University of Maryland component of the Center for Multiscale Plasma Dynamics: Final Technical Report

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The Center for Multiscale Plasma Dynamics (CMPD) was a five-year Fusion Science Center that involved scientists from several universities and PPPL. We focused on plasma physics problems for which the traditional separation of the dynamics into microscale and macroscale processes breaks down. Maryland and UCLA led the effort.

Foremost among these problems are the sawtooth crash, the growth of neoclassical magnetic islands, and the formation and collapse of transport barriers. Each involves large scale flows and magnetic fields tightly coupled to the small scale, kinetic dynamics of turbulence, particle acceleration and energy cascade. The interaction between these vastly disparate scales controls the evolution of the system. The enormous range of temporal and spatial scales associated with these problems renders direct simulation intractable even in computations that use the largest existing parallel computers. Substantial progress toward solving these problems was made as a result of the Center. This report summarizes specific contributions from the Maryland component of the Center.

This report summarizes only the research that was funded directly (at least in significant part) through Maryland. Over the five-year lifetime, CMPD scientists funded through Maryland published 112 papers. According to the Web of Science (which is significantly more conservative than Google Scholar), there are presently 3282 citations of these papers. The *h*-factor of the Maryland CMPD publications is 31. The most cited papers focused on magnetic reconnection, kinetic turbulence theory and simulations, and V&V activities. Additional important papers established new algorithms for multiscale simulations. In this category, the development of the Trinity code and algorithm marks the high point of Maryland CMPD progress.

Magnetic reconnection Many papers were published on this topic by Maryland CMPD scientists. The most cited described the acceleration of electrons by contracting magnetic islands (Drake, et al., 2006), the breakup of current sheets into plasmoids in high Lundquist number, reconnecting plasmas and the formation of secondary islands (Loureiro, et al., 2007; Drake, et al., 2006), the detailed micro-scale structure of the current sheet in large-scale reconnection (Shay, et al., 2007), a catastrophe model for the onset of magnetic reconnection (Cassak et al., 2005), “asymmetric” magnetic reconnection (Cassak et al., 2007), cosmic ray generation *via* magnetic reconnection (Drake, et al., 2010), and the relations between Hall fields and fast magnetic reconnection (Drake, et al., 2008). Two junior scientists working at Maryland at the beginning of the CMPD grant are now faculty members at research universities (Shay, Univ of Delaware; Cassak, West Virginia University). Loureiro is head of theory at the Instituto Superior Técnico in Lisbon, Portugal.

Kinetic turbulence theory and simulation In this topic area, the most cited Maryland CMPD paper is an 80-page treatise on kinetic and fluid turbulent cascades in magnetized, weakly collisional plasmas (Schekochihin, et al., 2009), with antecedents (Schekochihin et al., 2007 and 2008). Additional important and well-cited papers include a fundamental paper on the application of gyrokinetic theory and simulation to astrophysical plasmas (Howes et al., 2005), two very important series of papers on the transport of angular momentum in tokamaks (Parra et al., 2008, 2009, 2009, 2010; Catto et al, 2008, 2009) [Parra was half-funded as an MIT graduate student from a Maryland CMPD sub-contract] and zonal flow physics (Xiao et al., 2007; Ricci et al., 2006, 2006, 2010), the theory and simulation of the entropy cascade (alternatively discussed as the free energy cascade) (Tatsuno et al., 2008, 2009, 2012; Plunk et al., 2010, 2011; Zhu et al., 2010) which was subsequently observed experimentally in Taiwan, and a series of papers on island physics and neoclassical tearing modes (Militello et al., 2008, 2008, 2009; Fitzpatrick et al, 2006; Waelbroeck et al, 2009). Rogers and Dorland published a lengthy and hopefully influential paper on gyrokinetic dynamics of the edge plasma (Rogers and Dorland, 2005). Parra was a UMD CMPD graduate student and is now a faculty member at the University of Oxford. Tatsuno and Xiao joined the UMD CMPD effort as research scientist and graduate student and now hold regular faculty positions in Japan and China, respectively. Militello began as a CMPD post-doc paid through the UMD CMPD grant and now has a permanent research scientist position at Culham Laboratory in the UK.

Verification and validation There is obvious overlap of this area with the previous paragraph, but V&V is generally an important subset that deserves special focus. The key paper in this area was a major benchmark effort for electron temperature gradient-driven (ETG) turbulence in tokamaks (Nevins, et al., 2006). A second key paper established that conventional simulation practices in gyrokinetic delta-f PIC for ETG turbulence were highly unresolved and noise-dominated (Nevins et al., 2005). This work led to a large and significant change of practice in the international GK PIC community, from using 1-4 particles per cell to using several hundred. A third important paper documented the AstroGK code which was developed by Maryland CMPD scientists, and includes numerous verification tests (Numata et al., 2010; Rogers et al., 2007) of nonlinear gyrokinetics. The AstroGK code was used for high profile validation of gyrokinetic turbulence simulations in the context of the well-diagnosed, high-β solar wind (Howes et al., 2006, 2008, 2008, 2011) and for several additional papers below. A series of UMD CMPD papers were also focused on V&V in low-aspect ratio (spherical) tokamaks (Applegate et al., 2007; Joiner et al., 2010; Roach et al., 2009; Stutman et al., 2006; Gates et al., 2009), on transport barriers (Ernst et al., 2009) and on turbulence and density transport in the LDX experiment (Ricci et al., 2006, 2006; Kobayashi et al., 2009, 2010). Howes, Ricci and Numata joined the UMD CMPD project as junior scientists and now hold faculty positions.

Algorithm development New algorithms developed and deployed by Maryland CMPD scientists are led by the time-dependent transport solver Trinity, which calculates the transport coefficients from a large number of subsidiary gyrokinetic turbulence simulations (Barnes et al., 2009, 2010, 2010), based on specific theoretical advances developed at Maryland and elsewhere within the CMPD effort (Abel et al., 2008; Abel et al., Reports on Progress in Physics, **76**, 116201, 2013). Additional algorithm developments from the UMD CMPD effort include an iterative semi-implicit scheme with robust damping (Loureiro and Hammett, 2008), a Kevrekidis-style equation-free solver (Shay et al., 2007), an efficient PIC algorithm for GPUs (Stantchev et al., 2008), a lattice-Boltzman solver for MHD (Macnab et al., 2006), and a radically more efficient velocity-space coordinate structure for GS2 simulations of stellarators (Baumgaertel et al, 2011). Gumerov, et al., developed advanced fast multipole algorithms for GPU architectures (Gumerov et al., 2008, 2008). Barnes was a UMD CMPD graduate student and now holds a faculty position at the University of Oxford. Stantchev was a UMD CMPD post-doc and now has a permanent research scientist position at the Naval Research Laboratory.

APPENDIX

The abstracts of all papers published with the support of the University of Maryland's Center for Multiscale Plasma Dynamics contract are listed here in chaotic order.

Error field penetration in the presence of diamagnetic effects

By: Militello, F; Waelbroeck, FL

NUCLEAR FUSION

Volume: 49 **Issue:** 6
Article Number: 065018
DOI: 10.1088/0029-5515/49/6/065018
Published: JUN 2009

Abstract

The penetration of the magnetic field in a rotating inhomogeneous plasma is investigated with direct numerical simulations. The main focus of this work is to test the linear, singular-layer models when diamagnetic and finite Larmor radius effects are included. Our results confirm the existing analytical prediction when the plasma velocity at the resonant surface is outside the drift band, which is the band bounded by the electric drift velocity and the electron diamagnetic velocity. In the drift band, however, a revision of the theory is required. In this regime of velocity, the magnetic island radiates drift waves which can affect the dynamics of the system. Our results show that the penetration of the magnetic field occurs more easily than predicted by the theoretical models, which commonly neglect drift wave radiation effects.

Effect of electrostatic turbulence on magnetic islands

By: Waelbroeck, FL; Militello, F; Fitzpatrick, R; Horton, W

PLASMA PHYSICS AND CONTROLLED FUSION

Volume: 51 **Issue:** 1
Article Number: 015015
DOI: 10.1088/0741-3335/51/1/015015
Published: JAN 2009

Abstract

A numerical analysis of the interaction of resistive drift wave and interchange turbulence with a magnetic island in a two-dimensional slab is presented. The time-scale for the evolution of the island is assumed to be much longer than that for the turbulence, allowing the use of an electrostatic model. The effects of the turbulence are isolated by choosing the parameters such that only even modes are unstable. This makes it possible to compare turbulent states with quiescent states in which turbulence is suppressed by enforcing odd parity. The turbulence is found to reduce the propagation velocity of the island. Its effect is destabilizing for thin islands but becomes stabilizing for islands greater than a few times the Larmor radius. Analysis of the quiescent solutions reveals the possibility of oscillations of the island amplitude and frequency through hysteretic transitions between bistable states.

Influence of higher-order harmonics on the saturation of the tearing mode

By: Arcis, N; Loureiro, NF; Militello, F

PLASMA PHYSICS AND CONTROLLED FUSION

Volume: 51 **Issue:** 3
Article Number: 035002
DOI: 10.1088/0741-3335/51/3/035002
Published: MAR 2009
View Journal Information

Abstract
The nonlinear saturation of the tearing mode is revisited in slab geometry by taking into account higher-order harmonics in the outer solution. The general formalism for tackling this problem in the case of a vanishing current gradient at the resonant surface is derived. It is shown that, although the higher-order harmonics lead to corrections in the final saturation equation, they are of higher order in the perturbation parameter, which provides a formal proof that the standard one-harmonic approach is asymptotically correct.

Interaction between turbulence and a nonlinear tearing mode in the low beta regime

By: Militello, F; Waelbroeck, FL; Fitzpatrick, R; Horton, W

PHYSICS OF PLASMAS

Volume: 15 **Issue:** 5
Article Number: 050701
DOI: 10.1063/1.2917915
Published: MAY 2008
View Journal Information

Abstract
The interaction between turbulence and a nonlinear tearing mode is investigated numerically using a 2D electrostatic model. Turbulence is found to cause transitions between the different roots for the propagation velocity of the mode. The transitions take the mode towards roots with slower propagation that are characterized by a locally flattened density profile. For sufficiently large islands the transition reduces the drive for the tearing mode.

Saturation of tearing modes in reversed field pinches with locally linear force-free magnetic fields and its application to quasi-single-helicity states

By: Tassi, E; Militello, F; Porcelli, F; Hastie, RJ

PHYSICS OF PLASMAS

Volume: 15 **Issue:** 5
Article Number: 052104
DOI: 10.1063/1.2913263
Published: MAY 2008
View Journal Information

Abstract
A simple formula for predicting the width of a saturated island, formed as a consequence of tearing perturbation of linear force-free fields in cylindrical geometry, is derived. The formula makes it possible to calculate the saturated island width in terms of the values of parameters characterizing the initial force-free equilibrium and can be applied to equilibria of interest for reversed field pinches. In particular it is applied, in this paper, to force-free equilibria with piecewise constant radial profile of the pinch parameter, which have been recently suggested to be relevant for the formation of quasi-single-helicity states. The main result is that the island width becomes larger as a parameter, that quantifies the departure from a relaxed Taylor state, increases.

Neoclassical tearing mode saturation in periodic current sheets

By: Militello, F; Ottaviani, M; Porcelli, F

PHYSICS OF PLASMAS

Volume: 15 **Issue:** 4
Article Number: 042104
DOI: 10.1063/1.2901193
Published: APR 2008
View Journal Information

Abstract
The saturation of Neoclassical Tearing Mode islands in a periodic slab configuration is investigated. Several theoretical models, all based on a generalization of Rutherford's procedure, that aim at reducing the complete system to a single equation of the magnetic island width, are compared against numerical simulations. When the effects of the bootstrap current and of the second derivative of the equilibrium current profile are included, the numerical saturation levels are well matched with the predictions of this equation in a wide region of the stability diagram. However, the numerical results diverge from the standard theory when evaluating the threshold for nonlinear destabilization, since the theoretical value appears to be strongly conservative. In other words, the standard generalization of Rutherford's equation is not able to capture the minimum value of the linear stability parameter and of the island width such that below them the Neoclassical Tearing Mode is always suppressed. To correct this discrepancy, a new theoretical model in which the transverse propagation of the island affects the bootstrap current term is proposed.

The influence of the ion polarization current on magnetic island stability in a tokamak plasma

By: Fitzpatrick, R; Waelbroeck, FL; Militello, F

PHYSICS OF PLASMAS

Volume: 13 **Issue:** 12
Article Number: 122507
DOI: 10.1063/1.2402914
Published: DEC 2006
View Journal Information

Abstract

The influence of the ion polarization current on the stability of a constant-psi magnetic island in a tokamak plasma is investigated numerically using a reduced two-fluid model in two-dimensional slab geometry. The polarization current is found to be negligibly small when the island is either too narrow or too wide. However, under certain circumstances, there exists an intermediate regime in which the polarization current is appreciable, and has a stabilizing influence on the island. This effect may account for the metastable nature of neoclassical tearing modes in tokamak plasmas.

Non-local closure and parallel performance of lattice Boltzmann models for some plasma physics problems

By: Macnab, AID; Vahala, G; Vahala, L; Carter, J; Soe, M; Dorland, W

PHYSICA A-STATISTICAL MECHANICS AND ITS APPLICATIONS

Volume: 362 **Issue:** 1 **Pages:** 48-56
DOI: 10.1016/j.physa.2005.09.018
Published: MAR 15 2006
View Journal Information

Conference

Conference: 13th International Conference on Discrete Simulation of Fluid Dyanmics
Location: Cambridge, MA
Date: AUG 16-20, 2004
Sponsor(s): Tufts Univ

Abstract

The lattice Boltzmann (LB) method is a mesoscopic approach to solving nonlinear macroscopic conservation equations. Because the LB algorithm yields a simple collide-stream sequence it has been extensively applied to Navier-Stokes flows, but its MHD Counterpart is less well known in the plasma physics community. several plasma problems that should be amenable to LB are discussed. In particular, Landau damping-a collisionless kinetic phenomenon of wave-particle interaction-can be Studied by LB since non-local macroscopic closures have been generated by plasma physicists. The parallel performance of 2D LB codes for MHD are presented, including scaling performance on the Earth Simulator.

