collisional laboratory plasma for exploration of Fermi heating and the realization of a miniature Magnetosphere

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Coulomb collisions effectively relax plasma velocity distribution function to a near-Maxwellian form and often hamper the relevance of laboratory experiments to tenuous and near-collisionless space plasma. To overcome this challenge, the Terrestrial Reconnection Experiment (TREX)[1] at the Wisconsin Plasma Physics Laboratory (WiPPL)[2] is specially designed to be relevant to reconnection in the Earth's magnetosphere. The experiment deploys an optimized reconnection drive circuit with the ability to drive the electron fluid through the reconnection region faster than the Coulomb collision time of tei=10-6 s. The achieved low collisional regime is characterized by Lundquist numbers on the order of S = 10^5[3], and the configuration permits multiple magnetic islands to be induced within reconnection current layer allowing the dynamics of coalescing islands to be examined. The aim of these experiments is to explore electron heating and energization due to island coalescing. In addition, TREX is also investigating magnetic reconnection in a miniature magnetopause with a size on the order of a few ion skin depths. This is accomplished by placing an electromagnetic dipole in the exhaust region of a TREX magnetic reconnection event. Utilizing arrays of magnetic and electrostatic diagnostics in multiple reproducible plasma discharges, the 3D dynamics associated with the topological rearrangement of the magnetic field is currently being studied.

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[2] The Wisconsin Plasma Astrophysics Laboratory C. B. Forest et al., J Plasma Physics, 81, Oct 2015.
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Electron-only reconnection and ion heating in 3D hybrid-Vlasov plasma turbulence

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Turbulence and magnetic reconnection are intrinsic to space and astrophysical plasmas. Recent observations revealed a novel type of reconnection occurring in the turbulent Earth's magnetosheath, dubbed "electron-only reconnection"[Phan 2018]. This distinctive form of reconnection occurs in the absence of ion outflows, signifying a reconnection event without an Ion Diffusion Region (IDR). 2D simulations have found that electron-only reconnection manifests when the current sheet's length is less than approximately 10 times the ion skin depth (d_i) [Califano et al. (2020)]. Moreover, for current sheets smaller than the ion gyroradius (ρ_i) the ion response is further weakened, further enhancing the reconnection rate [Guan 2023]. In this work, we perform 3D3V hybrid-Vlasov simulations of turbulence across and below the ion scales, exploring the occurrence of electron-only reconnection for different values of the ion beta (β_i = 0.25, 1, 4). Electron-inertia terms are included in the model, serving as a physical mechanism for collisionless magnetic reconnection to occur. In these simulations, electron only reconnection events are clearly identified. A spectral analysis of turbulent fluctuations is roughly consistent with a transition from Kinetic Alfvén Waves (KAW) to Inertial Kinetic Alfvén Wave (IKAW) and Whistler Wave regimes close to the scale of the electron skin depth. Velocity spectra show a clear decoupling between ions and electron as β_i increases, attributed to the presence of strong electron outflows in an Electron Dissipation Region (EDR) and the simultaneous absence of ion jets. Finally, turbulent heating of ions at different β_i is also addressed. The overall picture that emerges from this study has fundamental implications for the dynamics of space and astrophysical plasmas.

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Laboratory Experiments of Alfvén Wave Interactions in the Transition to the Kinetic Range

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Turbulence is ubiquitous throughout different space plasma environments, facilitating the cascade of energy down to smaller and smaller length scales. That said, the different parameter regimes at which these plasmas exist have a significant effect on the way the cascade develops- turbulence at the MHD limit will not have the same attributes as turbulence at the kinetic limit. For instance, kinetic fluctuations are compressive and much more liable to Landau damping than those at the MHD-scale, but despite this the kinetic solar wind turbulent cascade is well-documented. Though in-situ measurements can provide a wealth of knowledge about the properties of space turbulence, they are limited by their spatial extent relative to the plasma environment and their reproducibility. Laboratory plasmas can provide insight complementary to satellite data; this has already been the case with several experiments run on the LArge Plasma Device (LAPD) at the University of California-Los Angeles. The space plasma turbulence group at Queen Mary University of London (QMUL) has run Alfvén wave experiments on LAPD studying weak and strong interactions at a range of $k_\perp \rho_s$ values, from negligibly small up to order unity. The change in the properties of the drive waves and their interaction products between these limits has been quantified via detailed measurements of magnetic and electric field fluctuations in multiple different counter-propagating wave configurations. Further data runs driven over a range of power inputs allow for an analysis of the residual energy- and cross helicity-dependent properties of the interactions. With this experimental setup, the fundamental physics of the three-wave interaction can be studied in detail while minimizing

the impact of other solar wind phenomena. Also being presented at this meeting are results from previous complementary QMUL-group experiments, which showed novel nonlinear interactions in the traditionally MHD regime.

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Nonideal Fields in Relativistic Reconnection

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Magnetic reconnection has been established as a fast and efficient particle accelerator in dramatic astrophysical flares. However, the significance of nonideal fields in the early states (”injection”) of acceleration has been debated. Using particle-in-cell simulations, we demonstrate the importance of nonideal fields in accelerating the particles to high energies. We define nonideal fields as regions where the assumptions of ideal (regions with E $>$ B or nonzero $E_{\|} = \mathbf{E} \cdot \mathbf{B}/B$). Thus, we find that injection is necessary for acceleration.

ISSS poster / 17

Turbulence in Molecular Clouds - A laboratory for understanding waves in partially ionized media

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Plasma in space are omnipresent, but generally found in a partially ionized state only. Thus, we need to consider the interaction between ionized and neutral gases. Since the coupling between both gases is mediated via collisions we expect, on scales shorter than their collision frequency, the gases to increasingly decouple while on larger scales the gases to move in unison. This has immediate consequences for MHD waves in the medium requiring a deviation from a single-fluid treatment, i.e. two-fluid MHD (2FMHD).
Although 2FMHD predicts a „decoupling gap“for MHD modes in which propagation is prohibited, simulations of 2FMHD turbulence do not show such a gap. This suggests that within the framework of ideal 2FMHD an as of yet unknown process that mediates energy through this gap is present.
As Molecular Clouds (MCs) are of generally high interest in Astrophysics and Astronomy due to their role in star formation and Cosmic Ray (CR) propagation, while covering a vast variety of plasma conditions under turbulent conditions over a wide range of scales, they pose as an ideal „laboratory “to empirically improve current understanding of MHD waves in partially ionized media.

Plenary / 124

New insights into the inner machinery of collisionless magnetic reconnection

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NASA's Magnetospheric Multiscale mission (MMS) has provided and continues to provide heretofore unimaginable insight into the kinetic machinery of the magnetic reconnection process. These successes are based on innovative combinations of extreme-precision observations of magnetic reconnection at the Earth's magnetopause and inside the nightside magnetotail, with concurrent theoretical analyses and numerical modeling. For example, we now have a very good understanding of the physics of the central diffusion region even when reconnection occurs in conjunction with plasma turbulence. We are also advancing our knowledge of how the central electron diffusion region couples to its environment, from ion scales to very large scales –a critical multi-scale problem, and we do have an ever-growing insight into the reconnection rate
problem. This presentation will provide an overview of the new knowledge recent research has created, and it will discuss open questions, and possible follow-on avenues for investigations in near-Earth space and elsewhere in space- and astrophysical plasmas.

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Particle Acceleration during Three-Dimensional Turbulent Magnetic Reconnection

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Magnetic reconnection has long been known to be the most important mechanism not only for the mixing of plasmas by changing the magnetic field topology, but also for the release of magnetic field energy into plasma kinetic energy. In addition, part of the heated plasma can be accelerated to energies much higher than the thermal energy during reconnection. So far, the energy partitioning of thermal and nonthermal energy has been mainly studied using two-dimensional (2D) particle-in-cell (PIC) simulations. It has been shown that the acceleration efficiency of nonthermal particles increases with increasing plasma temperature, and the nonthermal energy density occupies more than 90% of the total heated plasma when the Alfven velocity is close to the speed of light. Here we report on the effects of three-dimensional (3D) relativistic reconnection on a pair plasma with a guide magnetic field using 3D PIC simulations. The results show that the efficiency of nonthermal particle acceleration decreases with increasing guide magnetic field for both 2D and 3D reconnection, but the decrease in nonthermal particle production is smaller for 3D guide-field reconnection compared to 2D. More importantly, because patchy and turbulent structures are generated over a large area of the plasma sheet in 3D guide-field reconnection, 3D reconnection is able to maintain a hard nonthermal energy spectrum even in the presence of a strong guide magnetic field.

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Turbulent and magnetic angular momentum transport in the solar convection zone

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We carried out a high-resolution simulation of the solar convection zone and, for the first time, reproduced the solar-like differential rotation without using any manipulation.
The sun rotates differentially with the fast equator and the slow poles, called solar-like differential rotation (DR). The DR is thought to be maintained by the turbulent thermal convection in the convection zone, but recent high-resolution simulations cannot reproduce the solar-like DR, i.e., the fast equator. The small-scale turbulence tends to transport the angular momentum radially inward, and the DR results in the anti-solar-like topology. This problem is one of the most essential mysteries in solar physics, called the convective conundrum. In order to resolve the problem, we carried out an unprecedentedly high-resolution simulation using Fugaku, and the solar-like DR is nicely reproduced. The result shows that the magnetic field is unexpectedly strong and has a dominant role in the angular momentum transport.

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GPIC: An advanced Particle-In-Cell code using GPU acceleration and its application in magnetic reconnection

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The emerging computable devices, graphical processing units (GPU), are gradually applied in the simulations of space physics for their high efficiency. Here we present a fully kinetic particle-in-cell (PIC) simulation code running on GPU devices called GPIC, which adopts CUDA Fortran programming. Compared with the simulations running on the Intel Xeon Gold processor, our program working on NVIDIA A100 can achieve amazing accelerated computing up to 724 times faster than the former. Besides, we also implement it on multiple GPUs across computing nodes and obtain relatively low latency. By applying this program in the simulations of magnetic reconnection, we find there exists a crater structure behind the reconnection front, which is well supported by the MMS observations. This structure is formed by the continuous impact of high-speed electron outflow jets. Our advanced program shows its capability and superiority in performing PIC simulations with low cost. The scientific discovery in the magnetic reconnection indicates a new energy conversion pattern between electrons and the magnetic field.

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Effects of spontaneously-generated and artificially-controlled electrostatic fields in high guide-field magnetic reconnection in laboratory experiment

Author: Michiaki Inomoto[1]

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Axial merging of two torus plasmas is utilized to form a high ion temperature plasma in fusion devices through energy conversion by magnetic reconnection. In a spherical tokamak merging experiment [1] in which the guide magnetic field is more than ten times larger than the reconnecting magnetic field, the inductive reconnection electric field is almost parallel to the magnetic field particularly in the inboard-side downstream region where larger guide field is applied. Thus large in-plane electrostatic field is required to sustain the steady plasma outflow motion, but the self-generated electrostatic field does not always balance with the inductive electric field to make the total electric field strictly perpendicular to the total magnetic field, resulting in a residual parallel electric field that drastically change the plasma dynamics.

Experimental results from the soft X-ray (SXR) imaging diagnostic in the UTST device [2] revealed that an intense SXR emission was observed in the inboard-side downstream region in the early phase of the plasma merging, suggesting that the electrons are accelerated by the transient parallel electric field [3]. Simultaneous measurement of inductive and electrostatic fields revealed that the self-generated electrostatic field in the latter merging period is even larger than that just cancels out the parallel component of the inductive electric field [4]. The excess of the electrostatic field contributes to shape change of the in-plane magnetic field because the reconnection current in the toroidal direction needs to be reversed in order to form a final closed magnetic surface.

The in-plane electrostatic field is moderately suppressed by using small electrode pairs inserted in the downstream region, resulting in a late current reversal as well as an enhancement of the parallel electric field. These experimental results suggest that the electric field condition in the guide-field reconnection in the laboratory experiment could be easily controlled to modify the reconnection dynamics of energy conversion and macroscopic change in magnetic structure.

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Curvilinear magnetic fields and ULF waves: A local frame approach to linear MHD waves analysis

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ULF waves are MHD waves observed in the Earth's inner magnetosphere, especially oscillations with periods ranging from a few seconds to a few hundred seconds. The excitation and propagation processes of ULF waves have been extensively studied. Field line resonance (FLR) is a process in which Alfvén waves resonate with fast modes that are excited at the magnetopause and propagate toward the inner magnetosphere. This process excites ULF waves in the inner magnetosphere and explains field line oscillations associated with the Pc4-5 phenomenon (Dungey, 1954; Chen & Hasegawa, 1974; Southwood, 1974). This is one of the most important processes in the excitation of ULF waves whose energy source is outside the magnetosphere; the FLR process has been extensively studied theoretically in cartesian, cylindrical, and dipole coordinate systems (e.g., Mann et al., 1995; Allan et al., 1986; Wright & Elsden, 2016). As a result, it has become clear that the resonance between fast modes and Alfvén waves occurs in the inner magnetosphere, where the Alfvén speed varies with spatial variations in plasma mass density, strength of magnetic field, and field line length.

We have further developed this viewpoint by analyzing how the geometrical characteristics of the background magnetic field geometry, i.e., the curvature and torsion of the field lines, play a role in generating FLR in an arbitrary background magnetic field geometry. The real configuration of the inner magnetosphere is not a dipole-shaped magnetic field or a magnetic field that can be represented by a potential, and its shape changes drastically due to the solar wind and other factors. Therefore, by focusing on the geometrical shape of the magnetic field lines, rather than the shape of the magnetic field, the process of FLR formation can be clarified, and a theoretical study of the region where FLR occurs can be performed even in a realistic magnetosphere shape. We apply an analytical method of Yoshikawa (JpGU 2023). The method employs a local frame with three axes: tangential, normal, and subnormal directions with respect to the magnetic field. The local frame makes it possible to analyze the effects of geometrical properties of arbitrary background magnetic field geometries.

We derived the linearized equations of cold MHD in the local frame. We examined the impacts of the curvature and tortuosity of the magnetic field lines on the orientation of plasma fluctuation and its alteration. The findings propose that the excitation of Alfvén waves might be influenced by magnetospheric compression owing to the dynamic pressure of solar wind and torsion of the flux tube.