Gyrokinetic simulations of the tearing instability

By: Numata, R; Dorland, W; Howes, GG; Loureiro, NF; Rogers, BN; Tatsuno, T

PHYSICS OF PLASMAS

Volume: 18 **Issue:** 11
Article Number: 112106
DOI: 10.1063/1.3659035
Published: NOV 2011
View Journal Information

Abstract
Linear gyrokinetic simulations covering the collisional-collisionless transitional regime of the tearing instability are performed. It is shown that the growth rate scaling with collisionality agrees well with that predicted by a two-fluid theory for a low plasma beta case in which ion kinetic dynamics are negligible. Electron wave-particle interactions (Landau damping), finite Larmor radius, and other kinetic effects invalidate the fluid theory in the collisionless regime, in which a general non-polytropic equation of state for pressure (temperature) perturbations should be considered. We also vary the ratio of the background ion to electron temperatures and show that the scalings expected from existing calculations can be recovered, but only in the limit of very low beta.

Gyrokinetic simulations of spherical tokamaks

By: Roach, CM; Abel, IG; Akers, RJ; Arter, W; Barnes, M; Camenen, Y; Casson, FJ; Colyer, G; Connor, JW; Cowley, SC...More

PLASMA PHYSICS AND CONTROLLED FUSION

Volume: 51 **Issue:** 12
Article Number: 124020
DOI: 10.1088/0741-3335/51/12/124020
Published: DEC 2009
View Journal Information
Conference
Conference: 36th European-Physical-Society Conference on Plasma Physics
Location: Natl Palace Culture, Sofia, BULGARIA
Date: JUN 29-JUL 03, 2009
Sponsor(s): European Phys Soc; Union Physicists; Sofia Univ St Kliment Ohrids, Fac Phys

Abstract
This paper reviews transport and confinement in spherical tokamaks (STs) and our current physics understanding of this that is partly based on gyrokinetic simulations. Equilibrium flow shear plays an important role, and we show how this is consistently included in the gyrokinetic framework for flows that greatly exceed the diamagnetic velocity. The key geometry factors that influence the effectiveness of turbulence suppression by flow shear are discussed, and we show that toroidal equilibrium flow shear can sometimes entirely suppress ion scale turbulence in today's STs. Advanced nonlinear simulations of electron temperature gradient (ETG) driven turbulence, including kinetic ion physics, collisions and equilibrium flow shear, support the model that ETG turbulence can explain electron heat transport in many ST discharges.

An iterative semi-implicit scheme with robust damping

By: Loureiro, NF; Hammett, GW

JOURNAL OF COMPUTATIONAL PHYSICS

Volume: 227 **Issue:** 9 **Pages:** 4518-4542
DOI: 10.1016/j.jcp.2008.01.015
Published: APR 20 2008
View Journal Information

Abstract

An efficient, iterative semi-implicit (SI) numerical method for the time integration of stiff wave systems is presented. Physics-based assumptions are used to derive a convergent iterative formulation of the SI scheme which enables the monitoring and control of the error introduced by the SI operator. This iteration essentially turns a semi-implicit method into a fully implicit method. Accuracy, rather than stability, determines the timestep. The scheme is second order accurate and shown to be equivalent to a simple preconditioning method. We show how the diffusion operators can be handled so as to yield the property of robust damping, i.e. dissipating the solution at all values of the parameter D Delta t, where D is a diffusion operator and At the timestep. The overall scheme remains second order accurate even if the advection and diffusion operators do not commute. In the limit of no physical dissipation, and for a linear test wave problem, the method is shown to be symplectic. The method is tested on the problem of Kinetic Alfven wave mediated magnetic reconnection. A Fourier (pseudo-spectral) representation is used. A two-field gyrofluid model is used and an efficacious k-space SI operator for this problem is demonstrated. CPU speed-up factors over a CFL-limited explicit algorithm ranging from similar to 20 to several hundreds are obtained, while accurately capturing the results of an explicit integration. Possible extension of these results to a real-space (grid) discretization is discussed.

Instability of current sheets and formation of plasmoid chains

By: Loureiro, NF; Schekochihin, AA; Cowley, SC

PHYSICS OF PLASMAS

Volume: 14 **Issue:** 10
Article Number: 100703
DOI: 10.1063/1.2783986
Published: OCT 2007
View Journal Information

Abstract

Current sheets formed in magnetic reconnection events are found to be unstable to high-wavenumber perturbations. The instability is very fast: its maximum growth rate scales as $S^{-1/4}$ v_A/L_{CS}, where L_{CS} is the length of the sheet, v_A the Alfven speed, and S the Lundquist number. As a result, a chain of plasmoids (secondary islands) is formed, whose number scales as $S^{-3/8}$.

Freely decaying turbulence in two-dimensional electrostatic gyrokinetics

By: Tatsuno, T; Plunk, GG; Barnes, M; Dorland, W; Howes, GG; Numata, R

PHYSICS OF PLASMAS

Volume: 19 **Issue:** 12
Article Number: 122305
DOI: 10.1063/1.4769029
Published: DEC 2012

Abstract

In magnetized plasmas, a turbulent cascade occurs in phase space at scales smaller than the thermal Larmor radius ("sub-Larmor scales") [Tatsuno et al., Phys. Rev. Lett. 103, 015003 (2009)]. When the turbulence is restricted to two spatial dimensions perpendicular to the background magnetic field, two independent cascades may take place simultaneously because of the presence of two collisionless invariants. In the present work, freely decaying turbulence of two-dimensional electrostatic gyrokinetics is investigated by means of phenomenological theory and direct numerical simulations. A dual cascade (forward and inverse cascades) is observed in velocity space as well as in position space, which we diagnose by means of nonlinear transfer functions for the collisionless invariants. We find that the turbulence tends to a time-asymptotic state, dominated by a single scale that grows in time. A theory of this asymptotic state is derived in the form of decay laws. Each case that we study falls into one of three regimes (weakly collisional, marginal, and strongly collisional), determined by a dimensionless number D*, a quantity analogous to the Reynolds number. The marginal state is marked by a critical number D* = D-0 that is preserved in time. Turbulence initialized above this value become increasingly inertial in time, evolving toward larger and larger D*; turbulence initialized below D0 become more and more collisional, decaying to progressively smaller D*.

Direct multiscale coupling of a transport code to gyrokinetic turbulence codes

By: Barnes, M; Abel, IG; Dorland, W;; Hammett, GW; Jenko, F

PHYSICS OF PLASMAS

Volume: 17 **Issue:** 5
Article Number: 056109
DOI: 10.1063/1.3323082
Published: MAY 2010

Abstract
Direct coupling between a transport solver and local, nonlinear gyrokinetic calculations using the multiscale gyrokinetic code TRINITY [M. Barnes, "TRINITY: A unified treatment of turbulence, transport, and heating in magnetized plasmas," Ph.D. thesis, University of Maryland, 2008 (eprint arXiv:0901.2868)] is described. The coupling of the microscopic and macroscopic physics is done within the framework of multiscale gyrokinetic theory, of which we present the assumptions and key results. An assumption of scale separation in space and time allows for the simulation of turbulence in small regions of the space-time grid, which are embedded in a coarse grid on which the transport equations are implicitly evolved. This leads to a reduction in computational expense of several orders of magnitude, making first-principles simulations of the full fusion device volume over the confinement time feasible on current computing resources. Numerical results from TRINITY simulations are presented and compared with experimental data from JET [M. Keilhacker, Plasma Phys. Controlled Fusion 41, B1 (1999)] and ASDEX Upgrade [O. Gruber, Nucl. Fusion 47, S622 (2007)] plasmas.

Resolving velocity space dynamics in continuum gyrokinetics
By: Barnes, M; Dorland, W]; Tatsuno, T

PHYSICS OF PLASMAS

Volume: 17 **Issue:** 3
Article Number: 032106
DOI: 10.1063/1.3313348
Published: MAR 2010

Abstract
Many plasmas of interest to the astrophysical and fusion communities are weakly collisional. In such plasmas, small scales can develop in the distribution of particle velocities, potentially affecting observable quantities such as turbulent fluxes. Consequently, it is necessary to monitor velocity space resolution in gyrokinetic simulations. In this paper, we present a set of computationally efficient diagnostics for measuring velocity space resolution in gyrokinetic simulations and apply them to a range of plasma physics phenomena using the continuum gyrokinetic code GS2. For the cases considered here, it is found that the use of a collisionality at or below experimental values allows for the resolution of plasma dynamics with relatively few velocity space grid points. Additionally, we describe the implementation of an adaptive collision frequency, which can be used to improve velocity space resolution in the collisionless regime, where results are expected to be independent of collision frequency.

Linearized model Fokker-Planck collision operators for gyrokinetic simulations. I. Theory

By: Abel, IG; Barnes, M; Cowley, SC; Dorland, W; Schekochihin, AA

PHYSICS OF PLASMAS

Volume: 15 **Issue:** 12
Article Number: 122509
DOI: 10.1063/1.3046067
Published: DEC 2008

Abstract
A new analytically and numerically manageable model collision operator is developed specifically for turbulence simulations. The like-particle collision operator includes both pitch-angle scattering and energy diffusion and satisfies the physical constraints required for collision operators: it conserves particles, momentum, and energy, obeys Boltzmann's H-theorem (collisions cannot decrease entropy), vanishes on a Maxwellian, and efficiently dissipates small-scale structure in the velocity space. The process of transforming this collision operator into the gyroaveraged form for use in gyrokinetic simulations is detailed. The gyroaveraged model operator is shown to have more suitable behavior at small scales in phase space than previously suggested models. Model operators for electron-ion and ion-electron collisions are also presented.

Linearized model Fokker-Planck collision operators for gyrokinetic simulations. II. Numerical implementation and tests

By: Barnes, M; Abel, IG; Dorland, W; Ernst, DR; Hammett, GW; Ricci, P; Rogers, BN; Schekochihin, AA; Tatsuno, T

PHYSICS OF PLASMAS

Volume: 16 **Issue:** 7
Article Number: 072107
DOI: 10.1063/1.3155085
Published: JUL 2009

Abstract
A set of key properties for an ideal dissipation scheme in gyrokinetic simulations is proposed, and implementation of a model collision operator satisfying these properties is described. This operator is based on the exact linearized test-particle collision operator, with approximations to the field-particle terms that preserve conservation laws and an H-theorem. It includes energy diffusion, pitch-angle scattering, and finite Larmor radius effects corresponding to classical (real-space) diffusion. The numerical implementation in the continuum gyrokinetic code GS2 [Kotschenreuther , Comput. Phys. Comm. 88, 128 (1995)] is fully implicit and guarantees exact satisfaction of conservation properties. Numerical results are presented showing that the correct physics is captured over the entire range of collisionalities, from the collisionless to the strongly collisional regimes, without recourse to artificial dissipation.

Finite Larmor radius effects on nondiffusive tracer transport in a zonal flow

By: Gustafson, K; del-Castillo-Negrete, D; Dorland, W

PHYSICS OF PLASMAS

Volume: 15 **Issue:** 10
Article Number: 102309
DOI: 10.1063/1.3003072
Published: OCT 2008

Abstract

Finite Larmor radius (FLR) effects on nondiffusive transport in a prototypical zonal flow with drift waves are studied in the context of a simplified chaotic transport model. The model consists of a superposition of drift waves from the linearized Hasegawa-Mima equation and a zonal shear flow perpendicular to the density gradient. High frequency FLR effects are incorporated by gyroaveraging the E x B velocity. Transport in the direction of the density gradient is negligible and we therefore focus on transport parallel to the zonal flows. A prescribed asymmetry produces strongly asymmetric non-Gaussian probability distribution functions (PDFs) of particle displacements, with Levy flights in one direction only. For k(perpendicular to)rho(th)=0, where k(perpendicular to) is the characteristic wavelength of the flow and rho(th) is the thermal Larmor radius, a transition is observed in the scaling of the second moment of particle displacements: sigma(2) similar to t(gamma). The transition separates ballistic motion (gamma approximate to 2) at intermediate times from superdiffusion (gamma=1.6) at larger times. This change of scaling is accompanied by the transition of the PDF of particle displacements from algebraic decay to exponential decay. However, FLR effects seem to eliminate this transition. In all cases, the Lagrangian velocity autocorrelation function exhibits nondiffusive algebraic decay, C similar to tau(-kappa), with kappa=2-gamma to a good approximation. The PDFs of trapping and flight events show clear evidence of algebraic scaling with decay exponents depending on the value of k(perpendicular to)rho(th). The shape and spatiotemporal self-similar anomalous scaling of the PDFs of particle displacements are reproduced accurately with a neutral (alpha=beta), asymmetric, effective fractional diffusion model, where alpha and beta are the orders of the spatial and temporal fractional derivatives, respectively.

Self-consistent particle tracking in a simulation of the entropy mode in a Z pinch

By: Gustafson, K; Broemstrup, I; Del-Castillo-Negrete, D; Dorland, W; Barnes, M
Edited by: Garbet, X; Sauter, O; Sindoni, E

THEORY OF FUSION PLASMAS

Book Series: AIP Conference Proceedings
Volume: 1069 **Pages:** 277-282
Published: 2008

Abstract
A single particle tracking technique for studying nondiffusive transport is implemented in it new particle-in-cell gyrokinetic simulation of the entropy mode in a Z pinch geometry. Radial transport is characterized in terms of tire time dependence of the variance of displacements. The vertical zonal flow dynamics of the nonlinear phase of the instability seem to cause subdiffusive traransport for ions during the simulation lengths Used here. Electrons follow subdiffusive transport, except for later little,; in the case of tire largest gradient, where tire transport becomes superdiffusive. The probability distribution of displacements shows a positive skew and long tails relative to the Gaussian distribution for both ions and electrons.