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Anti-symmetric and Positivity Preserving Formulation of a Spectral Method for Vlasov-Poisson Equations.

Author: Opal Issan[1]

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Paper: Issan O, Koshkarov O, Halpern F, Kramer B, Delzanno GL (2024). Anti-symmetric and Positivity Preserving Formulation of a Spectral Method for Vlasov-Poisson Equations. Journal of Computational Physics (in press). doi: 10.1016/j.jcp.2024.113263

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Self-consistent theory of cosmic ray penetration into molecular clouds

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We study penetration of interstellar cosmic rays (CRs) into molecular clouds surrounded by nonuniform diffuse envelopes. The present work generalizes our earlier model of CR self-modulation [1,2], in which the value for the envelope's gas density where CRs excite MHD waves was treated as a free parameter. Now, we investigate the case where the density monotonically increases toward the center. We obtain a universal analytical solution which does not depend on the particular shape of gas distribution in the envelope, and self-consistently derive boundaries of the diffusion zone formed within the envelope, where CRs are scattered at the self-excited waves. The values of the gas density at the boundaries are found to be substantially smaller than those assumed in the earlier model, which leads to a significantly stronger modulation of penetrating CRs. We compute the impact of CR self-modulation on the gamma-ray emission, and show that the results of our theoretical model are in excellent agreement with recent observations of nearby giant molecular clouds [3].

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Neural Network-driven Electric and Magnetic Field Reconstruction for Ion Radiography

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Co-authors: Akira Mizuta [2]; Fuka Nikaido [3]; Kentaro Sakai [4]; Shogo Isayama [5]; Shutaro Kurochi [3]; Takumi Minami [3]; Yao-Li Liu [1]; Yasuhiro Kuramitsu [3]; Yen-Chen Chen [6]; Yuki Abe [3]

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In controlled laboratory setups, when lasers interact with solid or gaseous targets, various phenomena such as shock formation, plasma instability, and magnetic reconnection can be observed. Understanding the behavior of electromagnetic fields in plasmas is crucial in these experiments. To measure these fields, scientists utilize a method called ion radiography, also known as proton imaging. High-energy protons are generated from a point-like source and directed through the plasma system. As they travel through the plasma, they interact with electromagnetic fields, causing changes to their paths. When these protons reach a detector, they create an image that reveals the electromagnetic field patterns within the plasma. However, a major challenge in proton imaging techniques is determining the path-integrated electromagnetic fields based on the observed proton fluence. To address this challenge, we aim to use neural network techniques to reconstruct electric and magnetic fields for ion radiography applications. We will present the development plan and recent advancements in this context.

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Insights from Simulation for the Design of the Multi-Needle Langmuir Probe Instrument

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Langmuir probes are essential diagnostic instruments used in laboratory plasma experiments and space missions. While traditional Langmuir probes are limited by their sampling rate due to voltage sweeping processes, the multi-needle Langmuir probe (m-NLP) instrument has been developed to overcome this limitation, offering a higher sampling rate that is particularly advantageous for in-situ measurements in space environments. However, it is well-known that moving objects can disrupt the local plasma environment, potentially resulting in measurement errors. While the primary disturbance during experiments on instrument-carrying rockets and satellites is expected to come from the main rocket or spacecraft body, the interaction between the probes within the m-NLP instrument and the surrounding plasma can also contribute to these errors. In this study, we investigate this interaction using a three-dimensional unstructured particle-in-cell code, Pietra. Initially, we examine the wake formation behind a single Langmuir probe. Subsequently, we extend our analysis to include two probes in the simulation system to assess the effects on the collected current of the Langmuir probes in the plasma flow. This study provides valuable insights for future instrument design aimed at minimizing measurement errors in the m-NLP instrument.

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Welcome & Introduction

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Closing remarks

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Discovering Fluid Closure Equations using Machine Learning

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In computational plasma physics kinetic models are used to simulate plasma phenomena where small scale physics is expected to be of importance. These models contain the full information of the particle velocity distribution function but are computationally expensive. Therefore, computationally cheaper models are utilized, which can then be deployed to larger scales, e. g. 10-moment fluid models or magnetohydrodynamics (MHD). However, the large scale behavior can be influenced by small scale processes (Verscharen et al., 2022). Thus, models are required that can include kinetic processes, in reduced form, into large scale simulations. At the moment, analytical closures are used to close the hierarchy of fluid equations, but these closures are strictly valid only in certain regimes. Finding suitable closure equations is an ongoing research topic that gets increasingly more difficult

in complex systems. In this study, we try to improve fluid models by learning a suitable symbolic closure applying machine learning methods to data from kinetic simulations.\par

At first, less complex physical settings are chosen to be able to compare results with theory, such as Landau damping and the Kelvin-Helmholtz instability. For these test cases the robustness of the method to the choice of parameters and data selection is investigated. Hereby, we aim to reproduce results from previous works, e. g. Long et al. (2019) and Cheng et al. (2023). In the long term the method will be applied to more complex physical settings and could improve existing closure equations and provide insights into the underlying physics.

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Study of Electron Acceleration and Ion Acoustic Waves during Low-beta Magnetic Reconnection using Laser-powered Capacitor Coils

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Magnetic reconnection is a ubiquitous fundamental process in space and astrophysical plasmas that rapidly converts magnetic energy into some combination of flow energy, thermal energy, and non-thermal energetic particles. Over the past decade, a new experimental platform has been developed to study magnetic reconnection using strong coil currents powered by high power lasers at low plasma beta, typical conditions under which reconnection is energetically important in astrophysics [1]. KJ-class lasers were used to drive parallel currents to reconnect MG-level magnetic fields in a quasi-axisymmetric geometry, similar to the Magnetic Reconnection Experiment or MRX [2], and thus this platform is named micro-MRX. This presentation summarizes two major findings from micro-MRX: direct measurement of accelerated electrons [3] and observation of ion acoustic waves [4] during anti-parallel reconnection. The angular dependence of the measured electron energy spectrum and the resulting accelerated energies, supported by particle-in-cell simulations, indicate that direct acceleration by the out-of-plane reconnection electric field is at work. Furthermore, a sudden onset of ion acoustic bursts has been measured by collective Thomson scattering in the exhaust of magnetic reconnection, followed by electron acoustic bursts with electron heating and bulk acceleration. These results demonstrate that the micro-MRX platform offers a novel and unique approach to study magnetic reconnection in the laboratory beyond the capabilities provided by traditional magnetized plasma experiments such as MRX and the upcoming FLARE or (Facility for Laboratory Reconnection experiments) [5]. Implications of these laboratory findings to astrophysical scenarios and future work on studying other particle acceleration mechanisms and ion acoustic waves during magnetic reconnection are discussed.

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Extended MHD and Coupled Fluid-Kinetic Simulations of Planetary Magnetospheres: Applications to Mercury and Ganymede

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Global simulations have become an invaluable tool for studies of planetary magnetospheres, aiding in interpreting satellite observations, uncovering new physics and processes, and deepening our understanding of the fundamental magnetospheric behavior. Because of their relatively large system sizes, planetary magnetospheres are normally simulated with ideal magnetohydrodynamics (MHD) models, treating plasma ions and electrons as a combined fluid. Nevertheless, a proper treatment of key processes in planetary magnetospheres, such as magnetic reconnection, calls for global models that go beyond the ideal MHD approach. Towards this end, the Space Weather Modeling Framework (SWMF) modeling group at the University of Michigan have developed extended MHD models and coupled fluid-kinetic models that enable us to incorporate kinetic physics into global magnetosphere simulations. In this presentation, we will focus on the applications of these sophisticated models to the innermost planet, Mercury, and Jupiter's moon, Ganymede, both of which are magnetized bodies and thus possess intrinsic magnetospheres. We will use these examples to demonstrate our novel modeling capabilities and to discuss the new insights gained from the simulations regarding reconnection-driven dynamics as well as their implications for the global coupling between the ambient plasma and the magnetosphere.

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Effect of plasma composition on the dynamics of astrophysical jets

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The exact plasma composition of astrophysical jets remains an open question to date. Jets originate near compact objects, protostars, and active galactic nuclei. Hence, the composition of the jets depends upon the environment in which they form, and it is expected that the composition should affect the dynamics and morphology of the jets. In this work, we aim to investigate the effect of plasma composition on the dynamics of the jets using exact solutions and numerical simulations. We have addressed various aspects, like the formation of reverse shock in the jet, the effect of an expanding cross-section of the jet head on the structure of the jet, and the effect of fluid composition on the evolution of jets. To probe this problem through simulations, we considered various jet models. These models were characterized by the same injection parameters, the same jet kinetic luminosity, and the same Mach numbers but different plasma compositions. The evolution of these models showed that the plasma composition affects the jet head propagation speed, the structure of the jet head, and the morphology despite fixing the initial parameters. We conclude that the electron-proton jets are the slowest and show more pronounced turbulent structures in comparison to other plasma compositions.

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Role of magnetic fields on Rayleigh-Taylor instability

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The magnetic Rayleigh Taylor instability (MRTI) is ubiquitous in a wide range of astrophysical and laboratory systems. However, the evolution and the dynamics of MRTI is not fully understood. Magnetic fields play a crucial role in the instability dynamics of these systems. Towards understanding the interplay between gravity and magnetic forces on the evolution of instability, we study MRTI under simplified setting using analytical and numerical techniques. Our study shows that the imposed magnetic field delays the onset of self-similarity. However, when sufficiently evolved, MRTI grew with similar temporal scaling as HD instability. The study revealed various physical processes, like energy dissipation (ED), kinetic and magnetic energy partition that determine the non-linear growth of instability across a wide range of magnetic field strengths. A particularly interesting finding is the drastic increase in energy dissipation with marginal increase in field strength, with magnetic ED thrice the kinetic ED for all field strengths. To understand this surprising behaviour, we investigate the potential role of magnetic reconnection. A new technique for the detection of magnetic reconnection sites was developed. Quantitative analysis of these showed that the weak fields have greater reconnection events with small RMS current, while the strong fields have lesser reconnection events but with large RMS current. This could potentially be responsible for greater ED at intermediate fields where the number of reconnection events and mean RMS current optimize to result in maximum energy dissipation. We aim to further investigate the role of magnetic reconnection on MRTI dynamics. Thus, the current study presents a comprehensive understanding on the influence of magnetic fields on the evolution and growth of non-linear MRTI, and the impact of magnetic reconnection on MRTI dynamics. The unspecialized configuration meant the results are applicable in a wide range of practical systems.

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Supernovae as cosmic-ray sources in cosmological hydrodynamical simulations

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In large-scale simulations, that also include spectral cosmic-ray physics, high-energy protons and electrons accelerated at the shocks of supernova remnants have to be described by a sub-grid model. Usually, the injected cosmic rays are represented by a simple power-law spectrum in momentum space. However, in the recent past several models for more realistic cosmic-ray spectra from supernova remnants have been published. They rely heavily on results from state-of-the-art simulations of particle acceleration at strong, collisionless shocks. By combining different approaches, tabulated spectra can be generated, which are the basis for a physically motivated sub-grid description for cosmic-ray seeding by supernova remnants in the cosmological Tree-PM SPH code OpenGadget3. With this code simulations of galaxies in isolated and dense environments can be performed in order to check if the more realistic cosmic-ray spectra lead to quantitative differences in galactic properties and non-thermal radiation.

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Properties of the generation and propagation of whistler-mode chorus emissions in the Earth's inner magnetosphere

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We investigate nonlinear processes in the generation of whistler-mode chorus emissions in the Earth's inner magnetosphere by a series of electron hybrid code simulations. We also study propagation properties of chorus emissions under the presence of duct structure in the magnetosphere. Chorus emissions are coherent whistler-mode waves with varying frequencies in the typical frequency range of 0.2 to 0.8 f_ce0, where f_ce0 is the electron gyrofrequency at the magnetic equator. Chorus emissions play crucial roles in the evolution of radiation belt electrons. The generation process of chorus has been explained by the nonlinear wave growth theory [e.g., Omura, 2021] and has been reproduced by self-consistent numerical experiments [e.g., Katoh and Omura, GRL 2007, JGR 2011, 2013, EPS 2016; Katoh et al., JGR 2018]. The combination of the magnetic mirror force and the Lorentz force by coherent electromagnetic waves induces the phase-space deformation of the distribution function due to the nonlinear trapping of energetic electrons. The phase-space deformation results in the formation of nonlinear resonant currents, generating coherent wave elements with rising/falling tones. Theoretical and simulation studies revealed the existence of the threshold wave amplitude required for the chorus generation. The threshold amplitude depends not only on the properties of energetic electrons but also on the background plasma environment. These results suggest the importance of cross-scale coupling in the magnetosphere. The periodic enhancement of chorus emissions often observed in the magnetosphere can be explained by the modulation of the threshold wave amplitude under the presence of low-frequency magnetohydrodynamic waves. The modulation of the background plasma environment also alters the propagation property of whistler-mode waves.

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Structure-preserving semi-implicit particle-in-cell schemes for the Vlasov–Maxwell system

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Numerical schemes that preserve the structure of the underlying kinetic
equations can provide new insights into the long time behavior of plasmas. Implicit schemes offer the possibility to simulate large scale systems where the characteristic plasma parameters, skin depth and plasma frequency, are underresolved. A very efficient semi-implicit energy-conserving scheme can be derived for the non-relativistic Vlasov-Maxwell system. The situation is more complex for the relativistic case. In this talk, we will discuss a semi-implicit scheme that preserves Gauss' law exactly and in the non-relativistic limit.