Coherent Vorticity Extraction in 3D Homogeneous Isotropic Turbulence: Influence of the Reynolds Number and Geometrical Statistics

By: Kadoch, B; Domingues, MO; Broemstrup, I; Larcheveque, L; Schneider, K; Farge, M

BRAZILIAN JOURNAL OF PHYSICS

Volume: 39 **Issue:** 3 **Pages:** 531-538
Published: 2009

Abstract
The coherent vorticity extraction method (CVE) is based on the nonlinear filtering of the vorticity field projected onto an orthonormal wavelet basis made of compactly supported functions. CVE decomposes each turbulent flow realization into two orthogonal components: a coherent and an incoherent random flow. They both contribute to all scales in the inertial range, but exhibit different statistical behavior. We apply CVE to 2563 subcubes extracted from 3D homogeneous isotropic turbulent flows at different Taylor microscale Reynolds numbers (R(lambda) = 140,240 and 680), computed by a direct numerical simulation (DNS) at different resolutions (N = 256(3),512(3) and 2048(3)), respectively. We compare the total, coherent and incoherent vorticity fields obtained by using CVE and show that few wavelets coefficients are sufficient to represent the coherent vortices of the flows. Geometrical statistics in term of helicity are also analyzed and the lambda(2) criterion is applied to the filtered flow fields.

Using Graphics Processors for High-Performance Computation and Visualization of Plasma Turbulence

By: Stantchev, G; Juba, D; Dorland, W; Varshney, A

COMPUTING IN SCIENCE & ENGINEERING

Volume: 11 **Issue:** 2 **Pages:** 52-59
Published: MAR-APR 2009

Abstract
Direct numerical simulation (DNS) of turbulence is computationally intensive and typically relies on some form of parallel processing. The authors present techniques to map DNS computations to modern graphics processing units (GPUs), which are characterized by very high memory bandwidth and hundreds of SPMD (single-program-multiple-data) processors.

Fast parallel Particle-To-Grid interpolation for plasma PIC simulations on the GPU

By: Stantchev, G; Dorland, W; Gumerov, N

JOURNAL OF PARALLEL AND DISTRIBUTED COMPUTING

Volume: 68 **Issue:** 10 **Pages:** 1339-1349
DOI: 10.1016/j.jpdc.2008.05.009
Published: OCT 2008
View Journal Information
Conference
Conference: ACM Conference on Computing Frontiers
Location: Ischia, ITALY
Date: MAY 05-07, 2008
Sponsor(s): ACM

Abstract
Particle-In-Cell (PIC) methods have been widely used for plasma physics simulations in the past three decades. To ensure an acceptable level of statistical accuracy relatively large numbers of particles are needed. State-of-the-art Graphics Processing Units (GPUs), with their high memory bandwidth. hundreds of SPMD processors, and half-a-teraflop performance potential, offer a viable alternative to distributed memory parallel computers for running medium-scale PICplasma simulations on inexpensive commodity hardware. In this paper, we present an overview of a typical plasma PIC code and discuss its GPU implementation. In particular we focus on fast algorithms for the performance bottleneck operation of Particle-To-Grid interpolation.

Confluent volumetric visualization of gyrokinetic turbulence

By: Stantchev, G; Juba, D; Dorland, W; Varshney, A

IEEE TRANSACTIONS ON PLASMA SCIENCE

Volume: 36 **Issue:** 4 **Pages:** 1112-1113 **Part:** 1
DOI: 10.1109/TPS.2008.924509
Published: AUG 2008

Abstract
Data from gyrokinetic turbulence codes are often difficult to visualize due their high dimensionality, the nontrivial geometry of the underlying grids, and the vast range of spatial scales. We present an interactive visualization framework that attempts to address these issues. Images from a nonlinear gyrokinetic simulation are presented.

Limitations of gyrokinetics on transport time scales

By: Parra, FI; Catto, PJ

PLASMA PHYSICS AND CONTROLLED FUSION

Volume: 50 **Issue:** 6
Article Number: 065014
DOI: 10.1088/0741-3335/50/6/065014
Published: JUN 2008

Abstract
We present a new recursive procedure to find a full f electrostatic gyrokinetic equation correct to first order in an expansion of gyroradius over magnetic field characteristic length. The procedure provides new insights into the limitations of the gyrokinetic quasineutrality equation. We find that the ion distribution function must be known at least to second order in gyroradius over characteristic length to calculate the long wavelength components of the electrostatic potential self-consistently. Moreover, using the example of a steady-state theta-pinch, we prove that the quasineutrality equation fails to provide the axisymmetric piece of the potential even with a distribution function correct to second order. We also show that second order accuracy is enough if a more convenient moment equation is used instead of the quasineutrality equation. These results indicate that the gyrokinetic quasineutrality equation is not the most effective procedure to find the electrostatic potential if the long wavelength components are to be retained in the analysis.

Limitations, insights and improvements to gyrokinetics

By: Catto, PJ; Parra, FI; Kagan, G; Simakov, AN

NUCLEAR FUSION

Volume: 49 **Issue:** 9
Article Number: 095026
DOI: 10.1088/0029-5515/49/9/095026
Published: SEP 2009

Abstract
We first consider gyrokinetic quasineutrality limitations when evaluating the axisymmetric radial electric field in a non-turbulent tokamak by an improved examination of intrinsic ambipolarity. We next prove that the background ions in a pedestal of poloidal ion gyroradius scale must be Maxwellian and nearly isothermal in Pfirsch-Schluter and banana regime tokamak plasmas, and then consider zonal flow behaviour in a pedestal. Finally, we focus on a simplifying procedure for our transport time scale hybrid gyrokinetic-fluid treatment that removes the limitations of gyrokinetic quasineutrality and remains valid in the pedestal.

Electrostatic turbulence in tokamaks on transport time scales

By: Catto, PJ; Simakov, AN; Parra, FI; Kagan, G

PLASMA PHYSICS AND CONTROLLED FUSION

Volume: 50 **Issue:** 11
Article Number: 115006
DOI: 10.1088/0741-3335/50/11/115006
Published: NOV 2008

Abstract
Simulating electrostatic turbulence in tokamaks on transport time scales requires retaining and evolving a complete turbulence modified neoclassical transport description, including all the axisymmetric neoclassical and zonal flow radial electric field effects, as well as the turbulent transport normally associated with drift instabilities. Neoclassical electric field effects are particularly difficult to retain since they require evaluating the ion distribution function to higher order in gyroradius over background scale length than standard gyrokinetic treatments. To avoid extending gyrokinetics an alternate hybrid gyrokinetic-fluid treatment is formulated that employs moments of the full Fokker-Planck kinetic equation to remove the need for a higher order gyrokinetic distribution function. The resulting hybrid description is able to model all electrostatic turbulence effects withwavelengths much longer than an electron Larmor radius such as the ion temperature gradient (ITG) and trapped electron modes (TEM).

Gyrokinetic equivalence
By: Parra, FI; Catto, PJ

PLASMA PHYSICS AND CONTROLLED FUSION

Volume: 51 **Issue:** 6
Article Number: 065002
DOI: 10.1088/0741-3335/51/6/065002
Published: JUN 2009

Abstract
We compare two different derivations of the gyrokinetic equation: the Hamiltonian approach in Dubin D H E et al (1983 Phys. Fluids 26 3524) and the recursive methodology in Parra F I and Catto P J (2008 Plasma Phys. Control. Fusion 50 065014). We prove that both approaches yield the same result at least to second order in a Larmor radius over macroscopic length expansion. There are subtle differences in the definitions of some of the functions that need to be taken into account to prove the equivalence.

Vorticity and intrinsic ambipolarity in turbulent tokamaks
By: Parra, FI; Catto, PJ

PLASMA PHYSICS AND CONTROLLED FUSION

Volume: 51 **Issue:** 9
Article Number: 095008
DOI: 10.1088/0741-3335/51/9/095008
Published: SEP 2009

Abstract
Traditional electrostatic gyrokinetic treatments consist of a gyrokinetic Fokker-Planck equation and a gyrokinetic quasineutrality equation. Both of these equations can be found up to second order in a gyroradius over macroscopic length expansion in some simplified cases, but the versions implemented in codes are typically only first order. In axisymmetric configurations such as the tokamak, the accuracy to which the distribution function is calculated is insufficient to determine the neoclassical radial electric field. Moreover, we prove here that turbulence dominated tokamaks are intrinsically ambipolar, as are neoclassical tokamaks. Therefore, traditional gyrokinetic descriptions are unable to correctly calculate the toroidal rotation and hence the axisymmetric radial electric field. We study the vorticity equation, del . J = 0, in the gyrokinetic regime, with wavelengths on the order of the ion Larmor radius. We explicitly show that gyrokinetics needs to be calculated at least to third order in the gyroradius expansion if the radial electric field is to be retrieved from quasineutrality. The method employed to study the vorticity equation also suggests a solution to the problem, namely, solving a gyrokinetic vorticity equation instead of the quasineutrality equation. The vorticity equations derived here only obtain the potential within a flux function as required.

Turbulent transport of toroidal angular momentum in low flow gyrokinetics

By: Parra, FI; Catto, PJ

PLASMA PHYSICS AND CONTROLLED FUSION

Volume: 52 **Issue:** 4
Article Number: 045004
DOI: 10.1088/0741-3335/52/4/045004
Published: APR 2010

Abstract
We derive a self-consistent equation for the turbulent transport of toroidal angular momentum in tokamaks in the low flow ordering that only requires solving gyrokinetic Fokker-Planck and quasineutrality equations correct to second order in an expansion on the gyroradius over scale length. We also show that according to our orderings the long wavelength toroidal rotation and the long wavelength radial electric field satisfy the neoclassical relation that gives the toroidal rotation as a function of the radial electric field and the radial gradients of pressure and temperature. Thus, the radial electric field can be solved for once the toroidal rotation is calculated from the transport of toroidal angular momentum. Unfortunately, even though this methodology only requires a gyrokinetic model correct to second order in gyroradius over scale length, current gyrokinetic simulations are only valid to first order. To overcome this difficulty, we exploit the smallish ratio B(p)/B, where B is the total magnetic field and B(p) is its poloidal component. When B(p)/B is small, the usual first order gyrokinetic equation provides solutions that are accurate enough to employ for our expression for the transport of toroidal angular momentum. We show that current delta f and full f simulations only need small corrections to achieve this accuracy. Full f simulations, however, are still unable to determine the long wavelength, radial electric field from the quasineutrality equation.

Magneto-flow instability in symmetric field profiles

By: Tatsuno, T; Dorland, W

PHYSICS OF PLASMAS

Volume: 13 **Issue:** 9
Article Number: 092107
DOI: 10.1063/1.2338819
Published: SEP 2006

Abstract
Since Rayleigh's early work on shear-flow driven instabilities in fluids, it has been known that sheared flows are usually unstable only in the presence of an inflection point in the velocity profile. However, in magnetohydrodynamics, there are important instabilities for which no inflection point is required. In tokamak experiments, strongly sheared flows are associated with transport barriers. Instabilities that may limit the height and extent of transport barriers are of central importance. Here, we present linear and nonlinear simulations of an ideal magnetohydrodynamic instability that is driven by sheared flows without inflection points-instead, the instability mechanism requires reversed magnetic shear. Several symmetric field profiles are studied. In general, the instability leads to current profile modifications that push the local minimum value of the safety factor (q(min)) upward. The possibility of causing disruption in a relatively slow time scale is pointed out when q(min) crosses a rational (especially integral) value. The time scale of the instability is governed by the transit time of the shear flow, which is typically smaller than that of the Alfven velocity. Characteristics of this instability are compared with recent experimental observations.

Gyrokinetic simulations of collisionless magnetic reconnection

By: Rogers, BN; Kobayashi, S; Ricci, P; Dorland, W; Drake, J; Tatsuno, T

PHYSICS OF PLASMAS

Volume: 14 **Issue:** 9
Article Number: 092110
DOI: 10.1063/1.2774003
Published: SEP 2007

Abstract
Linear and nonlinear gyrokinetic simulations of collisionless magnetic reconnection in the presence of a strong guide field are presented. A periodic slab system is considered with a sinusoidally varying reconnecting magnetic field component. The linear growth rates of the tearing mode in both the large and small Delta(') regimes are compared to kinetic and fluid theory calculations. In the nonlinear regime, focusing on the limit of large Delta('), the nonlinear reconnection rates in the gyrokinetic simulations are found to be comparable to those obtained from a two-fluid model. In contrast to the fluid system, however, for T-i > T-e and very small initial perturbation amplitudes, the reconnection in the gyrokinetic system saturates in the early nonlinear phase. This saturation can be overcome if the simulation is seeded initially with sufficient random noise.

Kinetic simulations of magnetized turbulence in astrophysical plasmas

By: Howes, GG; Dorland, W; Cowley, SC; Hammett, GW; Quataert, E; Schekochihin, AA; Tatsuno, T

PHYSICAL REVIEW LETTERS

Volume: 100 **Issue:** 6
Article Number: 065004
DOI: 10.1103/PhysRevLett.100.065004
Published: FEB 15 2008

Abstract
This Letter presents the first ab initio, fully electromagnetic, kinetic simulations of magnetized turbulence in a homogeneous, weakly collisional plasma at the scale of the ion Larmor radius (ion gyroscale). Magnetic- and electric-field energy spectra show a break at the ion gyroscale; the spectral slopes are consistent with scaling predictions for critically balanced turbulence of Alfven waves above the ion gyroscale (spectral index -5/3) and of kinetic Alfven waves below the ion gyroscale (spectral indices of -7/3 for magnetic and -1/3 for electric fluctuations). This behavior is also qualitatively consistent with in situ measurements of turbulence in the solar wind. Our findings support the hypothesis that the frequencies of turbulent fluctuations in the solar wind remain well below the ion cyclotron frequency both above and below the ion gyroscale.