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Global MHD and Test-Particle Simulations of Solar Wind Charge Exchange from the Earth's magnetospheric boundaries

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The intricate energy exchanges within the Sun-Earth system, including geomagnetic storms, profoundly influence both ground and space technologies crucial for modern society. Effective forecasting and mitigation of space weather necessitate vigilant monitoring of the Earth's magnetosphere. However, this task is hindered by limited in-situ satellite measurements and ground-based observations. The Solar Wind Charge Exchange (SWCX) mechanism, which entails X-ray emissions from the interaction of heavy, high charge state solar wind ions, forms the basis for the upcoming SMILE (Solar wind Magnetosphere-Ionosphere Link Explorer) mission, designed to image the global magnetosphere using these X-rays. Our project aims to interpret SMILE's X-ray datasets through Global Magnetohydrodynamics (MHD) simulations, enhanced to incorporate heavy ions and X-ray emissions within the framework of space plasma dynamics. In this talk, we will present an analysis of SWCX from the Earth's magnetopause and cusp regions under various solar wind conditions, along with the initial comparisons between the predictions of the global MHD model and those generated from our embedded kinetic particle model. The outcome of the project is expected to unveil the fundamental physical processes governing the solar wind-magnetosphere interaction and energy circulation as observed by the SMILE mission.

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Small-scale dynamos create large-scale coherence in young galaxies

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The Universe was born without magnetic fields, yet in the modern Universe dynamically important magnetic fields are ubiquitous. The standard model of magnetogenesis explains this with small-scale dynamo (SSD) amplification of weak primordial fields to the levels we see today, followed by larger-scale coherence generated through large-scale dynamos (LSDs). This model, however, faces challenges in explaining large-scale ($\sim$ kpc) magnetic structures observed in merging and young (z $>$ 2) galaxies, where LSDs are absent. Incompressible SSD theories predict magnetic fields in these environments to be correlated on $\ll$ pc scales, significantly smaller than the fields we observe. We address this discrepancy by using direct numerical simulations to establish clear relationships between the magnetic field morphology produced by SSDs, and the global properties of these plasma environment, leading us to a resolution of the scale problem: supersonically-moving shocks within compressible plasmas violently reorganise magnetic fields into structures associated with denser regions of plasma. While magnetic fields naturally concentrate their energy near their dissipation scale ($\ll$ pc), turbulent, shock-filled environments like young galaxies, reorganise these fields to significantly larger-scales ($\sim$ kpc), and thus we can explain the ordered magnetic fields observed.

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Laboratory investigations of Terrella

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Terrella ("little Earth"[1]) is a metalized spherical magnet with a dipolar magnetic field that can serve as a laboratory model of compact space objects with large magnetic fields (neutron stars, white dwarfs, etc.). In our case, Terrella is a spherical neodymium magnet with a diameter of $19\ \mathrm{mm}$ supplied by high voltage (up to $400\,\mathrm{V}$) at a pressure between $2\,\mathrm{Pa}$ and $200\,\mathrm{Pa}$ in the environment of an inert gas (Ar). For positive polarity of applied voltage, the discharge appears mainly in the vicinity of magnetic poles, while for negative polarity, the discharge forms a disk perpendicular to the magnetic axis in the equatorial plane.

We investigated mainly the "disk"mode (negative applied voltage), where we measured electrical characteristics of the discharge, the radial distributions of Ar spectral lines by spectrograph and the radial distribution of the emitted light (integrated from all detectable wavelengths) by ICCD camera. In the selected area, the average light intensity (calculated from ICCD measurements) was determined depending on the distance from the edge of the Terrella. The resulting radial dependences were fitted by a power law in the distance of $1.1\ r_{\mathrm{Terr.}} - 2.44\ r_{\mathrm{Terr.}}$ from Terrella's edge (for large "r"). The exponent of the power law decreased with increasing pressure, e.g., $k = -1.93\ (2.1\ \mathrm{Pa})$, and $k = -3.17\ (200\ \mathrm{Pa})$. These results fairly well overlapped with the theoretical model AGNSLIM [2], where the radial surface brightness dependence was $L(r)\ \propto\ r^{-2}$.

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Magnetosheath jet contribution to mass, energy, and flux transport in the magnetosheath using Amitis

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Earth's magnetosheath is a turbulent region where magnetosheath jets, localized dynamic pressure enhancements, are often observed. These magnetosheath jets form primarily at the quasi-parallel bow shock and move through the magnetosheath towards the magnetopause. Jets therefore transport mass, momentum, and energy across the magnetosheath. However, so far there are no estimates on the contribution of jets in energy transport through the magnetosheath due to limitations of observations that are single point measurements. 3D simulations with realistic scales are therefore needed to estimate the contribution of jets to magnetosheath transport. For these estimates we make use of the Amitis code, a hybrid-kinetic plasma simulation (particle ions and fluid electrons). Amitis simulates the solar wind interaction with Earth at realistic scales in three-dimensions in both configuration and velocity space. Using the simulation results we identify the magnetosheath and jets. We then calculate the mass, momentum, and energy contained in jets and compare it to regions deficit of jets. We also calculate the mass and energy flux carried by jets across the bow shock and the magnetopause.

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How non-equilibrium thermodynamics constrains magnetohydrodynamics in dilute astrophysical plasmas

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The transport of energy and momentum and the heating of plasma particles by waves and turbulence are key ingredients in many problems at the frontiers of heliospheric and astrophysics research. This includes the heating and acceleration of the solar wind, the observational appearance of black-hole accretion flows on event-horizon scales, and the properties of the hot, diffuse plasmas that fill dark-matter halos. All of these plasmas are magnetized and weakly collisional, with plasma beta parameters of order unity or even much larger. In this regime, deviations from local thermodynamic equilibrium (LTE) and the kinetic instabilities they excite can dramatically change the material properties of such plasmas and thereby influence the macroscopic evolution of their host systems. This talk outlines an ongoing programme of hybrid-kinetic and fluid-kinetic calculations aimed at elucidating from first principles the multi-scale physics of magnetized, weakly collisional, high-beta astrophysical plasmas. Interrupting Alfvén waves, self-sustaining sound waves, microphysically modified magnetosonic modes, mirror-infested current sheets, and magneto-immutable turbulence will feature in a discussion of how self-generated pressure anisotropies fundamentally alter waves, turbulence, and heating in dilute astrophysical plasmas.

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PIC Simulations of Sunward and Anti-sunward Whistler Waves in the Solar Wind

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The heat flux of electrons plays a crucial role in energy transport processes in collisionless or weakly collisional plasma of the solar wind. Early observations indicated that the collisional Spitzer-Härm law cannot describe the heat flux in the solar wind. Various mechanisms for regulating heat flux in the solar wind have been proposed, such as the interaction of electrons with whistler waves generated by the so-called whistler heat flux instability (WHFI). This instability arises in plasma with at least two counter-streaming electron populations. Recent observations have demonstrated the development of WHFI in the solar wind, showing that this instability generates predominantly quasi-parallel whistler waves with amplitudes up to a few percent of the background magnetic field. However, the question of whether such whistler waves can regulate the heat flux remained open.

We present the results of simulations of whistler wave generation and the nonlinear evolution of WHFI using the TRISTAN-MP PIC code. This code simulates the self-consistent dynamics of two counter-streaming electron populations: warm (core) electrons and hot (halo) electrons. We investigated wave generation in two cases: for pure WHFI, when both populations are isotropic, and for anisotropic WHFI, when halo electrons have perpendicular temperature anisotropy. Our calculations show that the instability produces whistler-mode waves propagating both parallel (anti-sunward) and anti-parallel (sunward) to the electron heat flux. The saturated amplitudes of both sunward and anti-sunward whistler waves are strongly correlated with their initial linear growth

rates. We also studied spectral properties of the generated waves and demonstrated that the instability develops in quasi-linear regime. As far as the heat flux is concerned, we found that parallel and anti-parallel waves affect it in the opposite directions, but the net effect is a heat flux reduction. Our simulations indicate that while pure WHFI cannot regulate the heat flux in the solar wind, a combined heat flux and anisotropy instability can contribute to the heat flux regulation.

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Nonlinear Drift-Bounce Resonance Between Charged Particles and Ultralow Frequency Waves

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Ultra-low frequency (ULF) waves contribute significantly to the dynamic evolution of Earth's magnetosphere by accelerating and transporting charged particles within a wide energy range. A substantial excitation mechanism of these waves is their drift-bounce resonant interactions with magnetospheric particles. Here, we extend the conventional drift-bounce resonance theory to formulate the nonlinear particle trapping in the ULF wave-carried potential well, which can be approximately described by a pendulum equation. We also predict the observable signatures of the nonlinear drift-bounce resonance, and compare them with spacecraft observations. We further discuss potential drivers of the pendulum including the convection electric field and the magnetospheric dayside compression, which lead to additional particle acceleration or deceleration depending on magnetic longitude. These drivers indicate preferred regions for nonlinear ULF wave growth, which are consistent with previous statistical studies.

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Three-dimensional global hybrid simulations of interaction between the solar wind and the magnetospheres of Earth and Mercury

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The interactions between the solar wind and planetary magnetospheres dictate the planetary space environments. Three-dimensional global hybrid simulations allow us to better understand such interactions by considering particle kinetic effects in global configurations. I will talk about some of our simulation results for Earth's and Mercury's magnetospheres, including 1) Flux ropes and their effects on the magnetospheres, 2) magnetosheath high-speed jets and their effects on the magnetosphere, 3) magnetotail thin current sheet and magnetic reconnection therein.

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A new regime of plasma wave modes in Jupiter's polar cap

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The Juno satellite is the first satellite in polar orbit around Jupiter, leading to unprecedented coverage of Jupiter's magnetosphere. During the Juno extended mission, the satellite samples the polar regions of Jupiter at altitudes of less than 0.5 Jovian radii. Observations from Juno have indicated very low densities, as low as 10−3 cm−3, on polar cap field lines at Jupiter (Sulaiman et al., 2023). This region is strongly magnetized, with surface magnetic fields up to 20 G, or 2 mT (Connerney et al., 2022), leading to the unusual situation that the electron plasma frequency is less than the ion gyrofrequency. For example, in a 1 G (100 μT) field, the proton gyrofrequency is about 1.5 kHz, corresponding to the electron plasma frequency for a density of 0.03 cm−3. In a more typical plasma where the ion gyrofrequency is lower than the plasma frequency, the Alfvén mode transitions to an electromagnetic ion cyclotron wave, sometimes called the Alfvén-ion cyclotron mode at large wave number. However, in this extremely low-density plasma, the Alfven wave becomes a plasma oscillation at the plasma frequency. Analysis of this mode with a kinetic low-frequency dispersion solver indicates that at large wave number, this mode has the characteristics of the Langmuir wave. Thus, this mode can be called an Alfvén-Langmuir mode. Below the plasma frequency, the high-wave number behavior of this mode exhibits a resonance cone, with frequency determined by the angle of the wave vector with the background magnetic field.

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Preliminary concept for an electrodeless Magnetic Reconnection Thruster (e-MRT)

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Advanced thrusters are needed for deep space missions to Mars and beyond. For such thrusters, it is critical to determine how to generate large thrust-to-power at sufficiently high specific impulse with long lifetime and flexibility in propellant. To address these challenges, we are exploring a new electrodeless Magnetic Reconnection Thruster (e-MRT), which will use asymmetric, inductively-driven, partially ionized magnetic reconnection outflows to provide spacecraft thrust. One of the outflow jets may be blocked by strong magnetic pressure to help generate net momentum transfer to the spacecraft. Not requiring electrodes would mitigate electrode erosion, which is a key constraint on the lifetime of the existing candidate magnetoplasmadynamic and Z-pinch thrusters for deep space missions. Proof-of-principle experiments using a displacement sensor to measure thrust are underway on the Magnetic Reconnection Experiment at PPPL.

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The ESA M7 candidate mission Plasma Observatory

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2D PIC simulation of particle acceleration in oblique pickup ion mediated shocks

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Two-dimensional full particle-in-cell simulations of pickup ion mediated oblique shocks were conducted with unprecedentedly long simulation times (over 100 times the inverse ion gyro frequency) and large system sizes (2000 times the ion inertial length) along the shock normal direction. An oblique shock refers to a shock where the angle between the shock normal direction and the upstream magnetic field vector, known as the shock angle, is between 50 and 70 degrees in this case.

We tracked the long-term evolution of oblique shocks, including solar wind electrons, ions, and pickup ions. When the shock angle is 50 degrees, pickup ions reflected at the shock and backstreaming toward the upstream excite large-amplitude waves through resonant instability. These excited waves are convected and impact the shock front, leading to shock reformation and altering the downstream electromagnetic structure. Some pickup ions were accelerated to nonthermal energies over a timescale of about 100 times the inverse ion gyrofrequency. Orbit analysis of the accelerated particles revealed that the shock surfing acceleration mechanism operated during the initial stages, followed by the shock drift acceleration mechanism. The resultant downstream energy distribution function of pickup ions indicates a more efficient generation of nonthermal pickup ions compared to previous hybrid simulations.

While shock surfing acceleration has been considered ineffective at a perpendicular termination shock of the heliosphere, our findings indicate that the electrostatic potential associated with large-amplitude upstream waves contributes to the manifestation of this acceleration mechanism in oblique termination shocks.

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Magnetic Heating during State Transitions in Black Hole Accretion Flows

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We found by three-dimensional global radiation magnetohydrodynamic simulations that during the hard-to-soft state transition observed in stellar mass black hole candidates and in active galactic nuclei, toroidal magnetic field is amplified around the interface between the hard X-ray emitting hot accretion flow near the black hole and the radiatively cooled outer disk. Since the magnetic pressure supports the disk around the interface, the thermal and dynamical state of the region are distinct from the geometrically thin, standard accretion disk.
The magnetically supported toroidally magnetized accretion disk (Toroidal MAD) can explain why black hole candidates stay in the intermediate state between X-ray hard state and X-ray soft state for time scale much longer than the thermal time scale. We found that counter helicity toroidal flux tubes formed around the interface are injected into the radiatively cooled outer region, and keeps this region warm by releasing the magnetic energy through magnetic reconnection.

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4th-Order Accurate Methods for Relativistic MHD with Finite Conductivity

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Recent advancements in the state-of-the-art modelling of relativistic astrophysical plasma via numerical simulations are presented. In particular, I will focus on a novel implementation of a genuinely 4th-order accurate finite volume scheme for the solution of the relativistic MHD equations in the presence of a finite conductivity. The method has been successfully implemented and validated in the upcoming GPU version of the PLUTO code using either constant and effective resistivity models. Preliminary results and applications to relativistic magnetic reconnection in 2D and 3D will be discussed.

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Hybrid simulation study of high-frequency H-band EMIC waves in the Earth's magnetosphere

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Narrowband (Δf < 0.1 fcp), high-frequency (0.9 fcp < f < fcp) electromagnetic ion cyclotron (EMIC) waves, or HFEMIC waves for short, are a new type of EMIC waves found in the Earth's inner magnetosphere. Observations suggest that they can be excited by low energy (< ~100 eV), very anisotropic protons. Here, we explore the instability threshold condition and hybrid simulations of HFEMIC waves, and compare the results with the observations. Linear theory analysis at parallel propagation shows that the anisotropy-parallel beta relation at instability threshold approximately follows an inverse relation like the one for typical H-band EMIC waves. Unlike typical EMIC waves, however, the minimum temperature anisotropy required is very large (> 10), the convective growth rate at a fixed instability threshold is large because of small group velocity of HFEMIC waves, and heavy ions affect the instability only weakly, primarily through the introduction of stop bands. To investigate the quasilinear and nonlinear behavior, one-dimensional hybrid simulations are run in the dipole-like background magnetic field and with initial parameters constrained by observation. Despite a narrow source region (within about ±3◦ latitude due to a large anisotropy required for HFEMIC instability), HFEMIC waves in the simulations grow well above the thermal noise level, due in large part to to a small group velocity of HFEMIC waves at the equatorial source region. The saturation level is well within the range of observational amplitudes, and the wave evolution is primarily determined by the quasilinear process. We demonstrate that the present results compare favorably to the recent observational findings, thereby supporting anisotropic low-energy protons as free energy source for HFEMIC waves.

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Magnetic reconnection in 3D collisionless plasma turbulence: electron effects

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It is known that magnetic reconnection can occur in current sheets generated by collisionless turbulence in space and astrophysical plasmas, a process known as turbulence-driven reconnection. The importance of this process for the turbulence properties is, however, still not well understood. Although significant simulation work has been done on this topic in 2D and at MHD and ion-scales, the consequences of electron-scale effects such as electron inertia are relatively unexplored, and more so in 3D. Those effects can control the dissipation of turbulence and enable reconnection.
Here we focus on assessing and quantifying the consequences of turbulence-driven reconnection and current sheets by comparing 3D simulations carried out with three different plasma models: fully-kinetic and hybrid-kinetic with and without electron inertia. Our results show that electron effects are important for turbulence-driven reconnection not only at electron-scales, but even above them.

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Simulating ribs and tethers in AGN jets

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Context: The latest generation of radio telescopes, with their enhanced sensitivity and refined spatial resolution, are unveiling previously unidentified objects and capturing them with unprecedented details. One such enigmatic object is a radio galaxy located within the Abell 3266 cluster named "MysTail", observed as part of the MeerKAT Galaxy Cluster Legacy Survey. This galaxy exhibits complex morphological features, including a distinctive ribbed tail, referred to as 'ribs,' and thin, faint filamentary structures known as 'tethers' that stretch between two bright patches far from the host.
Aim: This work aims to unravel the origin of such distinctive, intricate morphologies of relativistic jets by examining the role of dynamical instabilities, with a specific focus on "MysTail".
Methods: We performed 3D relativistic magnetohydrodynamic (RMHD) simulations of rotating jets, with a particular focus on dynamical instabilities. We have further utilized the hybrid Eulerian-Lagrangian framework of the PLUTO code and generated synthetic synchrotron emission and polarisation maps at a radio frequency of 1.285 GHz to compare with the observed signatures of "MysTail". We conducted two types of simulation runs: one involving continuous jet injection and another where the jet injection was temporarily stopped for a significant period ($\approx$ 1.3 Myrs) before being restarted.
Results: Our analysis based on simulations of a continuously injected jet suggests that current-driven instabilities, notably the $|m| = 1$ mode, are crucial in generating ribs-like structures. In the case of restarted jet simulation, the rib-like structures were formed via kink instability and were relatively near the nozzle. In both of these cases, the jet dissipates its pre-existing magnetic energy through these instabilities, transitioning to a more kinetic energy-dominant state. The turbulent structures in the vicinity of the forward shock that result from this dissipation phase are found to be filamentary in nature and resemble the tethers as observed for the case of "MysTail". Our simulations suggest that "MysTail" is a single contiguous source in a phase of restarted AGN activity undergoing MHD instabilities (ribs) as it propagates and dissipates energy forming turbulent filaments (tethers).

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3D PIC simulations for relativistic jets with a toroidal magnetic field and results from 2D GRPIC simulations

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Particle-in-Cell simulations can provide a possible answer to an important key issue of astrophysical plasma jets, i.e., how a toroidal magnetic field affects the evolution of pair and electron-ion jets associated to the acceleration of particles. We show that Weibel, mushroom, and kinetic Kelvin-Helmholtz instabilities excited at the linear stage, generate a quasi-steady electric field component

along the jet, which accelerates and decelerates electrons. We find that the two different jet compositions (pair and electron-ion) generate different instability modes respectively and observe significant differences in the structure of the strong electromagnetic fields that are driven by the kinetic instabilities with the pair jet. Moreover, the magnetic field in the non-linear stage generated by different instabilities is dissipated and reorganized into new topologies. A 3D magnetic field topology depiction indicates possible reconnection sites in the non-linear stage where the particles are significantly accelerated by the dissipation of the magnetic field associated to a possible reconnection manifestation. We have investigated the temporal evolution of an axisymmetric magnetosphere around a rapidly rotating stellar-mass BH by applying a two-dimensional particle-in-cell simulation scheme. Adopting homogeneous pair production and assuming that the mass accretion rate is much less than the Eddington limit, We demonstrate that the extracted energy flux concentrates along the magnetic field lines threading the horizon in the middle latitudes. It is implied that this meridional concentration of the Poynting flux may result in the formation of limb-brightened jets from low-accreting BH systems. Magnetic islands are created by reconnection near the equator and migrate toward the event horizon, expelling magnetic flux tubes from the BH vicinity during a large fraction of time. When the magnetic islands stick to the horizon due to redshift and virtually vanish, a strong magnetic field penetrates the horizon, enabling efficient extraction of energy from the BH. During this flaring phase, a BH gap appears around the inner light surface with a strong meridional return current toward the equator within the ergosphere. We have shown that the jets exhibit limb-brightened structures in a wide range of viewing angles.

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Study of atmospheric ion escape from exoplanet TOI-700 d based on global multi-species MHD simulations

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TOI-700 d is the first Earth-sized planet in the habitable zone (HZ) discovered by the Transiting Exoplanet Survey Satellite. Here, we assess whether a Venus-like exoplanet at the TOI-700 d location could retain an atmosphere for a time comparable to the age of the host star based on multispecies magnetohydrodynamics simulations [1]. We investigate the effects of X-ray and EUV (XUV) radiation from the host star, the interplanetary magnetic field (IMF) orientation, and the planetary intrinsic magnetic field. In unmagnetized cases, major ion loss is caused
by O+ escape through a ring-shaped region by the mass loading process after the ionization of the extended oxygen corona. As the IMF Parker spiral angle increases, the escape flux in the magnetotail shows stronger enhancement around the meridional current sheet, and the escape rate of molecular ions (O2+ and CO2+) increases by an order of magnitude due to acceleration in the ionosphere by magnetic tension forces. In magnetized cases, the intrinsic magnetic field suppresses ion pickup loss from the neutral oxygen corona by deflecting the stellar wind and preventing ion pickup while promoting cusp-origin escape from the lower ionosphere. These results suggest that the unmagnetized exoplanet would have difficulty retaining its atmosphere over a few billion years under extreme conditions where XUV is 30 times stronger than at the current Earth. However, the dipole intrinsic magnetic field of 1,000 nT at the equatorial surface reduces the escape rate and would help the exoplanet to retain its atmosphere even under strong XUV conditions.

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Modelling the interaction of Galactic Cosmic Rays and Coronal Mass Ejections: Combined MHD and Test Particle simulations.

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Galactic cosmic rays (GCRs) are charged particles with extremely high energies originating from outside the heliosphere. Their passage through the solar wind is affected by many long and short term factors, including transient structures such as coronal mass ejections (CMEs). The short term decrease in GCR flux caused by CMEs, and observed by charged particle detectors on spacecraft and ground-based neutron monitors is called a Forbush decrease (FD). FDs have a varied and complex profile, often showing a 2-step decrease corresponding to the structure of the CME –the first decrease corresponding to the shock and turbulent sheath region, and the second caused by reduced radial transport into the magnetic cloud structure. Current analytic and numerical models of this phenomenon have considered diffusion through the shock or into the magnetic cloud as separate processes, but have not been applied to realistic, 3-dimensional CME field geometries. We present progress in combining magnetohydrodynamic simulations of CMEs and background solar wind with full-orbit test particle simulations to reproduce the entirety of a 2-step FD, and to gain a greater understanding of how energetic particle observations can be used to infer global structure of CMEs.

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Behaviour of Kinetic Electron Instabilities in the Magnetosheath Modelled with Semi-Implicit PIC

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Variation of plasma density and magnetic field in space plasma drives the development of temperature anisotropies in the component species. A sufficiently large anisotropy of electrons in the direction perpendicular to the ambient magnetic field causes whistler and mirror instabilities to grow. It has been suggested that the anisotropy of the electron species can affect the growth of instabilities in the proton species (Ahmadi et. al., 2016), which may help to explain why observations of proton instabilities in Earth's Magnetosheath show the growth of unstable mirror modes (Kaufmann et al., 1970) in regions where linear theory predicts cyclotron instabilities will dominate. Given the potential for cross-species interplay, a thorough understanding of the behaviour of the electron whistler instability, which typically dominates the electron species, is crucial. By leveraging multidimensional kinetic simulations with the Energy Conserving Semi-Implicit Method (Gonzalez-Herrero et al., 2018), this work examines the behaviour of the electron whistler instability in parameter space typical of Earth's Magnetosheath. Recent work has shown that the effect of high-energy tails found in kappa distributions on reducing the growth rate of the whistler instability is insufficient to counteract the consumption of electron temperature anisotropy. Thus the suitability of a low-electron

beta parameter space, where the whistler instability is stable but electron temperature anisotropy is sufficient to enhance the proton mirror instability, is being investigated for its suitability to explain observations in the Magnetosheath.

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Test Particle Simulation of Relativistic Proton Acceleration by Electromagnetic Ion Cyclotron Waves in the Jovian Magnetosphere

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We present a physical mechanism for generating GeV protons in the Inner Jovian Magnetosphere [1], which may contribute to formation of the proton radiation belts. The mechanism consists of two nonlinear processes called anomalous trapping and relativistic turning acceleration (RTA) and involves a special form of nonlinear wave trapping by electromagnetic ion cyclotron (EMIC) waves. Necessary conditions for anomalous trapping and RTA include a near-equatorial source of EMIC waves, strong wave amplitudes (of the order of a few percent of the background magnetic field strength), and a source of protons of sufficiently high energy. The anomalous trapping occurs for energetic protons at low pitch angels, and it transports most of protons at low pitch angels to the energy and pitch angles satisfying the cyclotron resonance condition. Then the RTA occurs when the equatorward moving protons encounter pole-ward moving EMIC waves, and they become entrapped and undergoes a turning motion due to increasing kinetic energy. The trapped ions then move poleward in the same direction as the waves and eventually become detrapped, but during the turning motion the ions undergo significant acceleration. We rigorously verify this process by providing the theory of nonlinear interactions between relativistic protons and coherent EMIC waves. The RTA process has been previously established for the analogous whistler mode wave-electron interaction [2]. We carry out test particle simulations for protons at r = 2 RJ (where RJ = Jovian radius) interacting with EMIC waves of amplitude Bw = 0.02 B0eq where B0eq = background magnetic field strength at the equator). We confirm that a large portion of test protons experience RTA and that some protons of critical energy 240 MeV can be accelerated to 10GeV in a period of 5 seconds.

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High Power Ion Heating by Magnetic Reconnection in Two Merging Toroidal Plasmas with High Guide Field

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In two toroidal plasma merging experiments with high guide field (B_t » B_p), the ion heating energy by magnetic reconnection is shown to scale with the reconnecting magnetic energy ($B_{rec}^2/2\mu_0$) where B_{rec}~B_p. This B_{rec}^2- scaling of ion heating energy by reconnection can be understood by the fact that in the reconnection downstream the ion energy is mainly in the form of outflow kinetic energy before ions are thermalized in further downstream. The ion outflow velocity is produced mainly by the large $E \times B$ drift velocity associated with large poloidal electric field E_z, resulting from the formation of quadrupolar electrostatic potential structure in the downstream region and E_z depends linearly on $B_t B_{rec}$~$B_t B_p$ as observed in the experiments. Hence, the outflow velocity scales with B_{rec}, and thus the ion heating energy scales with B_{rec}^2. High power ion heating with about 40-50% of $B_{rec}^2/2\mu_0$ can only be achieved when the reconnection current sheet thickness δ is compressed to smaller than the ion gyroradius ρ_i. If δ»ρ_i, the magnetic reconnection converts only 5-10% of $B_{rec}^2/2\mu_0$ into ion energy. The B_{rec}^2-scaling of high-power reconnection ion heating provides an efficient way to produce burning plasmas with T_i > 10keV by increasing B_{rec} to 0.6T (for n_e ~ $1.5 \times 10^{19} m^{-3}$) without using any auxiliary heating methods.

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Simulation Study of Solitary Waves in the Martian Magnetosphere

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Mars lacks a global magnetic field but it has a weak induced magnetosphere resulting from the solar wind interaction with its upper atmosphere. Despite its slender spatial profile, it can facilitate various plasma wave activities. The Langmuir Probe and Waves (LPW) experiment aboard the MAVEN (Mars And Volatile EvoluioN) spacecraft has observed electrostatic solitary structures in the Martian magnetosheath. However, their generation mechanisms needs to be examined. In this investigation, we perform fluid simulations to analyze the evolution and characteristics of solitary waves observed within the induced Martian magnetosphere. By introducing density perturbations at equilibrium, we excited solitary waves for the observed plasma parameters. The results obtained from the simulation will be discussed in light of the observed solitary waves in the Martian magnetosphere.