Cited: 117

Secondary tearing mode in the nonlinear evolution of magnetorotational instability

By: Tatsuno, T; Dorland, W

ASTRONOMISCHE NACHRICHTEN

Volume: 329 **Issue:** 7 **Pages:** 688-700
DOI: 10.1002/asna.200811013
Published: SEP 2008

Abstract
Numerical investigation of the two-dimensional magnetic reconnection is given in the context of the nonlinear evolution of the Magneto-Rotational Instability (MRI). With a careful comparison to various theories using both one- and two-dimensional analysis, it is found that a new stabilizing effect of the centrifugal force on tearing instability must be present in the specific geometry of the MRI. Magnetic reconnection might play a key role to the formation of the nonaxisymmetric structures observed in MRI experiments. The results may also be useful for the estimate of the accretion rate in various astrophysical objects.

Cited: 4

ASTROPHYSICAL GYROKINETICS: KINETIC AND FLUID TURBULENT CASCADES IN MAGNETIZED WEAKLY COLLISIONAL PLASMAS

By: Schekochihin, AA; Cowley, SC; Dorland, W; Hammett, GW; Howes, GG; Quataert, E; Tatsuno, T

ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES

Volume: 182 **Issue:** 1 **Pages:** 310-377
DOI: 10.1088/0067-0049/182/1/310
Published: MAY 2009

Abstract

This paper presents a theoretical framework for understanding plasma turbulence in astrophysical plasmas. It is motivated by observations of electromagnetic and density fluctuations in the solar wind, interstellar medium and galaxy clusters, as well as by models of particle heating in accretion disks. All of these plasmas and many others have turbulent motions at weakly collisional and collisionless scales. The paper focuses on turbulence in a strong mean magnetic field. The key assumptions are that the turbulent fluctuations are small compared to the mean field, spatially anisotropic with respect to it and that their frequency is low compared to the ion cyclotron frequency. The turbulence is assumed to be forced at some system-specific outer scale. The energy injected at this scale has to be dissipated into heat, which ultimately cannot be accomplished without collisions. A kinetic cascade develops that brings the energy to collisional scales both in space and velocity. The nature of the kinetic cascade in various scale ranges depends on the physics of plasma fluctuations that exist there. There are four special scales that separate physically distinct regimes: the electron and ion gyroscales, the mean free path and the electron diffusion scale. In each of the scale ranges separated by these scales, the fully kinetic problem is systematically reduced to a more physically transparent and computationally tractable system of equations, which are derived in a rigorous way. In the "inertial range" above the ion gyroscale, the kinetic cascade separates into two parts: a cascade of Alfvenic fluctuations and a passive cascade of density and magnetic-field-strength fluctuations. The former are governed by the reduced magnetohydrodynamic (RMHD) equations at both the collisional and collisionless scales; the latter obey a linear kinetic equation along the (moving) field lines associated with the Alfvenic component (in the collisional limit, these compressive fluctuations become the slow and entropy modes of the conventional MHD). In the "dissipation range" below ion gyroscale, there are again two cascades: the kinetic-Alfven-wave (KAW) cascade governed by two fluid-like electron reduced magnetohydrodynamic (ERMHD) equations and a passive cascade of ion entropy fluctuations both in space and velocity. The latter cascade brings the energy of the inertial-range fluctuations that was Landau-damped at the ion gyroscale to collisional scales in the phase space and leads to ion heating. The KAW energy is similarly damped at the electron gyroscale and converted into electron heat. Kolmogorov-style scaling relations are derived for all of these cascades. The relationship between the theoretical models proposed in this paper and astrophysical applications and observations is discussed in detail.

Nonlinear Phase Mixing and Phase-Space Cascade of Entropy in Gyrokinetic Plasma Turbulence

By: Tatsuno, T; Dorland, W; Schekochihin, AA; Plunk, GG; Barnes, M; Cowley, SC; Howes, GG

PHYSICAL REVIEW LETTERS
Volume: 103 **Issue:** 1
Article Number: 015003
DOI: 10.1103/PhysRevLett.103.015003
Published: JUL 3 2009

Abstract
Electrostatic turbulence in weakly collisional, magnetized plasma can be interpreted as a cascade of entropy in phase space, which is proposed as a universal mechanism for dissipation of energy in magnetized plasma turbulence. When the nonlinear decorrelation time at the scale of the thermal Larmor radius is shorter than the collision time, a broad spectrum of fluctuations at sub-Larmor scales is numerically found in velocity and position space, with theoretically predicted scalings. The results are important because they identify what is probably a universal Kolmogorov-like regime for kinetic turbulence; and because any physical process that produces fluctuations of the gyrophase-independent part of the distribution function may, via the entropy cascade, result in turbulent heating at a rate that increases with the fluctuation amplitude, but is independent of the collision frequency.

Numerical modeling of Large Plasma Device Alfveacuten wave experiments using AstroGK

By: Nielson, KD; Howes, GG; Tatsuno, T; Numata, R; Dorland, W

PHYSICS OF PLASMAS
Volume: 17 **Issue:** 2
Article Number: 022105
DOI: 10.1063/1.3309486
Published: FEB 2010

Abstract
Collisions between counterpropagating Alfveacuten waves represent the fundamental building block of plasma turbulence, a phenomenon of great importance to a wide variety of fields, from space physics and astrophysics to controlled magnetic fusion. Proposed experiments to study Alfveacuten wave collisions on the Large Plasma Device (LAPD) [W. Gekelman, H. Pfister, Z. Lucky, J. Bamber, D. Leneman, and J. Maggs, Rev. Sci. Instrum. 62, 2875 (1991)] at the University of California, Los Angeles, will benefit significantly from numerical modeling capable of reproducing not only the linear dispersive effects of kinetic and inertial Alfveacuten waves, but also the nonlinear evolution of the Alfveacutenic turbulence. This paper presents a comparison of linear simulation results using the astrophysical gyrokinetics code, AstroGK, to the measured linear properties of kinetic and inertial Alfveacuten waves in the LAPD plasma. Results demonstrate that: (1) finite frequency effects due to the ion cyclotron resonance do not prevent satisfactory modeling of the LAPD plasma using gyrokinetic theory; and (2) an advanced collision operator, recently implemented in AstroGK, enables the code to successfully reproduce the collisionally enhanced damping rates of linear waves measured in recent LAPD experiments. These tests justify the use of AstroGK in the modeling of LAPD Alfveacuten wave experiments and suggest that AstroGK will be a valuable tool in modeling the nonlinear evolution of proposed Alfveacuten wave collision experiments.

Two-dimensional gyrokinetic turbulence

By: Plunk, GG; Cowley, SC; Schekochihin, AA; Tatsuno, T

JOURNAL OF FLUID MECHANICS

Volume: 664 **Pages:** 407-435
DOI: 10.1017/S002211201000371X
Published: DEC 2010

Abstract
Two-dimensional gyrokinetics is a simple paradigm for the study of kinetic magnetised plasma turbulence. In this paper, we present a comprehensive theoretical framework for this turbulence. We study both the inverse and direct cascades (the 'dual cascade'), driven by a homogeneous and isotropic random forcing. The key characteristic length of gyrokinetics, the Larmor radius, divides scales into two physically distinct ranges. For scales larger than the Larmor radius, we derive the familiar Charney-Hasegawa- Mima equation from the gyrokinetic system, and explain its relationship to gyrokinetics. At scales smaller than the Larmor radius, a dual cascade occurs in phase space (two dimensions in position space plus one dimension in velocity space) via a nonlinear phase-mixing process. We show that at these sub-Larmor scales, the turbulence is self-similar and exhibits power-law spectra in position and velocity space. We propose a Hankel-transform formalism to characterise velocity-space spectra. We derive the exact relations for third-order structure functions, analogous to Kolmogorov's four-fifths and Yaglom's four-thirds laws and valid at both long and short wavelengths. We show how the general gyrokinetic invariants are related to the particular invariants that control the dual cascade in the long-and short-wavelength limits. We describe the full range of cascades from the fluid to the fully kinetic range.

AstroGK: Astrophysical gyrokinetics code

By: Numata, R; Howes, GG; Tatsuno, T; Barnes, M; Dorland, W

JOURNAL OF COMPUTATIONAL PHYSICS

Volume: 229 **Issue:** 24 **Pages:** 9347-9372
DOI: 10.1016/j.jcp.2010.09.006
Published: DEC 10 2010

Abstract
The gyrokinetic simulation code AstroGK is developed to study fundamental aspects of kinetic plasmas and for applications mainly to astrophysical problems. AstroGK is an Eulerian slab code that solves the electromagnetic gyrokinetic-Maxwell equations in five-dimensional phase space, and is derived from the existing gyrokinetics code GS2 by removing magnetic geometry effects. Algorithms used in the code are described. The code is benchmarked using linear and nonlinear problems. Serial and parallel performance scalings are also presented.

Energy Transfer and Dual Cascade in Kinetic Magnetized Plasma Turbulence

By: Plunk, GG; Tatsuno, T

PHYSICAL REVIEW LETTERS

Volume: 106 **Issue:** 16
Article Number: 165003
DOI: 10.1103/PhysRevLett.106.165003
Published: APR 20 2011

Abstract
The question of how nonlinear interactions redistribute the energy of fluctuations across available degrees of freedom is of fundamental importance in the study of turbulence and transport in magnetized weakly collisional plasmas, ranging from space settings to fusion devices. In this Letter, we present a theory for the dual cascade found in such plasmas, which predicts a range of new behavior that distinguishes this cascade from that of neutral fluid turbulence. These phenomena are explained in terms of the constrained nature of spectral transfer in nonlinear gyrokinetics. Accompanying this theory are the first observations of these phenomena, obtained via direct numerical simulations using the gyrokinetic code ASTROGK. The basic mechanisms that are found provide a framework for understanding the turbulent energy transfer that couples scales both locally and nonlocally.

Cited: 6

Gyrokinetic Simulations of Solar Wind Turbulence from Ion to Electron Scales

By: Howes, GG; TenBarge, JM; Dorland, W; Quataert, E; Schekochihin, AA; Numata, R; Tatsuno, T

PHYSICAL REVIEW LETTERS

Volume: 107 **Issue:** 3
Article Number: 035004
DOI: 10.1103/PhysRevLett.107.035004
Published: JUL 14 2011

Abstract
A three-dimensional, nonlinear gyrokinetic simulation of plasma turbulence resolving scales from the ion to electron gyroradius with a realistic mass ratio is presented, where all damping is provided by resolved physical mechanisms. The resulting energy spectra are quantitatively consistent with a magnetic power spectrum scaling of k(-2.8) as observed in in situ spacecraft measurements of the "dissipation range" of solar wind turbulence. Despite the strongly nonlinear nature of the turbulence, the linear kinetic Alfven wave mode quantitatively describes the polarization of the turbulent fluctuations. The collisional ion heating is measured at subion-Larmor radius scales, which provides evidence of the ion entropy cascade in an electromagnetic turbulence simulation.

Cited: 55

Electron temperature gradient driven transport in a MAST H-mode plasma
By: Joiner, N; Applegate, D; Cowley, SC; Dorland, W; Roach, CM

PLASMA PHYSICS AND CONTROLLED FUSION

Volume: 48 **Issue:** 5 **Pages:** 685-697
DOI: 10.1088/0741-3335/48/5/013
Published: MAY 2006

Abstract
Gyrokinetic simulation of a MAST-like equilibrium is used to establish the turbulent transport resulting from the electron temperature gradient driven mode for core and edge parameters. The thermal diffusion coefficients calculated in these simulations are found to be experimentally significant for core parameters but underestimate the observed transport on outer flux-surfaces.

Gyrokinetic linear theory of the entropy mode in a Z pinch
By: Ricci, P; Rogers, BN; Dorland, W; Barnes, M

PHYSICS OF PLASMAS

Volume: 13 **Issue:** 6
Article Number: 062102
DOI: 10.1063/1.2205830
Published: JUN 2006

Abstract
The linear gyrokinetic theory of the entropy mode is presented in a Z-pinch configuration in the regime of plasma beta < 1, focusing primarily on the parameter regime in which the ideal interchange mode is stable. The entropy mode is a small-scale, nonmagnetohydrodynamic mode that typically has peak growth rates at k rho(s)similar to 1[rho(2)(s)=(T-0e+T-0i)/(m(i)Omega(2)(ci))], with magnitudes comparable to those of ideal modes. The properties of this mode are studied as a function of the density and temperature gradients, plasma collisionality, and electron to ion temperature ratio.

Studies of improved electron confinement in low density L-mode National Spherical Torus Experiment Discharges

By: Stutman, D; Finkenthal, M; Tritz, K; Redi, MH; Kaye, SM; Bell, MG; Bell, RE; LeBlanc, BP; Hill, KW; Medley, SS...More
Group Author(s): NSTX Team

PHYSICS OF PLASMAS

Volume: 13 **Issue:** 9
Article Number: 092511
DOI: 10.1063/1.2355664
Published: SEP 2006

Abstract
Electron transport is rapid in most National Spherical Torus Experiment, M. Ono , Nucl. Fusion 40, 557 (2000) beam heated plasmas. A regime of improved electron confinement is nevertheless observed in low density L-mode ("low-confinement") discharges heated by early beam injection. Experiments were performed in this regime to study the role of the current profile on thermal transport. Variations in the magnetic shear profile were produced by changing the current ramp rate and onset of neutral beam heating. An increased electron temperature gradient and local minimum in the electron thermal diffusivity were observed at early times in plasmas with the fastest current ramp and earliest beam injection. In addition, an increased ion temperature gradient associated with a region of reduced ion transport is observed at slightly larger radii. Ultrasoft x-ray measurements of double-tearing magnetohydrodynamic activity, together with current diffusion calculations, point to the existence of negative magnetic shear in the core of these plasmas. Discharges with slower current ramp and delayed beam onset, which are estimated to have more monotonic q-profiles, do not exhibit regions of reduced transport. The results are discussed in the light of the initial linear microstability assessment of these plasmas, which suggests that the growth rate of all instabilities, including microtearing modes, can be reduced by negative or low magnetic shear in the temperature gradient region. Several puzzles arising from the present experiments are also highlighted.