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Preliminary Measurements of Non-Maxwellian Electron Energy Distributions During Magnetic Reconnection in a Laboratory Plasma

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Nonthermal particle acceleration is believed to account for a large portion of the energy dissipated during magnetic reconnection. However, this process remains poorly understood, and laboratory observation of non-thermal acceleration remains limited. Here, we present a novel design for a multi-channel electron energy analyzer for studies of electron acceleration in magnetic reconnection. This analyzer uses selector grids biased at fixed voltages to obtain a time-resolved five-channel spectrum of electron energy, allowing microsecond-scale plasma evolution to be measured without creating strong polarization currents that plague single-channel sweeping probes. We implement this probe in the Magnetic Reconnection Experiment (MRX), and show preliminary observations of non-Maxwellian electron energy distributions formed during the magnetic reconnection process.

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Particle Acceleration due to Magnetic Reconnection in Laser-Powered Capacitive Coils

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Magnetic Reconnection is the ubiquitous astrophysical process in which a plasma rapidly converts magnetic field energy into a combination of flow energy, thermal energy and non-thermal energetic particles. Various particle acceleration mechanism (including Fermi acceleration, betatron acceleration, parallel electric field acceleration, out-of-reconnection plane acceleration) have been theoretically proposed and numerically studied in collisionless low-Beta environments. Recently [1], this environment has been experimentally studied using the Omega-EP platform. Using kJ lasers, we drive parallel currents through capacitive coil targets to achieve MegaGauss-level magnetic reconnection. We summarize results indicating that the primary acceleration mechanism in this setup is the out-of-plane reconnection electric field. We then present future laser-target reconnection concepts that will allow us to both further verify these results and study alternative particle acceleration mechanisms.

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Investigating the contribution of Simulated Background Solar Wind on WSA-ENLIL+CONE CME Model Prediction Error Using Machine Learning.

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Coronal Mass Ejections (CMEs) are major drivers of Space Weather (SWx) effects on Earth, and predicting their arrival is a major aspect of SWx forecast. Several CME propagation models have been developed for this purpose, but the overall arrival time error still exceeds 12 hours. In this study, we aim to improve these predictions by employing machine learning (ML) techniques that utilize the differences between observed and simulated solar wind (SW) profiles ahead of CMEs. Our analysis includes 160 CME events from March 2012 to March 2023. We found that the mean average error (MAE) for the WSA-ENLIL+CONE (WEC) modeling of these events is ~ 12.54 hours. We use OMNI data to get the near-Earth observed SW profile. The simulated background SW is borrowed from publicly available simulation results obtained by the ENLIL model. These datasets include key SW parameters such as speed, density, temperature, magnetic field strength, and total pressure. The mean difference between these observed and simulated parameters, from the time of insertion to the time of arrival, is calculated for each CME. We employ three ML models—1) k-nearest neighbors (KNN), 2) support vector machine (SVM), and 3) linear regression (LR) in our analysis. These models use errors in the upstream SW parameters as features. Our ML models are set up to estimate the error in the WEC prediction based on the errors in the upstream SW parameters. Our results identified the mean SW pressure difference as the most effective parameter for estimating WEC error. We were able to reduce the MAE given by the WEC model by 1.15 hours using the SVM model. This shows that the incorrect SW background created using WSA-ENLIL contributes to MAE, and our proposed ML-based methods can reduce the MAE by quantifying this contribution.

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Energy Conversion and Particle Heating in Electron-only Magnetic Reconnection with Intense Guide Fields

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Magnetic reconnection is an ubiquitous phenomenon observed in laboratory, fusion and space plasmas. It is usually accompanied by the energy conversion between electromagnetic fields and plasmas [1]. Recently, a new regime called "electron-only magnetic reconnection"(e-rec hereafter) was observed and studied in the Earth's magnetosheath [2] and in laboratory plasmas [3]. The novelty of e-rec lies in that its temporal and spatial scales are so small that only electrons are involved in this process and ion outflow jets existing in standard ion-coupled reconnection are absent in this new regime. It has been discovered in numerical simulations that electronscale reconnection is an integral part of plasma turbulence and may play a role in the energy cascade and dissipation. The energy conversion and particle heating in standard ion-coupled reconnection has been extensively investigated in both experiments and simulations. However, the energy transfer in e-rec is poorly investigated, especially in the presence of intense guide fields. In our work, we analyze the energy conversion and electron heating of electron-only reconnection in the presence of intense guide fields through 2.5D Particle-in-Cell (PIC) simulations. We initialize our setup with a force-free equilibrium and study different cases by adjusting the strength of the out-of-plane guide field Bg (with values of Bg up to 20 times the reconnecting in-plane magnetic field). The electron heating is anisotropic and primarily concentrated along the reconnection separatrices. The width of the heating region on the separatrices is influenced by the strength of the guide field. Non-Maxwellian electron velocity distribution functions are also observed in multiple regions.

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The plasma physics of the Galaxy's most extreme particle accelerators

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With the advent of Ultra-High Energy gamma-ray astronomy (photons above 100 TeV energies) it is at last possible to directly probe the most extreme particle accelerators in our galaxy. Two source classes have emerged as highly prominent producers of the cosmic rays above PeV energies, namely massive stellar clusters and microquasars, adding a new dimension to the long held supernova remnant paradigm for galactic cosmic-ray origins. The mechanisms underpinning the energisation of these energetic particles however remains inconclusive. I will review some of the key recent observational developments, progress in theoretical modelling of these sources, and introduce a new open-source software, Sapphire++, that can be used to self-consistently study cosmic-ray plasma physics at extreme energies.

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Laboratory study of lunar magnetic reconnection with laser-driven mini-magnetospheres

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Mini-magnetospheres are ion-scale structures that are ideal for studying the kinetic-scale physics of collisionless space plasmas. Such ion-scale magnetospheres can be found on local regions of the Moon, associated with the interaction of the solar wind with the lunar crustal magnetic field. In this work, we report on the experimental study of magnetic reconnection in laser-driven lunar-like ion-scale magnetospheres on the Large Plasma Device (LAPD) at UCLA. In our experiment, we use a high-repetition rate (1 Hz), nanosecond laser to drive a fast moving plasma that expands into the field generated by a pulsed magnetic dipole embedded into a background plasma and magnetic field [1].

The dipole and background fields are oriented to be anti-parallel, allowing a magnetic reconnection geometry. The high-repetition rate enables the acquisition of time-resolved volumetric data of the magnetic and electric fields to characterize magnetic reconnection and calculate the reconnection rate. We notably observe the formation of Hall fields associated with reconnection. Particle-in-cell simulations reproducing the experimental results were performed to study the micro-physics of the interaction. We carry out a generalized Ohm's law terms analysis and find that the electron-only reconnection is mostly driven by kinetic effects, through the electron pressure anisotropy [2].

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On the Effect of Driving Turbulent-like Fluctuations on a Harris-Current Sheet Configuration and the Formation of Plasmoids

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Energy dissipation in collisionless plasmas is one of the most outstanding open questions in plasma physics. Magnetic reconnection and turbulence are two phenomena that can produce the conditions for energy dissipation. These two phenomena are closely related to each other in a wide range of plasmas. Turbulent fluctuations can emerge in critical regions of reconnection events, and magnetic reconnection can occur as a product of the turbulent cascade. In this study, we perform 2D particle-in-cell simulations of a reconnecting Harris current sheet in the presence of turbulent fluctuations to explore the effect of turbulence on the reconnection process in collisionless non-relativistic pair-plasmas. We find that the presence of a turbulent field can affect the onset and evolution of magnetic reconnection. Moreover, we observe the existence of a scale dependent amplitude of magnetic field fluctuations above which these fluctuations are able to disrupt the growing of magnetic islands. These fluctuations provide thermal energy to the particles within the current sheet and preferential perpendicular thermal energy to the background population.

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A Multi-Scale Kinetic Simulation of Plasma Dynamics from Magnetotail Reconnection to the Inner Magnetosphere

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During magnetospheric substorms, plasma from magnetic reconnection in the magnetotail is thought to reach the inner magnetosphere and form a partial ring current. We simulate this process using a fully kinetic particle-in-cell (PIC) numerical code starting from a global magnetohydrodynamics (MHD) model run for nominal solar wind parameters and a southward interplanetary magnetic field. The PIC simulation extends from the solar wind outside of the bow shock to beyond the reconnection region in the tail. By the end of the PIC calculation, ions and electrons from the tail reconnection reach the inner magnetosphere and form a partial ring current and diamagnetic current. The primary source of particles reaching the inner magnetosphere is bursty bulk flows (BBFs) that originate from a complex pattern of reconnection in the near-Earth magnetotail. Most ion acceleration occurs in this region, gaining from 10 to 50 keV as they traverse the sites of active reconnection. Electrons jet away from the reconnection region much faster than the ions, setting up an ambipolar electric field allowing the ions to catch up after approximately 10 ion inertial lengths. The initial energy flux in

the BBFs is mainly kinetic energy flux from the ions, but as they move earthward, the energy flux changes to enthalpy flux at the ring current.

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Perpendicular subcritical shock structure in a collisional plasma

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Shock waves are ubiquitous in astrophysical, space and laboratory plasmas and often include an embedded, dynamically significant magnetic field. This magnetic field modifies the RH shock jump conditions, and allows dissipation mechanisms specific to magneto-hydrodynamics, such as Ohmic heating, to contribute to shock shaping. In fact, low Mach number shocks can be shaped exclusively by resistive heating. Such shocks are referred to as subcritical, having a magnetosonic Mach number M_MS = 1 - 2.76. Subcritical shocks have been studied experimentally in collisionless plasmas [1] but have not yet been measured in a collisional regime.

We present experimental and numerical investigations of perpendicular subcritical shock structure in a highly collisional plasma [2]. A supersonic (M_S ~ 2.5), super-Alfvénic (M_A ~ 3) plasma flow is produced by the current driven ablation of an inverse wire array z-pinch at the MAGPIE pulsed power facility (1.4 MA, 500 ns). Shocks are studied by placing obstacles into the flow and are measured with a suite of laser probing diagnostics. We find that hydrodynamic variables are continuous across the shock, as predicted by theory, and that the shock width is equal to the classical (Spitzer) resistive diffusion length.

We discuss links between these experiments and recent *in situ* measurements of the interstellar medium [3]. Furthermore, we show that MHD simulations using the Gorgon and AstroBEAR codes are consistent with most features of the experiment but do not reproduce features which we attribute to two-fluid effects [4].

This work was supported by First Light Fusion Ltd. and by the US Department of Energy (DoE) including awards no. DE-NA0003764 and DE-SC0020434.

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Linear analysis of the parametric decay instability in the expanding solar corona considering temperature anisotropy

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Alfvén waves play an important role in coronal heating and solar wind acceleration. Despite the recent progress of theoretical and observational studies on Alfvén waves, their dissipation processes have not been fully understood. Parametric Decay Instability (PDI) is a coupling process between waves in which a large-amplitude, forward-propagating Alfvén wave resonates and decays into a backward-propagating Alfvén wave and a forward-propagating slow magnetosonic wave. The slow magnetosonic waves generated by PDI contribute to the efficient heating of the solar wind ions through the formation of shock waves. Alfvén turbulence enhanced by Alfvén waves reflected by the density fluctuations contributes to the turbulent heating.[e.g., Shoda et al., 2018]. Therefore, PDI is an important physical process in coronal heating and solar wind acceleration. Recent studies have advanced our understanding of PDI in the solar atmosphere. Theoretical and observational studies showed that PDI operates in the solar wind [e.g., Tenerani and Velli, 2013; Bowen et al., 2018], and in the near-transition layer of the lower solar atmosphere [e.g., Hahn et al., 2022]. Previous studies have shown that the growth rate of PDI increases with higher temperature perpendicular to the magnetic field than parallel, lower plasma beta parallel to the magnetic field, and larger amplitude of the parent wave [e.g., Tenerani et al., 2017].

In this study, using the dispersion relation derived from the linearized CGL equations, we evaluated the linear growth rate of PDI in the solar corona. We investigated the effect of the expansion of plasma volume to PDI quantitatively. In the computation of the linear growth rate, we used the parameter representing the temperature ratio between parallel and perpendicular to the background magnetic field (ξ), the plasma beta computed by the parallel component of the plasma pressure ($\beta_{\|}$), and the amplitude of the parent wave normalized by the background magnetic field intensity ($\hat{B_\perp}$ = $B_\perp$ / B_0). To incorporate the effect of expansion, we expressed physical quantities in a form proportional to a power of the radial distance R from the Sun. By using these parameters, we calculated ξ, $\beta_{\|}$, and $\hat{B_\perp}$ at positions of 10,000 km, R = $\sqrt{2}$×10,000 km, and R = 20,000 km. We set the position of the lower boundary of the solar corona as R = 10,000 km and (ξ, $\beta_{\|}$, $\hat{B_\perp}^2$) as (3, 0.01, 0.01) in this region, which is determined by Huang et al.,2023 and Gary et al., 2001. Then we calculated the linear growth rate.

Results have shown that the maximum growth rate is $0.1131\omega_0$ at R = 10000km, $0.124\omega_0$ at R = $\sqrt{2}$×10,000 km, and $0.128\omega_0$ at R =20000km, where ω_0 is the frequency of the parent wave.
It is the opposite trend previous studies reported that expansion suppresses PDI [e.g., Tenerani et al.,2013, Shoda et al.,2018]. In previous studies, to consider expansion, a term representing the effect of expansion was added to the basic equation, incorporating both the stretching in the r direction (acceleration) and the stretching perpendicular to the r direction (expansion). On the other hand, in the present study, the expansion perpendicular to to the r direction without the acceleration is considered. Our results suggest that the acceleration may play an important effect in suppressing PDI.