Astrophysical gyrokinetics: Basic equations and linear theory

By: Howes, GG; Cowley, SC; Dorland, W; Hammett, GW; Quataert, E; Schekochihin, AA

ASTROPHYSICAL JOURNAL

Volume: 651 **Issue:** 1 **Pages:** 590-614 **Part:** 1
DOI: 10.1086/506172
Published: NOV 1 2006

Abstract

Magnetohydrodynamic (MHD) turbulence is encountered in a wide variety of astrophysical plasmas, including accretion disks, the solar wind, and the interstellar and intracluster medium. On small scales, this turbulence is often expected to consist of highly anisotropic fluctuations with frequencies small compared to the ion cyclotron frequency. For a number of applications, the small scales are also collisionless, so a kinetic treatment of the turbulence is necessary. We show that this anisotropic turbulence is well described by a low-frequency expansion of the kinetic theory called gyrokinetics. This paper is the first in a series to examine turbulent astrophysical plasmas in the gyrokinetic limit. We derive and explain the nonlinear gyrokinetic equations and explore the linear properties of gyrokinetics as a prelude to nonlinear simulations. The linear dispersion relation for gyrokinetics is obtained, and its solutions are compared to those of hot-plasma kinetic theory. These results are used to validate the performance of the gyrokinetic simulation code GS2 in the parameter regimes relevant for astrophysical plasmas. New results on global energy conservation in gyrokinetics are also derived. We briefly outline several of the problems to be addressed by future nonlinear simulations, including particle heating by turbulence in hot accretion flows and in the solar wind, the magnetic and electric field power spectra in the solar wind, and the origin of small-scale density fluctuations in the interstellar medium.

Characterizing electron temperature gradient turbulence via numerical simulation

By: Nevins, WM; Candy, J; Cowley, S; Dannert, T; Dimits, A; Dorland, W; Estrada-Mila, C; Hammett, GW; Jenko, F; Pueschel, MJ … More

PHYSICS OF PLASMAS

Volume: 13 **Issue:** 12
Article Number: 122306
DOI: 10.1063/1.2402510
Published: DEC 2006

Abstract
Numerical simulations of electron temperature gradient (ETG) turbulence are presented that characterize the ETG fluctuation spectrum, establish limits to the validity of the adiabatic ion model often employed in studying ETG turbulence, and support the tentative conclusion that plasma-operating regimes exist in which ETG turbulence produces sufficient electron heat transport to be experimentally relevant. We resolve prior controversies regarding simulation techniques and convergence by benchmarking simulations of ETG turbulence from four microturbulence codes, demonstrating agreement on the electron heat flux, correlation functions, fluctuation intensity, and rms flow shear at fixed simulation cross section and resolution in the plane perpendicular to the magnetic field. Excellent convergence of both continuum and particle-in-cell codes with time step and velocity-space resolution is demonstrated, while numerical issues relating to perpendicular (to the magnetic field) simulation dimensions and resolution are discussed. A parameter scan in the magnetic shear, s, demonstrates that the adiabatic ion model is valid at small values of s ($s < 0.4$ for the parameters used in this scan) but breaks down at higher magnetic shear. A proper treatment employing gyrokinetic ions reveals a steady increase in the electron heat transport with increasing magnetic shear, reaching electron heat transport rates consistent with analyses of experimental tokamak discharges.

Small-scale turbulence in a closed-field-line geometry

By: Ricci, P; Rogers, BN; Dorland, W

PHYSICAL REVIEW LETTERS

Volume: 97 **Issue:** 24
Article Number: 245001
DOI: 10.1103/PhysRevLett.97.245001
Published: DEC 15 2006

Abstract
Plasma turbulence due to small-scale entropy modes is studied with gyrokinetic simulations in a simple closed-field-line geometry, the Z pinch, in low-beta parameter regimes that are stable to ideal interchange modes. We find an enormous variation in the nonlinear dynamics and particle transport as a function of two main parameters, the density gradient and the plasma collisionality. This variation is explained in part by the damping and stability properties of spontaneously formed zonal flows in the system. As in toroidal systems, the zonal flows can lead to a strong nonlinear suppression of transport below a critical gradient that is determined by the stability of the zonal flows.

Dissipation-scale turbulence in the solar wind

By: Howes, GG; Cowley, SC; Dorland, W; Hammett, GW; Quataert, E; Schekochihin, AA
Edited by: Shaikh, D; Zank, GP

TURBULENCE AND NONLINEAR PROCESSES IN ASTROPHYSICAL PLASMAS

Book Series: AIP CONFERENCE PROCEEDINGS
Volume: 932 **Pages:** 3-8
Published: 2007

Abstract
We present a cascade model for turbulence in weakly collisional plasmas that follows the nonlinear cascade of energy from the large scales of driving in the MHD regime to the small scales of the kinetic Alfven wave regime where the turbulence is dissipated by kinetic processes. Steady-state solutions of the model for the slow solar wind yield three conclusions: (1) beyond the observed break in the magnetic energy spectrum, one expects an exponential cut-off, (2) the widely held interpretation that this dissipation range obeys power-law behavior is an artifact of instrumental sensitivity limitations; and, (3) over the range of parameters relevant to the solar wind, the observed variation of dissipation range spectral indices from -2 to -4 is naturally explained by the varying effectiveness of Landau damping, from an undamped prediction of -7/3 to a strongly damped index around -4.

Cited: 3

Effects of finite poloidal gyroradius, shaping, and collisions on the zonal flow residual

By: Xiao, Y; Catto, PJ; Dorland, W

PHYSICS OF PLASMAS

Volume: 14 **Issue:** 5
Article Number: 055910
DOI: 10.1063/1.2718519
Published: MAY 2007

Abstract
Zonal flow helps reduce and regulate the turbulent transport level in tokamaks. Rosenbluth and Hinton have shown that zonal flow damps to a nonvanishing residual level in collisionless [M. Rosenbluth and F. Hinton, Phys. Rev. Lett. 80, 724 (1998)] and collisional [F. Hinton and M. Rosenbluth, Plasma Phys. Control. Fusion 41, A653 (1999)] banana regime plasmas. Recent zonal flow advances are summarized including the evaluation of the effects on the zonal flow residual by plasma cross-section shaping, shorter wavelengths including those less than an electron gyroradius, and arbitrary ion collisionality relative to the zonal low frequency. In addition to giving a brief summary of these new developments, the analytic results are compared with GS2 numerical simulations [M. Kotschenreuther, G. Rewoldt, and W. Tang, Comput. Phys. Commun. 88, 128 (1991)] to demonstrate their value as benchmarks for turbulence codes.

Cited: 21

Interplanetary and interstellar plasma turbulence
By: Schekochihin, AA; Cowley, SC; Dorland, W

PLASMA PHYSICS AND CONTROLLED FUSION

Volume: 49 **Issue:** 5A **Pages:** A195-A209 **Special Issue:** SI
DOI: 10.1088/0741-3335/49/5A/S16
Published: MAY 2007

Abstract
Theoretical approaches to low-frequency magnetized turbulence in collisionless and weakly collisional astrophysical plasmas are reviewed. The proper starting point for an analytical description of these plasmas is kinetic theory, not fluid equations. The anisotropy of the turbulence is used to systematically derive a series of reduced analytical models. Above the ion gyroscale, it is shown rigourously that the Alfven waves decouple from the electron-density and magnetic-field-strength fluctuations and satisfy the reduced MHD equations. The density and field-strength fluctuations (slowwaves and the entropy mode in the fluid limit), determined kinetically, are passively mixed by the Alfven waves. The resulting hybrid fluid-kinetic description of the low-frequency turbulence is valid independently of collisionality. Below the ion gyroscale, the turbulent cascade is partially converted into a cascade of kinetic Alfven en waves, damped at the electron gyroscale. This cascade is described by a pair of fluid-like equations, which are a reduced version of the electron MHD. The development of these theoretical models is motivated by observations of the turbulence in the solar wind and interstellar medium. In the latter case, the turbulence is spatially inhomogeneous and the anisotropic Alfvenic turbulence in the presence of a strong mean field may coexist with isotropic MHD turbulence that has no mean field.

Cited: 20

Verification of gyrokinetic delta f simulations of electron temperature gradient turbulence
By: Nevins, WM; Parker, SE; Chen, Y; Candy, J; Dimits, A; Dorland, W; Hammett, GW; Jenko, F

PHYSICS OF PLASMAS
Volume: 14 **Issue:** 8
Article Number: 084501
DOI: 10.1063/1.2759890
Published: AUG 2007

Abstract
The GEM gyrokinetic delta f simulation code [Y. Chen and S. Parker, J. Comput. Phys. 189, 463 (2003); and ibid.220, 839 (2007)] is shown to reproduce electron temperature gradient turbulence at the benchmark operating point established in previous work [W. M. Nevins, J. Candy, S. Cowley, T. Dannert, A. Dimits, W. Dorland, C. Estrada-Mila, G. W. Hammett, F. Jenko, M. J. Pueschel, and D. E. Shumaker, Phys. Plasmas 13, 122306 (2006)]. The electron thermal transport is within 10% of the expected value, while the turbulent fluctuation spectrum is shown to have the expected intensity and two-point correlation function.

Cited: 22

Micro-tearing modes in the mega ampere spherical tokamak

By: Applegate, DJ; Roach, CM; Connor, JW; Cowley, SC; Dorland, W; Hastie, J; Joiner, N

PLASMA PHYSICS AND CONTROLLED FUSION

Volume: 49 **Issue:** 8 **Pages:** 1113-1128
DOI: 10.1088/0741-3335/49/8/001
Published: AUG 2007

Abstract
Recent gyrokinetic stability calculations have revealed that the spherical tokamak is susceptible to tearing parity instabilities with length scales of a few ion Larmor radii perpendicular to the magnetic field lines. Here we investigate this 'micro-tearing' mode in greater detail to uncover its key characteristics and compare it with existing theoretical models of the phenomenon. This has been accomplished using a full numerical solution of the linear gyrokinetic-Maxwell equations. Importantly, the instability is found to be driven by the free energy in the electron temperature gradient as described in the literature. However, our calculations suggest it is not substantially affected by either of the destabilizing mechanisms proposed in previous theoretical models. Instead the instability is destabilized by interactions with magnetic drifts and the electrostatic potential. Further calculations reveal that the mode is not significantly destabilized by the flux surface shaping or the large trapped particle fraction present in the spherical tokamak. Its prevalence in spherical tokamak plasmas is primarily due to the higher value of plasma P and the enhanced magnetic drifts due to the smaller radius of curvature.

Dimits shift in realistic gyrokinetic plasma-turbulence simulations

By: Mikkelsen, DR; Dorland, W

PHYSICAL REVIEW LETTERS

Volume: 101 **Issue:** 13
Article Number: 135003
DOI: 10.1103/PhysRevLett.101.135003
Published: SEP 26 2008

Abstract
In simulations of turbulent plasma transport due to long wavelength (k perpendicular to p(i) <= 1) electrostatic drift-type instabilities, we find a persistent nonlinear up-shift of the effective threshold. Next-generation tokamaks will likely benefit from the higher effective threshold for turbulent transport, and transport models should incorporate suitable corrections to linear thresholds. The gyrokinetic simulations reported here are more realistic than previous reports of a Dimits shift because they include nonadiabatic electron dynamics, strong collisional damping of zonal flows, and finite electron and ion collisionality together with realistic shaped magnetic geometry. Reversing previously reported results based on idealized adiabatic electrons, we find that increasing collisionality reduces the heat flux because collisionality reduces the nonadiabatic electron microinstability drive.

A model of turbulence in magnetized plasmas: Implications for the dissipation range in the solar wind

By: Howes, GG; Cowley, SC; Dorland, W; Hammett, GW; Quataert, E; Schekochihin, AA

JOURNAL OF GEOPHYSICAL RESEARCH-SPACE PHYSICS

Volume: 113 **Issue:** A5
Article Number: A05103
DOI: 10.1029/2007JA012665
Published: MAY 23 2008

Abstract

This paper studies the turbulent cascade of magnetic energy in weakly collisional magnetized plasmas. A cascade model is presented, based on the assumptions of local nonlinear energy transfer in wave number space, critical balance between linear propagation and nonlinear interaction times, and the applicability of linear dissipation rates for the nonlinearly turbulent plasma. The model follows the nonlinear cascade of energy from the driving scale in the MHD regime, through the transition at the ion Larmor radius into the kinetic Alfven wave regime, in which the turbulence is dissipated by kinetic processes. The turbulent fluctuations remain at frequencies below the ion cyclotron frequency due to the strong anisotropy of the turbulent fluctuations, k parallel to << k perpendicular to (implied by critical balance). In this limit, the turbulence is optimally described by gyrokinetics; it is shown that the gyrokinetic approximation is well satisfied for typical slow solar wind parameters. Wave phase velocity measurements are consistent with a kinetic Alfven wave cascade and not the onset of ion cyclotron damping. The conditions under which the gyrokinetic cascade reaches the ion cyclotron frequency are established. Cascade model solutions imply that collisionless damping provides a natural explanation for the observed range of spectral indices in the dissipation range of the solar wind. The dissipation range spectrum is predicted to be an exponential fall off; the power-law behavior apparent in observations may be an artifact of limited instrumental sensitivity. The cascade model is motivated by a program of gyrokinetic simulations of turbulence and particle heating in the solar wind.

Effects of plasma shaping on nonlinear gyrokinetic turbulence

By: Belli, EA; Hammett, GW; Dorland, W

PHYSICS OF PLASMAS

Volume: 15 **Issue:** 9
Article Number: 092303
DOI: 10.1063/1.2972160
Published: SEP 2008

Abstract

The effects of flux surface shape on the gyrokinetic stability and transport of tokamak plasmas are studied using the GS2 code [M. Kotschenreuther, G. Rewoldt, and W. M. Tang, Comput. Phys. Commun. 88, 128 (1995); W. Dorland, F. Jenko, M. Kotschenreuther, and B.N. Rogers, Phys. Rev. Lett. 85, 5579 (2000)]. Studies of the scaling of nonlinear turbulence with shaping parameters are performed using analytic equilibria based on interpolations of representative shapes of the Joint European Torus [P.H. Rebut and B. E. Keen, Fusion Technol. 11, 13 (1987)]. High shaping is found to be a stabilizing influence on both the linear ion-temperature-gradient (ITG) instability and the nonlinear ITG turbulence. For the parameter regime studied here, a scaling of the heat flux with elongation of chi similar to kappa(-1.5) or kappa(-2.0), depending on the triangularity, is observed at fixed average temperature gradient. While this is not as strong as empirical elongation scalings, it is also found that high shaping results in a larger Dimits upshift of the nonlinear critical temperature gradient due to an enhancement of the Rosenbluth-Hinton residual zonal flows.

Cited: 17

Effect of Quasihelical Symmetry on Trapped-Electron Mode Transport in the HSX Stellarator

By: Guttenfelder, W; Lore, J; Anderson, DT; Anderson, FSB; Canik, JM; Dorland, W; Likin, KM; Talmadge, JN

PHYSICAL REVIEW LETTERS

Volume: 101 **Issue:** 21
Article Number: 215002
DOI: 10.1103/PhysRevLett.101.215002
Published: NOV 21 2008

Abstract

This Letter presents theory-based predictions of anomalous electron thermal transport in the Helically Symmetric eXperiment stellarator, using an axisymmetric trapped-electron mode drift wave model. The model relies on modifications to a tokamak geometry that approximate the quasihelical symmetry in the Helically Symmetric eXperiment (particle trapping and local curvature) and is supported by linear 3D gyrokinetic calculations. Transport simulations predict temperature profiles that agree with experimental profiles outside a normalized minor radius of rho > 0.3 and energy confinement times that agree within 10% of measurements. The simulations can reproduce the large measured electron temperatures inside rho < 0.3 if an approximation for turbulent transport suppression due to shear in the radial electric field is included.

Cited: 9

Verification and application of numerically generated magnetic coordinate systems in gyrokinetics

By: Xanthopoulos, P; Mikkelsen, D; Jenko, F; Dorland, W; Kalentev, O

PHYSICS OF PLASMAS

Volume: 15 **Issue:** 12
Article Number: 122108
DOI: 10.1063/1.3010708
Published: DEC 2008

Abstract
In the context of linear gyrokinetic simulations, an analysis of the application of field-aligned coordinate systems generated numerically from magnetohydrodynamic equilibria is presented. This family of systems allows some flexibility in the choice of the coordinates, and gyrokinetic solvers often differ in this respect. Certain transformations are therefore required in order to compare physics results. Accordingly, benchmarks of a linear microinstability are carried out between two similar gyrokinetic codes. Effort is also put on the verification of the special properties of the generated systems through certain diagnostics.

Cited: 3

Gyrokinetic turbulence: a nonlinear route to dissipation through phase space

By: Schekochihin, AA; Cowley, SC; Dorland, W; Hammett, GW; Howes, GG; Plunk, GG; Quataert, E; Tatsuno, T

PLASMA PHYSICS AND CONTROLLED FUSION

Volume: 50 **Issue:** 12
Article Number: 124024
DOI: 10.1088/0741-3335/50/12/124024
Published: DEC 2008

Abstract
This paper describes a conceptual framework for understanding kinetic plasma turbulence as a generalized form of energy cascade in phase space. It is emphasized that conversion of turbulent energy into thermodynamic heat is only achievable in the presence of some (however small) degree of collisionality. The smallness of the collision rate is compensated for by the emergence of a small-scale structure in the velocity space. For gyrokinetic turbulence, a nonlinear perpendicular phase-mixing mechanism is identified and described as a turbulent cascade of entropy fluctuations simultaneously occurring at spatial scales smaller than the ion gyroscale and in velocity space. Scaling relations for the resulting fluctuation spectra are derived. An estimate for the collisional cutoff is provided. The importance of adequately modelling and resolving collisions in gyrokinetic simulations is briefly discussed, as well as the relevance of these results to understanding the dissipation-range turbulence in the solar wind and the electrostatic microturbulence in fusion plasmas.

Cited: 40

Role of stable eigenmodes in gyrokinetic models of ion temperature gradient turbulence

By: Hatch, DR; Terry, PW; Nevins, WM; Dorland, W

PHYSICS OF PLASMAS

Volume: 16 **Issue:** 2
Article Number: 022311
DOI: 10.1063/1.3079779
Published: FEB 2009

Abstract
Investigation of ion temperature gradient turbulence in gyrokinetic models shows that some of the key features of reduced models associated with saturation by nonlinearly excited damped eigenmodes carry over to gyrokinetics. For nonzonal wavenumbers the frequency spectrum in gyrokinetics is broader by a factor of 10 than simple nonlinear broadening of the most unstable eigenmode. The width, including its variations with wavenumber and temperature gradient scale length, closely tracks accessible stable eigenmodes as approximated by a gyro-Landau fluid model for the same parameters. Cross-phase probability distribution functions (pdfs) and fluxes show nonlinear behavior consistent with stable eigenmodes in nonzonal wavenumbers contributing to 30% of the fluctuation energy. Phase pdfs and cross-phase time histories show that multiple eigenmodes [in addition to high frequency geodesic acoustic modes (GAMs)] are a significant part of the k(y)=0 spectrum. Two possible roles of zonal modes in saturation are proposed. First, known nonlinearly accessible stable zonal eigenmodes (in addition to zonal flows and GAMs) are discussed and it is suggested that if these eigenmodes are excited they may be the primary arbiter of saturation. Second, zonal modes may facilitate energy transfer from unstable eigenmodes to stable eigenmodes at finite k(y).

Gyrokinetic Simulations of Turbulent Transport in a Ring Dipole Plasma

By: Kobayashi, S; Rogers, BN; Dorland, W

PHYSICAL REVIEW LETTERS
Volume: 103 **Issue:** 5
Article Number: 055003
DOI: 10.1103/PhysRevLett.103.055003
Published: JUL 31 2009

Abstract
Gyrokinetic flux-tube simulations of turbulent transport due to small-scale entropy modes are presented in a ring-dipole magnetic geometry relevant to the Columbia-MIT levitated dipole experiment (LDX) [J. Kesner et al., Plasma Phys. J. 23, 742 (1997)]. Far from the current ring, the dipolar magnetic field leads to strong parallel variations, while close to the ring the system becomes nearly uniform along circular magnetic field lines. The transport in these two limits are found to be quantitatively similar given an appropriate normalization based on the local out-board parameters. The transport increases strongly with the density gradient, and for small eta = L(n)/L(T) << 1, T(i) similar to T(e), and typical LDX parameters, can reach large levels. Consistent with linear theory, temperature gradients are stabilizing, and for T(i) similar to T(e) can completely cut off the transport when eta greater than or similar to 0.6.

Role of zonal flows in trapped electron mode turbulence through nonlinear gyrokinetic particle and continuum simulation

By: Ernst, DR; Lang, J; Nevins, WM; Hoffman, M; Chen, Y; Dorland, W; Parker, S

PHYSICS OF PLASMAS

Volume: 16 **Issue:** 5
Article Number: 055906
DOI: 10.1063/1.3116282
Published: MAY 2009

Abstract

Trapped electron mode (TEM) turbulence exhibits a rich variety of collisional and zonal flow physics. This work explores the parametric variation of zonal flows and underlying mechanisms through a series of linear and nonlinear gyrokinetic simulations, using both particle-in-cell and continuum methods. A new stability diagram for electron modes is presented, identifying a critical boundary at eta(e)=1, separating long and short wavelength TEMs. A novel parity test is used to separate TEMs from electron temperature gradient driven modes. A nonlinear scan of eta(e) reveals fine scale structure for eta(e)greater than or similar to 1, consistent with linear expectation. For eta(e)< 1, zonal flows are the dominant saturation mechanism, and TEM transport is insensitive to eta(e). For eta(e)>1, zonal flows are weak, and TEM transport falls inversely with a power law in eta(e). The role of zonal flows appears to be connected to linear stability properties. Particle and continuum methods are compared in detail over a range of eta(e)=d ln T(e)/d ln n(e) values from zero to five. Linear growth rate spectra, transport fluxes, fluctuation wavelength spectra, zonal flow shearing spectra, and correlation lengths and times are in close agreement. In addition to identifying the critical parameter eta(e) for TEM zonal flows, this paper takes a challenging step in code verification, directly comparing very different methods of simulating simultaneous kinetic electron and ion dynamics in TEM turbulence.

Cited: 21

Simulating gyrokinetic microinstabilities in stellarator geometry with GS2

By: Baumgaertel, JA; Belli, EA; Dorland, W; Guttenfelder, W; Hammett, GW; Mikkelsen, DR; Rewoldt, G; Tang, WM; Xanthopoulos, P

PHYSICS OF PLASMAS

Volume: 18 **Issue:** 12
Article Number: 122301
DOI: 10.1063/1.3662064
Published: DEC 2011

Abstract

The nonlinear gyrokinetic code GS2 has been extended to treat non-axisymmetric stellarator geometry. Electromagnetic perturbations and multiple trapped particle regions are allowed. Here, linear, collisionless, electrostatic simulations of the quasi-axisymmetric, three-field period national compact stellarator experiment (NCSX) design QAS3-C82 have been successfully benchmarked against the eigenvalue code FULL. Quantitatively, the linear stability calculations of GS2 and FULL agree to within similar to 10%.

Cited: 6

REMOTE HANDLING AND PLASMA CONDITIONS TO ENABLE FUSION NUCLEAR SCIENCE R&D USING A COMPONENT TESTING FACILITY

By: Peng, YKM; Burgess, TW; Carroll, AJ; Neumeyer, CL; Canik, JM; Cole, MJ; Dorland, WD; Fogarty, PJ; Grisham, L; Hillis, DL ...More

FUSION SCIENCE AND TECHNOLOGY

Volume: 56 **Issue:** 2 **Pages:** 957-964
Published: AUG 2009
View Journal Information

Conference

Conference: 18th American-Nuclear-Society Topical Meeting on the Technology of Fusion Energy

Location: San Francisco, CA

Date: SEP 28-OCT 02, 2008

Sponsor(s): Amer Nucl Soc, NO California Sect; Amer Nucl Soc, Fusion Energy Div; Atom Energy Soc Japan; Lawrence Livermore Natl Lab

Abstract

The use of a fusion component testing facility to study and establish, during the ITER era, the remaining scientific and technical knowledge needed by fusion Demo is considered and described in this paper. This use aims to lest components in an integrated fusion nuclear environment, for the first time, to discover and understand the underpinning physical properties, and to develop improved components for further testing, in a time-efficient manner. It requires a design with extensive modularization and remote handling of activated components, and flexible hot-cell laboratories. It further requires reliable plasma conditions to avoid disruptions and minimize their impact, and designs to reduce the divertor heat flux to the level of ITER design. As the plasma duration is extended through the planned ITER level (similar to 10(3) s) and beyond, physical properties with increasing time constants, progressively for similar to 10(4) s, similar to 10(5) s, and similar to 10(6) s, would become accessible for testing and R&D. The longest time constants of these are likely to be of the order of a week (106 S). Progressive stages of research operation are envisioned in deuterium, deuterium-tritium for the ITER duration, and deuterium-tritium with increasingly longer plasma durations. The fusion neutron fluence and operational duty factor anticipated for this "scientific exploration" phase of a component test facility are estimated to be up to 1 MW-yr/m(2) and up to 10%, respectively.

The turbulent heating rate in strong MHD turbulence with non-zero cross-helicity

By: Chandran, BDG; Quataert, E; Howes, GG; Hollweg, JV; Dorland, W
ASTROPHYSICAL JOURNAL
Volume: 701 **Issue:** 1 **Pages:** 652-657
DOI: 10.1088/0004-637X/701/1/652
Published: AUG 10 2009

Abstract

Different results for the cascade power epsilon in strong, incompressible magnetohydrodynamic turbulence with nonzero cross helicity appear in the literature. In this paper, we discuss the conditions under which these different results are valid. Our conclusions can be expressed in terms of the density rho, the rms amplitudes z(+) and z(-) of Alfvenic fluctuations propagating parallel and antiparallel to the background magnetic field B(0), and the correlation length (outer scale) measured perpendicular to B(0), denoted L(perpendicular to). We argue that if z(+) >> z(-) and if the z(-) fluctuations are sustained by the reflection of z(+) fluctuations in a strong background magnetic field, then epsilon similar to rho(z(+))(2)z(-)/L(perpendicular to) as in previous studies by Hossain, Matthaeus, Dmitruk, Lithwick, Goldreich, Sridhar, and others. On the other hand, if the minority wave type (z(-)) is sustained by some form of forcing that is uncorrelated with or only weakly correlated with the z(+) fluctuations, then epsilon can be much less than rho(z(+))(2)z(-)/L(perpendicular to), as in previous studies by Dobrowolny, Lazarian, Chandran, and others. The mechanism for generating the minority wave type strongly affects the cascade power because it controls the coherence time for interactions between oppositely directed wave packets at the outer scale.

Ion temperature gradient driven transport in tokamaks with square shaping

By: Joiner, N; Dorland, W
PHYSICS OF PLASMAS
Volume: 17 **Issue:** 6
Article Number: 062306
DOI: 10.1063/1.3432120
Published: JUN 2010

Abstract

Advanced tokamak schemes which may offer significant improvement to plasma confinement on the usual large aspect ratio Dee-shaped flux surface configuration are of great interest to the fusion community. One possibility is to introduce square shaping to the flux surfaces. The gyrokinetic code GS2 [Kotschenreuther et al., Comput. Phys. Commun. 88, 128 (1996)] is used to study linear stability and the resulting nonlinear thermal transport of the ion temperature gradient driven (ITG) mode in tokamak equilibria with square shaping. The maximum linear growth rate of ITG modes is increased by negative squareness (diamond shaping) and reduced by positive values (square shaping). The dependence of thermal transport produced by saturated JIG instabilities on squareness is not as clear. The overall trend follows that of the linear instability, heat and particle fluxes increase with negative squareness and decrease with positive squareness. This is contradictory to recent experimental results [Holcomb et al., Phys. Plasmas 16, 056116 (2009)] which show a reduction in transport with negative squareness. This may be reconciled as a reduction in transport (consistent with the experiment) is observed at small negative values of the squareness parameter.