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Test particle simulation for electrons accelerated by kinetic Alfvén waves and precipitating into the ionosphere

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Kinetic Alfvén waves (KAWs) have long wavelengths parallel to magnetic field lines and perpendicular wavelengths comparable to the ion Larmor radius. KAWs possess a parallel electric field component ($\delta E_{\parallel}$) that accelerates electrons along magnetic field lines [e.g., Hasegawa, 1976]. These waves are frequently observed in the terrestrial magnetosphere during substorms [e.g., Stasiewicz et al., 2000]. They can accelerate electrons to energies of several keV parallel to magnetic field lines [e.g., Wygant et al., 2002]. In the process of electron acceleration by KAWs, electrons satisfying the Landau resonance condition between their parallel velocity ($v_{\parallel}$) and the wave phase speed ($V_{\mathrm{ph}\parallel}$) can be trapped by the wave and transported to higher latitudes while being accelerated [e.g., Artemyev et al., 2015]. Additionally, it has been pointed out that trapped electrons with a first adiabatic invariant (μ) that is not small are affected by the mirror force and cannot reach the ionosphere due to escaping the trap [Watt and Rankin, 2009]. The details of these escape processes from KAWs remain poorly understood.

In this study, we apply the theory of the second-order resonance of charged particles trapped by coherent electromagnetic waves [e.g., Omura et al., 2008] to the electron acceleration process by KAWs. By considering the simple harmonic motion of the wave phase as viewed from the electron (ψ) and the inhomogeneity factor (S) due to background magnetic field gradients, we can describe the motion of electrons trapped by KAWs in velocity phase space. As trapped electrons move parallel to a magnetic field line, the background magnetic field gradients and S, as viewed from the electron, change accordingly. The range of energies at which electrons can be trapped narrows with increasing S, facilitating the escape of electrons from the trapped region as they move to higher latitudes with larger magnetic field gradients.
We focus on the detrapped state, where electrons have escaped from the KAW's trap. When considering an $L = 9$ magnetic field line and assuming $\delta E_{\parallel}$ around $1\,\mathrm{mV/m}$ at the magnetic equator, electrons detrapped between 10° and 20° magnetic latitude with initial energies under $2\,\mathrm{keV}$ can be accelerated up to approximately $10.5\,\mathrm{keV}$ at the ionosphere, particularly when ψ is in the range $(-\pi, 0)$, where the wave effectively accelerates the electrons. Our results also reveal that the energy spectrum of electrons precipitating into the ionosphere is influenced by the position where electrons are detrapped, with the potential for a broadband energy distribution resulting from the acceleration of a monochromatic KAW. Considering the maximum kinetic energy at the ionosphere and the conservation of μ during acceleration, it is found that electrons must have μ less than approximately $0.23\,\mathrm{eV/nT}$ to reach the ionosphere.

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Type III solar radio emission generated by current-driven Langmuir oscillations: Theory, simulation and Parker Solar Probe observations

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In earlier papers (Sauer and Sydora, 2015, 2016) it has been shown that an electron current in a plasma is directly linked to the formation of Langmuir oscillations at the electron plasma frequency ω_e. The current may arise due to a relative drift between electrons and protons or by a drifting electron

population. No kind of beam instability should be involved. The excitation of electromagnetic waves at ω_e by the current-driven Langmuir oscillations is a completely new mechanism of the generation of type III bursts. The electromagnetic radiation arises from the mode coupling between the left-hand polarized electromagnetic wave and the Langmuir wave in case of oblique propagation. The fact that no beam instability is required for the explanation of type III radiation resolves the Sturrock paradox (Sturrock, 1964) involving the incompatibility of short-lived beam instability with long-lived radiation bursts. Starting with simple considerations to the Langmuir oscillations, the system of fluid-Maxwell equations is used to calculate the amplitude of the electromagnetic field component in dependence of the driving current. By solving the nonlinear equations and using PIC simulations the second harmonic generation is additionally studied. If the electron current is caused by an electron plateau distribution which may result from a saturated beam instability, an electron-acoustic wave is excited by a similar decay process, but in the wave number range (k) far away that of the electromagnetic waves with kc/ωe~1. Measurements of type III radio bursts aboard the Parker Solar Probe (Mozer et al., 2024) in distances of about 35 solar radii indicate that the electron current related to the measured distribution function of core, halo and strahl is the driver of the simultaneously observed Langmuir waves and electromagnetic radiation.

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Bringing together HPC and QC: it is mainly a software challenge!

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As Quantum Computing systems continue their maturation, their addition to the spectrum of HPC accelerators slowly becomes more viable. For them to be usable, though, we require substantial efforts to integrate the quantum and the HPC ecosystem. On the hardware side, the needed efforts seem straightforward - integrating the quantum control system with lowest possible latency into the HPC network. That's only half of the story though. We must also connect the needed software stacks by bridging their radically different workflows, programming approaches and user expectations. This talk will highlight how we can achieve these goals and will present the Munich Quantum Software Stack (MQSS), developed as part of the Munich Quantum Valley (MQV) initiative. This software effort aims at providing efficient usage and integration of the quantum systems developed in the MQV and/or hosted at the Leibniz Supercomputing Centre. Beyond that it aims at setting a standard for the integration of HPC and QC as part of the EuroHPC QC efforts.

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Application of space simulations to atmospheric escape studies from terrestrial planets

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Interaction between the solar wind and upper atmosphere facilitates various atmospheric escape processes from terrestrial planets. The escape rate depends on various conditions such as the distance from the Sun, solar activities, planetary size, atmospheric composition, and intrinsic magnetic field. The atmosphere retention is one of necessary conditions for habitable terrestrial exoplanets. In this invited talk, recent global MHD simulation studies of ion escape from unmagnetized and

weakly magnetized planets will be reported with a focus on effects of the planetary intrinsic magnetic field.

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Relaxation of the Courant Condition and Reduction of Numerical Errors in the Explicit Finite-Difference Time-Domain Method for Plasma Kinetic Simulations

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This study provides a new numerical method for relaxation of the Courant condition and correction of numerical errors in the Finite-Difference Time-Domain (FDTD) method with the time-development equations using higher-degree difference terms. The FDTD method (Yee 1966) is a numerical method for solving the time development of electromagnetic fields by approximating Maxwell's equations in both space and time with the finite difference of the second-order accuracy, which is widely used in plasma kinetic simulations. A staggered grid system is adopted in the spatial differences, in which Gauss's law is always satisfied. The FDTD method has a disadvantage that numerical oscillations occur due to the error between the numerical phase velocity and the theoretical phase velocity. The FDTD(2,4) method (Fang 1989; Petropoulos 1994), which uses the fourth-order spatial difference, is proposed for reduction of the numerical errors. However, the Courant condition becomes more restricted by using higher-order finite differences in space and a larger number of dimensions. Recently, a numerical method has been developed by adding third-degree difference terms to the time-development equations of FDTD(2,4) (Sekido & Umeda, IEEE TAP, 2023). Although the new method relaxes the Courant condition, there exist large numerical errors with large Courant numbers. In the present study, a new explicit and non-dissipative FDTD method is proposed with two types of the higher-degree difference operators for relaxation of the Courant condition and reduction of numerical errors. First, the one-dimensional third- and fifth-degree difference terms are added to the time-development equations of FDTD(2,6) (Sekido & Umeda, PIER M, 2024). Second, the third-degree difference terms including Laplacian are added to those of FDTD(2,4) (Sekido & Umeda, EPS, 2024). The results of the test simulations show that numerical oscillations are not reduced so much with the one-dimensional difference operator, whereas the Laplacian operator suppresses an anisotropy in the waveforms and reduces the numerical oscillations. Furthermore, numerical instability is suppressed with large Courant numbers up to 1, which reduces the computational time of plasma kinetic simulations significantly.

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Determining wave fields from particle orbits

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Plasma wave theory involves understanding how the perturbation of particle orbits by mean-field waves produces charge densities and currents that self-consistently create the mean-fields. Exact

solutions are known in only a few special cases. However, given this self-consistent relationship, it is natural to ask –how much about the wave fields in a given region of space can be known by measuring a fluctuating velocity distribution of particles at a single location (for example a single spatial point in the laboratory, or a spacecraft). After a review of some previous efforts tested in the laboratory, we will look at some recent generalizations of the theory.

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Low Frequency Turbulence in the Ionosphere and Interaction with High Frequency Wave

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Analytical and numerical models of the linear and nonlinear stages of evolution of different types of short scale low frequency waves in the mid-latitude ionosphere will be presented. Density gradients and velocity shears observed in the Earth's ionosphere are likely to undergo Raleigh-Taylor (RT) or Kelvin-Helmholtz (KH) type instabilities, but typically live longer than expected. Possibility of enhanced ionization due to appearance of supra thermal electrons accelerated by excited wave turbulence will be also presented. Obtained density perturbations in the form of nonlinear vortex structures accompanied by short scale turbulent pulsations can strongly affect propagating high frequency electromagnetic waves used for example for GPS applications or satellite communications. These models will be used to estimate the impact on the propagation characteristics of waves ranging from HF to L band diapason. Related experiments on excitation of low frequency waves during the experimental campaigns at the HAARP and the Arecibo Observatory facilities will be also discussed.

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Charged particle dynamics in the Jupiter's Radiation Belts: A test particle simulation

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Jupiter possesses the most hazardous radiation belt in the solar system which is responsible of trapping ultra-relativistic protons (~ 100 GeV), electrons (~ 100 MeV) and heavy ions like O^+, O^{++}, S^+, S^{++}, S^{+++} (~100 MeV). Depending on the energy of the charged particles and the strength of Jupiter's magnetic field, these particles are either lost or trapped as they enter Jupiter's magnetic field. Once trapped in radiation belts, these particles gyrate along the magnetic field lines, bounce along the mirror points, and drift around the Jupiter. Since charged particles found in Jupiter's radiation belt are highly energetic, it is yet unknown whether they exhibit adiabatic or non-adiabatic behaviour. Several theoretical models exist to track the position of the particle, but they are all based on the gyro-centre approximation and are only applicable to charged particles that behave adiabatically. However, we do find charged particles with MeV-GeV ranges in Jupiter's radiation belts where

the gyro-center approach may fail due to their larger gyro radius. In this context, we have developed a three-dimensional relativistic model using test particle simulation including all the three motions by incorporating Jupiter's magnetic field (intrinsic + current source) to examine the behaviour of these energetic charged particles. Furthermore, we found a proxy that involves perpendicular velocity and ambient magnetic field, to predict the adiabatic or non-adiabatic behaviour of the charged particles trapped in Jupiter's radiation belts.

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Paradigmatic liquid-metal experiments on geo- and astrophysical phenomena

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Recent decades have seen great progress in the experimental investigation of fundamental processes that are relevant to geophysical and astrophysical fluid dynamics. For such studies, liquid metals have proven particularly suited, partly owing to their small Prandtl numbers which are comparable to those in planetary cores and stellar convection zones, partly due to their high electrical conductivity which allows the study of various magnetohydyrodynamic phenomena. After summarizing some theoretical basics, we discuss the most important liquid-metal experiments on Rayleigh-Bénard-convection, Alfvén waves, the magnetorotational and Tayler instability, and the dynamo effect. We recapitulate what has been learned so far from those experiments, and what could be expected from future ones.

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Proposal for Gyrokinetic Simulation of a Neutron Strar's Magnetosphere

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Neutron stars are rotating objects with a strong magnetic field. The consequent induced field in the rotating reference frame is expected to support the creation of pair plasma in the vicinity of the neutron star. Presumably, electrons and positrons reside in separated domains above the poles and around the equator. This model is supported by several fully kinetic particle-in-cell (PIC) simulations. However, the magnetic field needs to be scaled down by several orders of magnitude in these simulations, such that the gyromotion can be resolved. We propose to use a gyrokinetic simulation in order to overcome this difficulty. In a first step, the simulation can be benchmarked against experimental results obtained by the APEX collaboration. The APEX collaboration has the goal to create a pair plasma in a levitated dipole trap. In a second step we plan to gradually introduce the properties that distinguish the lab experiment from the neutron star's magnetosphere. This involves for example the extreme magnetic field which leads to radiative processes with consequent pair creation as well as relativistic velocities. One possible application of these simulations would be the investigation of the stability properties on the drift-timescale. Specifically the diocotron instability might affect the distribution of the plasma in the magnetosphere and its radio emission.

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Highlights from the path toward confined e+e- pair plasmas

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The grand challenge being pursued by the APEX (A Positron Electron eXperiment) Collaboration is to create and study cold, confined, strongly magnetized, matter-antimatter "pair plasmas"in the laboratory. This unusually simple, symmetric type of plasma has been the subject of theory/simulation predictions, in part motivated by astrophysical e+e- pair plasmas, going back over four decades; we would like to test some of these experimentally. Our path to pair plasmas involves joining together and further developing state-of-the-art physics and engineering in several disciplines. This talk will give an overview of recent highlights —including novel techniques in the areas of positron beams, non-neutral plasmas, and gamma diagnostics — as well as the progress on our two, complementary, tabletop-sized, pair-plasma traps: a levitated dipole and an optimized stellarator, both based on small, non-insulated, HTS (high-temperature superconducting) coils. Finally, I will describe our plans for the few next year(s), when we will put all of these elements together.

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Reconstructing Equatorial Electron Flux Measurements from LEO

Author: Dominique L. Stumbaugh[1]

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Local precipitation loss due to pitch angle scattering by magnetospheric waves is the focus of our analysis. Plasma waves can alter the course of a charged particle and influence a previously trapped electron from the magnetosphere to penetrate the Earth's upper atmosphere. Once in the upper atmosphere, a charge particle can ionize air molecules leading to the destruction of ozone and interfere with technological systems. It is critical that particle measurements from different platforms are inter-calibrated and validated as LEO data can be a proxy for high latitude data for radiation belt models.
The proposed project aims to establish a predictable relationship between low-Earth-orbit and high altitude orbit data. We use coordinated electron measurements from the Van Allen Probes, or Radiation Belt Storm Probes (RBSP), and the Polar Operational Environmental Satellites (POES) to build a neural network. We reconstruct equatorial electron flux measurements using inputs from POES, geomagnetic indices, and L shell and MLT values.