Overview of results from the National Spherical Torus Experiment (NSTX)

By: Gates, DA; Ahn, J; Allain, J; Andre, R; Bastasz, R; Bell, M; Bell, R; Belova, E; Berkery, J; Betti, R ...More

NUCLEAR FUSION

Volume: 49 **Issue:** 10
Article Number: 104016
DOI: 10.1088/0029-5515/49/10/104016
Published: OCT 2009

Abstract
The mission of the National Spherical Torus Experiment (NSTX) is the demonstration of the physics basis required to extrapolate to the next steps for the spherical torus (ST), such as a plasma facing component test facility (NHTX) or an ST based component test facility (ST-CTF), and to support ITER. Key issues for the ST are transport, and steady state high beta operation. To better understand electron transport, a new high-k scattering diagnostic was used extensively to investigate electron gyro-scale fluctuations with varying electron temperature gradient scale length. Results from n = 3 braking studies are consistent with the flow shear dependence of ion transport. New results from electron Bernstein wave emission measurements from plasmas with lithium wall coating applied indicate transmission efficiencies near 70% in H-mode as a result of reduced collisionality. Improved coupling of high harmonic fast-waves has been achieved by reducing the edge density relative to the critical density for surface wave coupling. In order to achieve high bootstrap current fraction, future ST designs envision running at very high elongation. Plasmas have been maintained on NSTX at very low internal inductance l(i) similar to 0.4 with strong shaping (kappa similar to 2.7, delta similar to 0.8) with beta(N) approaching the with-wall beta-limit for several energy confinement times. By operating at lower collisionality in this regime, NSTX has achieved record non-inductive current drive fraction f(NI) similar to 71%. Instabilities driven by super-Alfvenic ions will be an important issue for all burning plasmas, including ITER. Fast ions from NBI on NSTX are super-Alfvenic. Linear toroidal Alfven eigenmode thresholds and appreciable fast ion loss during multi-mode bursts are measured and these results are compared with theory. The impact of n > 1 error fields on stability is an important result for ITER. Resistive wall mode/resonant field amplification feedback combined with n = 3 error field control was used on NSTX to maintain plasma rotation with beta above the no-wall limit. Other highlights are results of lithium coating experiments, momentum confinement studies, scrape-off layer width scaling, demonstration of divertor heat load mitigation in strongly shaped plasmas and coupling of coaxial helicity injection plasmas to ohmic heating ramp-up. These results advance the ST towards next step fusion energy devices such as NHTX and ST-CTF.

Parallel magnetic field perturbations in gyrokinetic simulations

By: Joiner, N; Hirose, A; Dorland, W

PHYSICS OF PLASMAS

Volume: 17 **Issue:** 7
Article Number: 072104
DOI: 10.1063/1.3432117
Published: JUL 2010

Abstract
At low beta it is common to neglect parallel magnetic field perturbations on the basis that they are of order beta(2). This is only true if effects of order beta are canceled by a term in the del B drift also of order beta [H. L. Berk and R. R. Dominguez, J. Plasma Phys. 18, 31 (1977)]. To our knowledge this has not been rigorously tested with modern gyrokinetic codes. In this work we use the gyrokinetic code GS2 [Kotschenreuther et al., Comput. Phys. Commun. 88, 128 (1995)] to investigate whether the compressional magnetic field perturbation B(parallel to) is required for accurate gyrokinetic simulations at low beta for microinstabilities commonly found in tokamaks. The kinetic ballooning mode (KBM) demonstrates the principle described by Berk and Dominguez strongly, as does the trapped electron mode, in a less dramatic way. The ion and electron temperature gradient (ETG) driven modes do not typically exhibit this behavior; the effects of B(parallel to) are found to depend on the pressure gradients. The terms which are seen to cancel at long wavelength in KBM calculations can be cumulative in the ion temperature gradient case and increase with eta(e). The effect of B(parallel to) on the ETG instability is shown to depend on the normalized pressure gradient beta' at constant beta.

Collisional damping of zonal flows due to finite Larmor radius effects

By: Ricci, P; Rogers, BN; Dorland, W

PHYSICS OF PLASMAS

Volume: 17 **Issue:** 7
Article Number: 072103
DOI: 10.1063/1.3447875
Published: JUL 2010

Abstract
The collisional damping of seeded E X B zonal flows on the ion Larmor radius scale is studied using a gyrokinetic model. The focus is on flow damping due to finite Larmor radius effects, which cause a nu(parallel to)/nu anisotropy of the ion distribution function that is damped by ion-ion collisions. The gyrokinetic equations are solved in a slab geometry with no gradients or curvature, and a gyroaveraged Lorentz collision operator that conserves particle number, momentum, and energy is used. The solution of the gyrokinetic equations explores the dependence of the damping rate on the wavelength of the flows and the impact of the collisions on the ion distribution function. These numerical results can be used as a benchmark test during the implementation of finite Larmor radius effects in the collision operator of gyrokinetic codes.

Particle Pinch in Gyrokinetic Simulations of Closed Field-Line Systems

By: Kobayashi, S; Rogers, BN; Dorland, W

PHYSICAL REVIEW LETTERS

Volume: 105 **Issue:** 23
Article Number: 235004
DOI: 10.1103/PhysRevLett.105.235004
Published: DEC 2 2010

Abstract

Gyrokinetic simulations of small-scale turbulent transport in a closed magnetic field-line plasma geometry are presented. The simulations are potentially applicable to dipolar systems such as the levitated dipole experiment (LDX) [J. Kesner et al., Plasma Phys. Rep. 23, 742 (1997).] and planetary magnetospheres, as well as simpler systems such as the Z pinch. We report here for the first time the existence of a robust particle (and weaker temperature) pinch regime, in which the particles are transported up the density gradient. The particle pinch is driven by non-MHD entropy-mode turbulence at k(perpendicular to) rho(i) similar to 1 and particle pinch appears at larger eta L(n)/L(T) greater than or similar to 0.7, consistent with quasilinear theory. Our results suggest that entropy-mode transport will drive the LDX plasma profiles toward a state with eta similar to 0.7 and pressure gradients that are near marginal ideal MHD interchange-mode stability.

Catastrophe model for fast magnetic reconnection onset

By: Cassak, PA; Shay, MA; Drake, JF

PHYSICAL REVIEW LETTERS

Volume: 95 **Issue:** 23
Article Number: 235002
DOI: 10.1103/PhysRevLett.95.235002
Published: DEC 2 2005

Abstract

A catastrophe model for the onset of fast magnetic reconnection is presented that suggests why plasma systems with magnetic free energy remain apparently stable for long times and then suddenly release their energy. For a given set of plasma parameters there are generally two stable reconnection solutions: a slow (Sweet-Parker) solution and a fast (Alfvenic) Hall reconnection solution. Below a critical resistivity the slow solution disappears and fast reconnection dominates. Scaling arguments predicting the two solutions and the critical resistivity are confirmed with two-fluid simulations.

A model for spontaneous onset of fast magnetic reconnection

By: Cassak, PA; Drake, JF; Shay, MA

ASTROPHYSICAL JOURNAL

Volume: 644 **Issue:** 2 **Pages:** L145-L148 **Part:** 2
DOI: 10.1086/505690
Published: JUN 20 2006

Abstract
We present a model for the spontaneous onset of fast magnetic reconnection in a weakly collisional plasma, such as the solar corona. When sheared magnetic fields in the corona undergo collisional (Sweet-Parker) reconnection, a narrow dissipation region forms around the X-line. This dissipation region dynamically becomes narrower during the reconnection process as stronger magnetic fields are convected toward the X-line. When the dissipation region becomes thinner than the ion skin depth, resistive magnetohydrodynamics breaks down as the Hall effect becomes important, and the Sweet-Parker solution ceases to exist. A transition to collisionless (Hall) reconnection ensues, increasing the reconnection rate by many orders of magnitude in a very short time. Predictions of the model are consistent with constraints set by observations of solar flares.

Cited: 53

Electron acceleration from contracting magnetic islands during reconnection

By: Drake, JF; Swisdak, M; Che, H; Shay, MA

NATURE

Volume: 443 **Issue:** 7111 **Pages:** 553-556
DOI: 10.1038/nature05116
Published: OCT 5 2006

Abstract
A long-standing problem in the study of space and astrophysical plasmas is to explain the production of energetic electrons as magnetic fields 'reconnect' and release energy. In the Earth's magnetosphere, electron energies reach hundreds of thousands of electron volts (refs 1 - 3), whereas the typical electron energies associated with large-scale reconnection-driven flows are just a few electron volts. Recent observations further suggest that these energetic particles are produced in the region where the magnetic field reconnects(4). In solar flares, upwards of 50 per cent of the energy released can appear as energetic electrons(5,6). Here we show that electrons gain kinetic energy by reflecting from the ends of the contracting 'magnetic islands' that form as reconnection proceeds. The mechanism is analogous to the increase of energy of a ball reflecting between two converging walls - the ball gains energy with each bounce. The repetitive interaction of electrons with many islands allows large numbers to be efficiently accelerated to high energy. The back pressure of the energetic electrons throttles reconnection so that the electron energy gain is a large fraction of the released magnetic energy. The resultant energy spectra of electrons take the form of power laws with spectral indices that match the magnetospheric observations.

Cited: 220

Catastrophic onset of fast magnetic reconnection with a guide field

By: Cassak, PA; Drake, JF; Shay, MA

PHYSICS OF PLASMAS

Volume: 14 **Issue:** 5
Article Number: 054502
DOI: 10.1063/1.2734948
Published: MAY 2007

Abstract
It was recently shown that the slow (collisional) Sweet-Parker and the fast (collisionless) Hall magnetic reconnection solutions simultaneously exist for a wide range of resistivities; reconnection is bistable [Cassak, Shay, and Drake, Phys. Rev. Lett., 95, 235002 (2005)]. When the thickness of the dissipation region becomes smaller than a critical value, the Sweet-Parker solution disappears and fast reconnection ensues, potentially explaining how large amounts of magnetic free energy can accrue without significant release before the onset of fast reconnection. Two-fluid numerical simulations extending the previous results for anti-parallel reconnection (where the critical thickness is the ion skin depth) to component reconnection with a large guide field (where the critical thickness is the thermal ion Larmor radius) are presented. Applications to laboratory experiments of magnetic reconnection and the sawtooth crash are discussed.

Onset of fast magnetic reconnection

By: Cassak, PA; Drake, JF; Shay, MA; Eckhardt, B

PHYSICAL REVIEW LETTERS

Volume: 98 **Issue:** 21
Article Number: 215001
DOI: 10.1103/PhysRevLett.98.215001
Published: MAY 25 2007

Abstract
We demonstrate the existence of a new steady-state magnetic reconnection configuration which lies at the boundary of the basins of attraction between the Sweet-Parker and Hall reconnection configurations. The solution is linearly unstable to small perturbations and its identification required a novel iterative numerical technique. The eigenmodes of the unstable solution are localized near the X line, suggesting that the onset of fast reconnection in a weakly collisional plasma is initiated locally at the X line as opposed to remotely at the boundaries.

Equation free projective integration: A multiscale method applied to a plasma ion acoustic wave

By: Shay, MA; Drake, JF; Dorland, B

JOURNAL OF COMPUTATIONAL PHYSICS

Volume: 226 **Issue:** 1 **Pages:** 571-585
DOI: 10.1016/j.jcp.2007.04.016
Published: SEP 10 2007

Abstract

Multiscale problems such as magnetic reconnection and turbulence are notoriously hard to simulate because the physics of micro and macroscales are strongly linked. This study is the first application of a novel numerical scheme called Equation Free Projective Integration (EFPI) to a plasma system: we simulate the propagation and steepening of a I D ion acoustic wave. In EFPI, the simulations act on two scales, an "inner" microscale and an "outer" coarse scale. The long timescale dynamic behavior of the system is determined by extrapolating forward estimates of the coarse scales obtained from short duration simulations of the microscale dynamics. There are no explicit closed-form equations governing the coarse scales, hence the name "Equation Free." In this study, a kinetic particle-in-cell code called P3D is used to simulate the microscale dynamics. We find excellent agreement between P3D) and EFREE, the EFPI code. The differences which occur between the two are not due to numerical accuracy issues, but instead are caused by an incomplete representation of the system at coarse scales. More specifically, as the ion acoustic wave becomes a shock with Debye length scales, the assumptions of quasi-neutrality and maxwellian ions become invalid. Generalizing the "outer" coarse representation of the system to include non-maxwellian ions and Debye length structures should minimize the differences between P3D and EFREE. The largest EFREE run in this study showed a speedup of about 13 times over its P3D counterpart. Remarkably, the speedup of EFREE over P3D scales linearly with system size: the larger the simulation, the greater the speedup. The results indicate that EFPI is a potential candidate for simulating multiscale plasma problems.

Scaling of asymmetric magnetic reconnection: General theory and collisional simulations

By: Cassak, PA; Shay, MA

PHYSICS OF PLASMAS

Volume: 14 **Issue:** 10
Article Number: 102114
DOI: 10.1063/1.2795630
Published: OCT 2007

Abstract
A Sweet-Parker-type scaling analysis for asymmetric antiparallel reconnection (in which the reconnecting magnetic field strengths and plasma densities are different on opposite sides of the dissipation region) is performed. Scaling laws for the reconnection rate, outflow speed, the density of the outflow, and the structure of the dissipation region are derived from first principles. These results are independent of the dissipation mechanism. It is shown that a generic feature of asymmetric reconnection is that the X-line and stagnation point are not colocated, leading to a bulk flow of plasma across the X-line. The scaling laws are verified using two-dimensional resistive magnetohydrodynamics numerical simulations for the special case of asymmetric magnetic fields with symmetric density. Observational signatures and applications to reconnection in the magnetosphere are discussed.