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Turbulence and transport from multiple entangled plasma pressure filaments in a magnetized plasma

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Steep pressure gradients in a magnetized plasma can induce a variety of spontaneous low frequency excitations such as drift-Alfven waves and vortices. We present results from basic experiments on energy and particle transport in magnetized plasmas with multiple heat sources in close proximity [1]. The experiments were carried out at the upgraded Large Plasma Device (LAPD) operated by the Basic Plasma Science Facility at the University of California, Los Angeles. The setup consists of three biased probe-mounted cerium-hexaboride crystal cathodes that inject low energy electrons along a strong magnetic field into a pre-existing cold afterglow plasma forming localized regions of elevated temperature and density. A cross-field triangular spatial pattern is chosen for the sources and multiple axial and transverse probe measurements allow for determination of the mode patterns and axial filament length. When the three sources are placed within a few collisionless electron skin depths, a non-azimuthally symmetric wave pattern emerges due to the overlap of drift-Alfven modes forming around each filament. This leads to enhanced nonlinear convective (E×B) chaotic mixing and rapid density and temperature profile collapse in the inner triangular region of the filaments. Steepened thermal gradients form in the outer triangular region, which spontaneously generates quasi-symmetric, higher azimuthal mode number drift-Alfven fluctuations. A statistical study of the fluctuations reveals amplitude distributions that are skewed which is signature of intermittency in the transport dynamics. Nonlinear gyrokinetic simulations using seeded filaments confirm the presence of unstable drift-Alfven modes driven by the steep thermal gradient along with fluctuation spatial patterns that are comparable to the experiments.

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Localized electron acceleration at X-point during magnetic reconnection of two merging tokamak plasmas

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Our multi-view soft X-ray measurement system detected for the first time high-energy electrons localized at the X-point of two merging tokamak plasmas. We found their energies increase with the guide toroidal field. These electrons are considered to be accelerated by the reconnection electric field along the guide magnetic field.
Under a high guide field, the reconnection electric field is observed to accelerate electrons to the downstream, forming quadra-pole type electrostatic potential profiles for the following ion acceleration and heating. In this key process, the production of energetic electrons has been studied both in PIC simulations [1], and in laboratory plasmas [2,3]. The spatial profile of energetic electrons is often measured by observing Bremsstrahlung emitted from them. In this study, we measured soft X-ray images of high-guide field reconnection formed by two merging tokamaks using a multi-view soft X-ray camera, which can simultaneously measure four images of Bremsstrahlung emission through four different filters.
On the midplane of TS-6 spherical merging tokamak, we installed a multi-view soft X-ray camera

composed of four built-in microchannel plates, four pinholes, and four filters: 1 µm and 2 µm mylar films for >100eV and >200eV electrons and 1 µm and 2.5 µm aluminum films for >20eV and >50eV electrons. We simultaneously measured the line-integrated images of soft X-ray emissions whose R-Z images were reconstructed using Tikhonov-Philips regularization and the minimum GCV criterion [4].
The emission profiles from high energy electrons: >200eV and >100eV peaked at the X-point. It is noted that the emission from >200eV electrons increased with the guide magnetic field strength. Therefore, the emission is thought to be from energetic electrons accelerated by the reconnection electric field along the guide magnetic field in the vicinity of the X point.

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Particle acceleration/heating of high guide field reconnection in merging spherical tokamak formation experiments

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Here we report the particle acceleration and heating of magnetic reconnection under the influence of high guide field in the merging spherical tokamak formation experiments in ST40 and TS-6. In addition to the extension of ion heating scaling $\Delta T_i \propto B_{rec}^2$ in keV range, our recent experiments explored the following 3 new findings using 96CH/320CH ion Doppler tomography and Thomson scattering diagnostics: (1) formation of poloidally asymmetric global ion heating structure in TS-6 and highly localized electron heating around the X-point in ST40 via parallel electric field acceleration, (2) update of the heating scaling to $\Delta U_i \propto B_{rec}^2$ by including the contribution of electron density in collaboration with Thomson scattering measurement in ST40 from 2023, and (3) exploration of further electron heating via magnetic reconnection under the influence of high guide field in the keV range in ST40. The poloidally asymmetric ion heating structure depends on the polarity of toroidal field and the fine structure gets flipped when the guide field direction is reversed. Under the influence of high guide field, E×B drift is mainly driven by in-plane/poloidal electric field E_p from the quadruple potential structure, while parallel electric field $E_\parallel$ is mainly driven by reconnection electric field Erec (spontaneously formed toroidal electric field E_t around X-point) and higher T_i appears where plasma potential is positive, while high T_e mainly appears around the X-point. Under the influence of toroidal effect to have higher guide field in the inboard side of outflow direction, downstream heating also forms poloidally asymmetric structure, and more heating appears in the high field side. Perpendicular heat conduction in the outflow region is strongly suppressed by high guide field $\kappa_\parallel^i/\kappa_\perp^i \sim 2(\omega_{ci}\tau_{ii})^2 >> 1$ and the field-aligned transport process leads to the formation of poloidally ring-like characteristic fine structure after merging.

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Hybrid gyrokinetics: Electromagnetic effects in weakly magnetized plasmas

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Weakly magnetized plasmas are found in natural plasmas such as the solar wind, but also in laboratory applications, e.g. in the edge of fusion plasmas. Ordering assumptions made in gyrokinetic theory—like low frequency or moderate gradients—may be challenged, particularly for the heavier ions. To overcome these limitations, the group derived equations for a hybrid model that includes fully kinetic physics for the ions, but gyrokinetic physics for the electrons.
The numerical implementation of the hybrid model has been implemented into the existing simulation code ssV, developed in the department of Theoretical Physics I at Ruhr-Universität Bochum. The ssV code is based on advanced Semi-Lagrangian-type methods (e.g. the PFC scheme [Filbet et al., JCP 2001]).
The study of instabilities and turbulence relevant to tokamak edge turbulence, has driven significant further enhancements to ssV: In particular when evolving the full particle distribution ("full-f"), it is challenging to preserve accurate long-term physics while resolving the gyration timescale. Both existing and novel higher-order schemes had to be implemented and tested as a remedy: For example, at least a 5th order scheme is needed in velocity space to gain sufficient accuracy for ion-temperature-gradient driven instability (ITG)
Ongoing work on ssV involves the addition of electromagnetic capabilities, which will enable application to space and astrophysical plasmas:For example, magnetic reconnection at the ion scales.

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Using the Magnetized Dusty Plasma Experiment (MDPX) to evaluate dust cloud detection between spacecraft

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The presence of charged dust particles in the space environment is well-known. From observations of structures in the dust tails of comets and the Voyager observations of radial structures ("spokes") in Saturn's rings, the role of charged dust in the solar system has been the subject of intense study for decades. More recently, the presence of flowing magnetized dust clouds has been postulated as a mechanism for introducing modifications in interplanetary magnetic field (H. R. Lai, et al., Geophys. Res. Letters, **46**, 14282, 2019). Therefore, it is of interest to perform a series of experimental investigations that may provide fundamental insights into the influence of dust in the solar system. In this study, we envision a pair of spacecraft (e.g., possibly cubesats), where the presence of charged dust modulates the transmission of electrostatic and electromagnetic waves between the two spacecraft. In preliminary studies presented here, the Magnetized Dusty Plasma Experiment (MDPX) device will be used to investigate the modification of low frequency waves (i.e., below the ion cyclotron frequency, $f \sim 10$ –1500 Hz « f_{ci}) in the presence of dusty plasma clouds in magnetized plasmas scaled

to near-earth space plasma conditions. This presentation will also report on plans for the next steps in the laboratory investigations.

Acknowledgements: The MDPX device was designed and built through a grant from the NSF Major Research Instrumentation (NSF-MRI) program, PHY-1126067. The laboratory has been supported by the NSF, NSF-EPSCoR, NASA, and Department of Energy.

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Overview of current research activities in the Magnetized Plasma Research Lab (MPRL): a collaborative research facility at Auburn University

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The Magnetized Plasma Research Laboratory (MPRL) at Auburn University explores fundamental plasma and complex/dusty plasma phenomena covering a large parameter regime from unmagnetized plasmas to strongly magnetized plasmas with a mission to serve as an open access, multi-user collaborative research facility. The centerpiece of the laboratory is the Magnetized Dusty Plasma Experiment (MDPX), a highly flexible plasma device with excellent diagnostic access to study the unique regime of high magnetic fields (up to 4 T), at relatively low density (~ 10^{14} –10^{16} m^{-3}) and low electron (T_e < 5 eV) and ion temperature (T_i < 0.05 eV). Other instruments include ALEXIS, a linear plasma device for simulating space plasma and basic plasma experiments, and a wide variety of "tabletop"scale unmagnetized, low temperature plasma devices. Here, we will give an overview of recent studies from MPRL such as pattern formation of filamentary structures at high magnetic fields, nanoparticle growth in plasmas, laser trapping of dust particles, studies of dust clusters and dust thermodynamics, using dust as a diagnostic, controlling dust charging and dynamics by externally applied UV light, studies of dust acoustic waves at high magnetic field, development of new laser-based plasma diagnostics etc.

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Evaluating the uncertainties in global MHD and Test-Particle simulations of the Earth's radiation belts

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Planetary radiation belts form a major hazard to orbiting satellites and predicting their variability is a primary goal of space weather forecasting efforts. While radiation belt dynamics are well-approximated by the Fokker Planck diffusion equation representing transport in energy, radial distance and pitch angle, more realistic magnetic field models and diffusive-advective transport have been shown to be important during storm-time scenarios. This study investigates the dynamics of high-energy radiation belts by analyzing the trajectories of test particles within Earth's magnetic field. We evaluate multiple relativistic particle integrators which resolve the full Lorentz particle motion and the guiding centre, and examine their effectiveness in simulating the test particles within fields generated by analytical and global magnetohydrodynamic (MHD) simulations. The focus of the assessment includes the conservation of adiabatic invariants and minimization of interpolation errors to identify the most accurate and efficient techniques for modeling the Earth's radiation belt using this approach. Following the theoretical uncertainty quantification, we seek to model a series of geomagnetic storms and quantify the model uncertainties for these real events.

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Particle acceleration at magnetized oblique mildly relativistic shocks

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Jets in active galactic nuclei (AGN) are known for their intense X-ray and gamma-ray emission, originating from non-thermal particles. These sources are also linked to high-energy neutrino events and are considered potential sites of ultra-high-energy cosmic ray production. Accelerated particles can be generated in shock waves formed in collisionless AGN plasmas. We study oblique mildly relativistic shock waves of moderate and high magnetisation applicable to AGN jets by the use of Particle-In-Cell (PIC) 2D3V simulations. We analyse a previously unexplored range of magnetic field obliquity angles around the supercritical angle, which effectively divides the regimes of sub- and super-luminal shocks. We show that both superluminal and subluminal shocks at both magnetisations accelerate particles and that particle acceleration is more efficient at subluminal configurations. We discuss mechanisms of ion and electron energisation in different regimes of plasma magnetization and shock obliquity.

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New integrator for relativistic equations of motion for charged particles

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Numerical methods for solving the relativistic motion of charged particles with a higher accuracy is an issue for scientific computing in various fields including plasma physics. The classic fourth-order Runge-Kutta method (RK4) has been used over many years for tracking charged particle motions, although RK4 does not satisfy any conservation law. However, the Boris method [Boris 1970] has been used over a half century in particle-in-cell plasma simulations because of its property of the energy conservation during the gyro motion.
Recently, a new method for solving relativistic charged particle motions has been developed, which conserves the boosted Lorentz factor during the E-cross-B motion [Umeda 2023]. The new integrator has the second-order accuracy in time and is less accurate than RK4. Then, new integrator is extended to the fourth-order accuracy in time by combining RK4 [Umeda and Ozaki 2023]. However, it is not easy to implement the new fourth-order integrator into PIC codes, because the new method with RK4 adopted co-located time stepping for position and velocity vectors, which is not compatible with the charge conservation method.
In this paper, the two new relativistic integrators are reviewed. Then, a new leap-frog integrator with fourth-order accuracy in time is developed, which adopts staggered time stepping for position and velocity vectors.

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Laboratory studies of energy partitioning in laser-driven, quasi-perpendicular collisionless shocks

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Collisionless shocks are ubiquitous objects in the universe. Many of these shocks are magnetized due to preexisting magnetic fields in the upstream, which is the case for the Earth's bowshock in heliophysics and supernova remnants. Despite decades of observations and numerical simulations, there remains no clear understanding on how energy is partitioned between electrons and ions across a shock. Some of the challenges of satellite and telescope measurements are the lack of controlled conditions over which collisionless shocks evolve. Moreover, spacecraft measurements are challenging to interpret in their global dynamics whereas remote observations cannot resolve the microphysics of the shock. Laboratory experiments can aid in bridging the gap between these two well-established methods.
We present novel platforms to study quasi-perpendicular magnetized collisionless shocks driven at the Omega laser facility at the University of Rochester. A plasma plume is launched by irradiating plastic (CH) targets with high-energy laser beams, creating a shock in a background hydrogen plasma premagnetized using inductive coils (B~7 T to 20 T). The magnetic field structure is probed using proton radiography and the plasma properties (namely, velocity, temperature and density) are probed by optical Thomson Scattering. We will describe the formation and evolution of these magnetized collisionless shocks, and the development of future experiments to probe anisotropic particle heating on laboratory scales

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The viability of NGC 1068 as a neutrino source

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Using tracer particles propagating in an environment that simulates the accretion disk surrounding a black hole, this work aims to provide insight into the confinement of high energy particles in the galaxy NGC 1068 (*J. Bland-Hawthorn et al., 1997, Astrophysics and Space Science*; *K. Murase, 2022, The Astrophysical Journal Letters*), which is believed to be the source of the neutrino fluxes measured in *IceCube Collaboration et al., 2022, Science.* The accretion disk is evolved according to the equations of General Relativistic MagnetoHydroDynamic (GRMHD), implemented in the code AthenaK, a re-implementation of the Athena++ (*J. M. Stone et al., 2020, The Astrophysical Journal Supplement Series*) code, with the addition of purely passive particles (*B. Ripperda et al., 2018, The Astrophysical Journal Supplement Series*; *F. Bacchini et al., 2019, The Astrophysical Journal Supplement Series*), such that their presence doesn't affect the
dynamics of the accretion disk. The simulations are run using parameters expected to be found in the environment of the galaxy NGC 1068, with tracer particles initialized to energies reaching $1\ PeV$, since these are believed to be of most interest for the generation of neutrinos. By running this setup, an estimate for the confinement times of such particles can be provided, which is otherwise usually modeled as a free parameter, but that plays a critical role in determining the properties of the injection spectrum of neutrinos, and thus in the identification of possible sources for such particles. Particular focus is dedicated to characterizing the role played by the magnetic field of the accretion disk.

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Gamma spectra of positronium from charge-exchange with magnetically confined positrons

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We present the formation of positronium (Ps) through charge-exchange of magnetically confined positrons and background gas in the laboratory. A bunch of 10^5 positrons is extracted from a buffer-gas trap and injected into the dipole field of a permanent magnet trap with E×B drifts [1]. Once injected, the positrons are confined through a combination of magnetic mirroring and electrostatic reflection off the biased magnet. A 21-BGO detector array situated in re-entrant ports 1cm from the confinement volume detects ~10,000 gammas per shot. FPGA processing timestamps detections to 8ns accuracy and records photon energy with 66keV resolution. The time evolution of the 511keV peak-to-valley ratio identifies Ps-formation through charge-exchange of the ~7eV positrons with

impurities (H2O, O2, ⋯) in the ~5·10-6 Pa vacuum as the dominant loss mechanism during the first ~500ms of confinement. An increase in the positron kinetic energy, achieved by reducing the electrostatic bias, leads to an increase in charge-exchange and associated triple coincidence detection. Inelastic collisions cool the positrons, enabling a ramp of the magnet bias to negative voltages to pull them into the loss cone. This cooling below the Ps-formation energy threshold cuts off the charge-exchange and allows transport to the wall through elastic collisions to become the dominant loss mechanism. A fraction of positrons created in solar flares will form positronium through charge-exchange. The resulting annihilation spectra depend on the traversed media's constituents, their density and ionization fraction [2]. In the future, plasma relevant to solar environments could be generated in the dipole field prior to the injection of positrons so that the interactions with Ps and the effect on the flux ratio of the 511keV of 2-gamma line to the 3-gamma continuum could be studied.

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[2] Murphy, R. J., Share, G. H., Skibo, J. G., & Kozlovsky, B. (2005). The Physics of Positron Annihilation in the Solar Atmosphere. The Astrophysical Journal Supplement Series, 161(2), 495–519.

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Statistical study of energy dissipation in magnetic structures during turbulent reconnection in the Earth's magnetotail

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Magnetic reconnection is a ubiquitous plasma phenomenon that plays an important role in particle heating and energization. During reconnection, the topology of magnetic field rearranges, depositing energy into the surrounding plasma through bulk flow, thermal heating, or non-thermal particle acceleration. The pathways of this transformation from magnetic energy into kinetic have been studied extensively in recent years, albeit mostly on a theoretical or case-by-case basis observationally. In this study, we conduct a statistical analysis using data from the Magnetospheric Multiscale (MMS) mission, and detail the particle energization mechanisms in magnetic structures found near reconnecting regions in turbulent Earth's magnetotail. We find that electron motion perpendicular to the magnetic field dominate j·E dissipation. In contrast to the conventional picture of unidirectional energy transfer to particles by laminar two-dimensional (2D) reconnection, we find that energy exchange within magnetic structures during turbulent reconnection tends to be bidirectional with only a small positive bias from magnetic field to particles. Specific electron energization mechanisms are quantified including parallel electric field energization, Fermi acceleration due to curvature drift, betatron heating from magnetic field inhomogeneity, and polarization drift.

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Observation of the standard magnetorotational instability in a modified Taylor-Couette cell

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The standard magnetorotational instability (SMRI) has been regarded as the most promising instability responsible for the turbulence required to explain the fast accretion observed across the Universe. However, unlike other fundamental plasma processes such as Alfvén waves and magnetic reconnection, which have been subsequently detected and studied in space and the laboratory, SMRI remains unconfirmed even for its existence long after its proposal, despite its widespread applications in modeling, including recent black hole imaging. Its direct detection has been hindered in observations due to its microscopic nature at astronomical distances and in the laboratory due to stringent requirements and interferences from other processes. Here, we report the first direct evidence showing that SMRI exists in a novel laboratory setup where a uniform magnetic field is imposed along the axis of a differentially rotating flow of liquid metal confined radially between concentric cylinders and axially by copper end rings. Through in situ measurement of the radial magnetic field B_r at the inner cylinder, the onset of the axisymmetric SMRI at magnetic Reynolds number Rm≥3 is identified from the nonlinear increase of B_r beyond a critical magnetic Reynolds number. Experimental data also reveals that the axisymmetric SMRI is accompanied by a nonaxiymmetric m=1 mode, a linear instability with exponential growth at its onset. Further analysis excludes the possibility that the m=1 mode is the conventional Rayleigh instability or the Stewartson-Shercliff layer instability, implying that it could be a non-axisymmetric version of SMRI that breaks the rotational symmetry of the system. We will discuss a possible mechanism causing the SMRI to be excited at Rm lower than the theoretical prediction for an ideal Couette flow. The experimental results are reproduced by nonlinear three-dimensional numerical simulations, showing that SMRI causes the velocity and magnetic fields to contribute an outward flux of axial angular momentum in the bulk region, just as in accretion disks.

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Linear and Nonlinear Dynamics of Self-Consistent Collisionless Tearing Modes in Toroidal Gyrokinetic Simulations

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We investigate tearing modes driven by current density gradient in collisionless tokamak plasmas by using the electromagnetic gyrokinetic simulation code ORB5. Two aspects of the dynamics of magnetic island due to the tearing mode, its width and rotation, are studied by simulations for flat and finite-gradient profiles of density and temperature. The evolution of the width (rotation) is elucidated by simulations for flat (finite-gradient) profiles because of small (large) rotation-speed in the absence (presence) of background diamagnetic effects. For flat profiles,
the initial saturation width of nonlinearly driven magnetic islands is related to the linear growth rate of the tearing mode; however, large islands in the initial saturation phase are prone to current density redistribution that reduces the island width in the following evolution. In addition, island-induced E × B and diamagnetic sheared flows develop
at the separatrix, able to destabilize the Kelvin-Helmholtz instability (KHI). The KHI driven turbulence enhances a strong quadrupole vortex flow that reinforces the island decay, resulting in a strong reduction of the island width in an eventual steady state. This strong reduction of the island width is enhanced by trapped electrons. For finite gradients
profile, the tearing mode rotates usually in the electron diamagnetic direction, but can change direction when the ion temperature gradient dominates the other gradients. The reduced growth of the tearing mode by diamagnetic effects results in a moderate island size, which remains almost unchanged after the initial saturation. At steady state,
strong zonal flows are non-linearly excited and dominate the island rotation, as expected from previous theoretical and numerical studies. When β is increased, the tearing mode is suppressed and a mode with the same helicity but with twisting parity, coupled with the neighboring poloidal harmonics, is destabilized, similar to the kinetic ballooning
mode.

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Effects of Alpha Particle Fraction on Kinetic Plasma Turbulence

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Solar activities have an extraordinary impact on interplanetary space, enriching the plasma dynamics including turbulent heating of various species. The small fraction of alpha particles is believed to play a significant role in the turbulent dynamics of the solar wind. Here we present fully kinetic particle-in-cell (PIC) simulations to reveal the influences of the alpha particles in decaying plasma turbulence. Multiple runs with different controlled variations of proton and alpha density are performed to compare and evaluate the energy conversion processes. It is found that the alpha particles can suppress the energy conversion rate with increasing density. Besides, the alpha particles show more heating intermittency than the proton species. These two positive charge species have more correlation in temperature anisotropy as their densities are comparable. Interestingly, on the other hand, the electrons do not show any change in their dynamics, including the overall heating. Our results provide valuable insights on the turbulence with different species compositions, especially with abundant heavy particles.

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Experimental verification of Petschek's double shock structure in a two-fluid magnetic reconnection layer

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In a prototypical two-dimensional antiparallel reconnection geometry, we experimentally verify a well- known Petshek-type reconnection layer of double wedge structure and explained by two-fluid dynamics. In a two-fluid reconnection layer, as electrons and ions move into the reconnection layer with different paths, the magnetized electrons penetrate deep into the reconnection layer generating a strong potential well in the diffusion region. The shape of the well expands towards the exit of exhaust region [1].
Recently we have identified a sharp current layer develops at the separatrix region generating abrupt changes of magnetic field vectors [2]. Magnetic field energy is converted to electric field potential energy through the motion of magnetized electrons in the background of non-magnetized ions. While some of the magnetic energy is deposited to the electrons in the electron-diffusion layer, ions gain substantial energy through electrostatic acceleration across the potential well in the broader ion diffusion region. The Petschek-type double shock structure [3] is formed and can be explained by the two-fluid dynamics of the reconnection layer around the electron diffusion region.

[1] M. Yamada et al, Phys. Plasmas 23, 055402 (2016)
[2] J. Yoo and M. Yamada, to be published (2024)
[3] D, Uzdensky and R. Kulsrud, Phys. Plasmas, 7(10) 4018

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Recent Observation of Waves in Laboratory Reconnection Experiments

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Magnetic reconnection serves as a crucial mechanism for generating various sources of free energy for waves and instabilities, including pressure gradients, temperature anisotropies, and large electric currents. In this talk, we focus on recent observations of waves in laboratory reconnection experiments, particularly in the Magnetic Reconnection Experiment (MRX).
Whistler waves, originating from electron temperature anisotropy, have been detected near the separatrix on the low-density (magnetosphere) side [Yoo et al., 2018]. The presence of these waves is attributed to the loss of electrons with high parallel speeds, leading to local temperature anisotropy and subsequent whistler wave generation. Additionally, enhanced electron transport with high parallel speed is likely associated with lower hybrid drift instabilities near the separatrix [Yoo et al., 2019].
Ion acoustic waves, triggered by large local currents, have been observed during low-beta reconnection in high-energy-density plasmas generated by high-power lasers [Zhang et al., 2023]. In these laser-generated plasmas, the condition where ion temperature normalized to charge state (Z) is smaller than the electron temperature is met, such that ion acoustic waves are not strongly Landau damped. The onset of ion acoustic wave instability results in the emergence of electron acoustic waves and electron heating. Moreover, ion acoustic waves are effective in inducing anomalous drag between electrons and ions.

Finally, quasi-electrostatic lower hybrid drift waves (ES-LHDW) have been observed during guide field reconnection in the electron diffusion region of MRX. ES-LHDW contributes significantly (~20% of the reconnection electric field) to anomalous resistivity by inducing fluctuations in density and the out-of-plane component of the electric field. The observed small phase difference (30 degrees) between two fluctuations aligns with results from a linear model [Yoo et al., 2022]. Through quasilinear analysis, we confirm that ES-LHDW can generate anomalous electron heating surpassing classical Ohmic heating in laboratory plasmas [Yoo et al., 2024]. Observations in space show that LHDW can be either quasi-electrostatic and electromagnetic, depending on the local condition [Yoo et al. 2021]. Only ES-LHDW is capable of generating a significant anomalous drag term [Yoo et al. 2021, Graham et al. 2022].

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Magnetogenesis via the canonical battery effect

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Although turbulent dynamo processes can amplify magnetic fields to the strength observed in astrophysical situations, how seed magnetic fields are generated in the first place is still a mystery. We show that by analyzing the evolution of canonical vorticity that the canonical battery effect is responsible for seed magnetogenesis. The process generalizes popular magnetogenesis mechanisms, namely the Weibel instability and the Biermann battery effect. The canonical battery term allows for the prediction of various other magnetogenesis mechanisms as well. An example of such a configuration, namely 2D-localized pressure anisotropy, is presented.

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Loading various velocity distributions in particle-in-cell (PIC) simulation

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Particle-in-cell (PIC) simulation is an important tool to study collective behavior of charged particles in space. At start of the simulation, it is necessary to initialize particle velocities, by using random variables. The distribution of particle velocities may vary from problem to problem. We may want to use a Maxwell distribution in many cases, a kappa distribution for heliospheric problems, a loss-cone distribution for inner-magnetospheric problems, and a Maxwell-Juttner distribution for relativistic problems. Meanwhile, it is not always clear how to prepare these distributions by using random variables. In this presentation, we will review Monte-Carlo methods for generating several velocity distributions in PIC simulation. Utilizing gamma-distributed random variables, we have successfully constructed Monte-Carlo algorithms for various distributions [1,2].

1. S. Zenitani & S. Nakano, *Phys. Plasmas* **29**, 113904 (2022)
2. S. Zenitani & S. Nakano, *J. Geophys. Res.* **128**, e2023JA031983 (2023)

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Dynamic Evolution of Bursty Bulk Flows (BBFs) Revealed by Two-way Coupled PIC and MHD Model and Multi-instrument Observations

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The dynamics of Bursty Bulk Flows (BBFs) is an outstanding magnetosphere-ionosphere-thermosphere (MIT) coupling problem associated with sudden magnetic field topology reconfiguration and explosive current formation, particle acceleration, and energy release in the magnetosphere, and is believed to be playing a central role in geomagnetic disturbances, such as substorms. Using a two-way coupled magnetohydrodynamics with embedded kinetic physics model, we perform a event simulation to study electron velocity distribution functions (VDFs) evolution associated with BBFs observed by Magnetospheric Multiscale (MMS) satellite on May 16, 2017. Multiple ground and space-based instruments, such as Poker Flat Incoherent Scatter Radar and magnetometers, are used to reveal the MIT coupling features associated with this BBF event. The simulated BBF macroscopic characteristics and electron VDFs agree well with observations. The VDFs from the BBF tail to its dipolarization front (DF) during its earthward propagation are revealed and they show clear energization and heating. The electron pitch angle distributions (PADs) at the DF are also tracked, which show interesting energy dependent features. Lower energy electrons develop a "two-hump" PAD while the higher energy ones show persist "pancake" distribution. Our study reveals for the first time the evolution of electron VDFs as a BBF moves earthward using a two-way coupled global and kinetic model, and provides valuable contextual understanding for the interpretation of satellite observations.