Two-scale structure of the electron dissipation region during collisionless magnetic reconnection

By: Shay, MA; Drake, JF; Swisdak, M

PHYSICAL REVIEW LETTERS

Volume: 99 **Issue:** 15
Article Number: 155002
DOI: 10.1103/PhysRevLett.99.155002
Published: OCT 12 2007

Abstract
Particle-in-cell simulations of collisionless magnetic reconnection are presented that demonstrate that reconnection remains fast in very large systems. The electron dissipation region develops a distinct two-scale structure along the outflow direction. Consistent with fast reconnection, the length of the electron current layer stabilizes and decreases with decreasing electron mass, approaching the ion inertial length for a proton-electron plasma. Surprisingly, the electrons form a super-Alfvenic outflow jet that remains decoupled from the magnetic field and extends large distances downstream from the x line.

Evidence for an elongated (> 60 ion skin depths) electron diffusion region during fast magnetic reconnection

By: Phan, TD; Drake, JF; Shay, MA; Mozer, FS; Eastwood, JP

PHYSICAL REVIEW LETTERS

Volume: 99 **Issue:** 25
Article Number: 255002
DOI: 10.1103/PhysRevLett.99.255002
Published: DEC 21 2007

Abstract
Observations of an extremely elongated electron diffusion region occurring during fast reconnection are presented. Cluster spacecraft in situ observations of an expanding reconnection exhaust reveal a broad current layer (similar to 10 ion skin depths thick) supporting the reversal of the reconnecting magnetic field together with an intense current embedded at the center that is due to a super-Alfvenic electron outflow jet with transverse scale of similar to 9 electron skin depths. The electron jet extends at least 60 ion skin depths downstream from the X-line.

Cited: 59

From solar and stellar flares to coronal heating: Theory and observations of how magnetic reconnection regulates coronal conditions

By: Cassak, PA; Mullan, DJ; Shay, MA

ASTROPHYSICAL JOURNAL LETTERS

Volume: 676 **Issue:** 1 **Pages:** L69-L72
DOI: 10.1086/587055
Published: MAR 20 2008

Abstract
There is currently no explanation of why the corona has the temperature and density it has. We present a model that explains how the dynamics of magnetic reconnection regulates the conditions in the corona. A bifurcation in magnetic reconnection at a critical state enforces an upper bound on the coronal temperature for a given density. We present observational evidence from 107 flares in 37 Sun-like stars that stellar coronae are near this critical state. The model may be important to self-organized criticality models of the solar corona.

Cited: 27

The Hall fields and fast magnetic reconnection

By: Drake, JF; Shay, MA; Swisdak, M

PHYSICS OF PLASMAS

Volume: 15 **Issue:** 4
Article Number: 042306
DOI: 10.1063/1.2901194
Published: APR 2008

Abstract
The results of large-scale, particle-in-cell simulations are presented on the role of Hall electric and magnetic fields on the structure of the electron dissipation region and outflow exhaust during the collisionless magnetic reconnection of antiparallel fields. The simulations reveal that the whistler wave plays the key role in driving the electrons away from the magnetic x-line. Further downstream the electron outflow exhaust consists of a narrow super-Alfvenic jet, which remains collimated far downstream of the x-line, flanked by a pedestal whose width increases monotonically with increasing distance downstream. The open outflow exhaust, which is required for fast reconnection in large systems, is driven by the Hall electric and magnetic fields. Finally, it is the whistler that ultimately facilitates fast reconnection by diverting the electrons flowing toward the current layer into the outflow direction and thereby limiting the length of this layer. The results are contrasted with reconnection in an electron-positron plasma where the Hall fields are absent. The consequence of the expanding outflow exhaust is that, consistent with recent observations, the extended super-Alfvenic electron outflow jet carries a smaller and smaller fraction of the outflowing electrons with increasing distance downstream of the x-line. The results suggest that the structure of the electron current layer and exhaust in simulations might be sensitive to boundary conditions unless the simulation boundary along the outflow direction is sufficiently far from the x-line.

Scaling of asymmetric Hall magnetic reconnection

By: Cassak, PA; Shay, MA

GEOPHYSICAL RESEARCH LETTERS

Volume: 35 **Issue:** 19
Article Number: L19102
DOI: 10.1029/2008GL035268
Published: OCT 2 2008

Abstract
The scaling of the reconnection rate and ion and electron outflow speeds with upstream magnetic field strengths and plasma mass densities during asymmetric collisionless (Hall) reconnection without a guide field is studied using two-dimensional two-fluid simulations. The results agree with a recent theory by Cassak and Shay (2007). It is found that the normalized reconnection rate is on the order of 0.1 and is independent of the asymmetry in field or density. Signatures of asymmetric Hall reconnection and applications to the magnetopause are briefly discussed.

Kinetic dissipation and anisotropic heating in a turbulent collisionless plasma

By: Parashar, TN; Shay, MA; Cassak, PA; Matthaeus, WH

PHYSICS OF PLASMAS

Volume: 16 **Issue:** 3
Article Number: 032310
DOI: 10.1063/1.3094062
Published: MAR 2009

Abstract

The kinetic evolution of the Orszag-Tang vortex is studied using collisionless hybrid simulations. In magnetohydrodynamics (MHD) this configuration leads rapidly to broadband turbulence. At large length scales, the evolution of the hybrid simulations is very similar to MHD, with magnetic power spectra displaying scaling similar to a Kolmogorov scaling of -5/3. At small scales, differences from MHD arise, as energy dissipates into heat almost exclusively through the magnetic field. The magnetic energy spectrum of the hybrid simulation shows a break where linear theory predicts that the Hall term in Ohm's law becomes significant, leading to dispersive kinetic Alfven waves. A key result is that protons are heated preferentially in the plane perpendicular to the mean magnetic field, creating a proton temperature anisotropy of the type observed in the corona and solar wind.

The hall effect in magnetic reconnection: Hybrid versus Hall-less hybrid simulations

By: Malakit, K; Cassak, PA; Shay, MA; Drake, JF

GEOPHYSICAL RESEARCH LETTERS

Volume: 36
Article Number: L07107
DOI: 10.1029/2009GL037538
Published: APR 14 2009

Abstract

To understand the role of the Hall effect during fast magnetic reconnection, hybrid simulations with and without the Hall term in the generalized Ohm's Law are compared, as done originally by Karimabadi et al. (2004). It is found that reconnection with the Hall term is fast, but reconnection in the so-called Hall-less hybrid simulations is Sweet-Parker like (slow) when the resistivity is constant and uniform. These results re-affirm the importance of the Hall term in allowing fast reconnection in the hybrid model.

Ion heating resulting from pickup in magnetic reconnection exhausts

By: Drake, JF; Swisdak, M; Phan, TD; Cassak, PA; Shay, MA; Lepri, ST; Lin, RP; Quataert, E; Zurbuchen, TH

JOURNAL OF GEOPHYSICAL RESEARCH-SPACE PHYSICS

Volume: 114
Article Number: A05111
DOI: 10.1029/2008JA013701
Published: MAY 30 2009

Abstract
The heating of ions downstream of the x-line during magnetic reconnection is explored using full-particle simulations, test particle simulations, and analytic analysis. Large-scale particle simulations reveal that the ion temperature increases sharply across the boundary layer that separates the upstream plasma from the Alfvenic outflow. This boundary layer, however, does not take the form of a classical switch-off shock as discussed in the Petschek reconnection model, so the particle heating cannot be calculated from the magnetohydrodynamic, slow-shock prediction. Test particle trajectories in the fields from the simulations reveal that ions crossing the narrow boundary into the exhaust instead behave like pickup particles: they gain both a directed outflow and an effective thermal speed given by the flow speed v(0) of the exhaust. The detailed dynamics of these particles are explored by taking 1-D cuts of the simulation data across the exhaust, transforming to the deHoffman-Teller frame, and calculating explicitly the increment in the temperature, m(i)v(0)(2)/3, with m(i), the ion mass. We compare the model predictions with the temperature increment in solar wind exhausts measured by the ACE and Wind spacecraft, confirming that the temperature increment is proportional to the ion mass. The Wind data from 22 high-shear exhaust encounters confirm the scaling of the proton temperature increment with the square of the exhaust velocity. However, the temperature increments are consistently lower than the model prediction. Implications for understanding the production of high-energy ions in flares and the broader universe are discussed.

A magnetic reconnection mechanism for ion acceleration and abundance enhancements in impusive flares

By: Drake, JF; Cassak, PA; Shay, MA; Swisdak, M; Quataert, E

ASTROPHYSICAL JOURNAL LETTERS

Volume: 700 **Issue:** 1 **Pages:** L16-L20
DOI: 10.1088/0004-637X/700/1/L16
Published: JUL 20 2009

Abstract
The acceleration of ions during magnetic reconnection in solar flares is explored with simulations and analytic analysis. Ions crossing into Alfvenic reconnection outflows can behave like pickup particles and gain an effective thermal velocity equal to the Alfven speed. However, with a sufficiently strong ambient out-of-plane magnetic field, which is the relevant configuration for flares, the ions can become adiabatic and their heating is then dramatically reduced. The threshold for nonadiabatic behavior, where ions are strongly heated, becomes a condition on the ion mass-to-charge ratio, m(i)/m(p)Z(i) > 10 root beta(0x)/2/pi, where m(i) and Z(i) are the ion mass and charge state, m(p) is the proton mass, and beta(0x) = 8 pi nT/B(0x)(2) is the ratio of the plasma pressure to that of the reconnecting magnetic field B(0x). Thus, during flares high mass-to-charge particles gain energy more easily than protons and a simple model reveals that their abundances are enhanced, which is consistent with observations.

Scaling of Sweet-Parker reconnection with secondary islands

By: Cassak, PA; Shay, MA; Drake, JF

PHYSICS OF PLASMAS

Volume: 16 **Issue:** 12
Article Number: 120702
DOI: 10.1063/1.3274462
Published: DEC 2009

Abstract
Sweet-Parker (collisional) magnetic reconnection at high Lundquist number is modified by secondary islands. Daughton [Phys. Rev. Lett. 103, 065004 (2009)] suggested the Sweet-Parker model governs the fragmented current sheet segments. If true, the reconnection rate would increase by the square root of the number of secondary islands. High Lundquist number resistive magnetohydrodynamic simulations are presented which agree, in a time-averaged sense, with the predicted scaling. This result may have important implications for energy storage before a solar eruption and its subsequent release.

A saddle-node bifurcation model of magnetic reconnection onset

By: Cassak, PA; Shay, MA; Drake, JF

PHYSICS OF PLASMAS

Volume: 17 **Issue:** 6
Article Number: 062105
DOI: 10.1063/1.3435269
Published: JUN 2010

Abstract

It was recently shown that magnetic reconnection exhibits bistability, where the Sweet Parker (collisional) and Hall (collisionless) reconnection solutions are both attainable for the same set of system parameters. Here, a dynamical model based on saddle-node bifurcations is presented which reproduces the slow to fast transition. It is argued that the properties of the dynamical model are a result of the Hall effect and the dispersive physics associated with it. Evidence from resistive two-fluid and Hall magnetohydrodynamics simulations are presented that show that the time evolution agrees with the dynamical model, the outflow speed is correlated with the dispersive physics due to the Hall effect, and bistability persists in the absence of electron inertia

Cited: 10

Scaling of asymmetric magnetic reconnection: Kinetic particle-in-cell simulations

By: Malakit, K; Shay, MA; Cassak, PA; Bard, C

JOURNAL OF GEOPHYSICAL RESEARCH-SPACE PHYSICS

Volume: 115
Article Number: A10223
DOI: 10.1029/2010JA015452
Published: OCT 12 2010

Abstract

Recently, Cassak and Shay (2007) applied a generalized Sweet-Parker analysis to derive scaling laws for gross properties of asymmetric magnetic reconnection, including the reconnection rate, outflow speed, and outflow density. This study presents the first comprehensive test of this scaling theory using fully electromagnetic particle-in-cell simulations of antiparallel asymmetric magnetic reconnection. By varying the upstream densities and magnetic fields, we find that the reconnection rates, outflow speeds, and outflow densities are consistent with the general scaling theory. This implies that kinetic electron and proton physics beyond the Hall term does not fundamentally alter the gross properties of the asymmetric diffusion region as understood in Cassak and Shay (2007). In addition, the results confirm the validity of the assumption of mixing of particles on recently reconnected flux tubes, which is of key importance for accurately predicting the location of the flow stagnation point in the diffusion region.

Cited: 11

The Weibel instability inside the electron-positron Harris sheet
By: Liu, YH; Swisdak, M; Drake, JF

PHYSICS OF PLASMAS

Volume: 16 **Issue:** 4
Article Number: 042101
DOI: 10.1063/1.3097474
Published: APR 2009

Abstract
Recent full-particle simulations of electron-positron reconnection revealed that the Weibel instability plays an active role in controlling the dynamics of the current layer and maintaining fast reconnection. A four-beam model is developed to explore the development of the instability within a narrow current layer characteristic of reconnection. The problem is reduced to two coupled second-order differential equations, whose growing eigenmodes are obtained via both asymptotic approximations and finite difference methods. Full particle simulations confirm the linear theory and help probe the nonlinear development of the instability. The current layer broadening in the reconnection outflow jet is linked to the scattering of high-velocity streaming particles in the Weibel-generated, out-of-plane magnetic field.

Equations of state in collisionless magnetic reconnection
By: Le, A; Egedal, J; Fox, W; Katz, N; Vrublevskis, A; Daughton, W; Drake, JF

PHYSICS OF PLASMAS

Volume: 17 **Issue:** 5
Article Number: 055703
DOI: 10.1063/1.3309425
Published: MAY 2010

Abstract
Kinetic simulation as well as in situ measurement of reconnecting current sheets in the Earth's magnetosphere show strong electron temperature anisotropy, with the parallel electron temperature becoming several times greater than the perpendicular temperature. This anisotropy is accounted for in a solution of the Vlasov equation recently derived for general reconnection geometries with magnetized electrons in the limit of fast transit time. A necessary ingredient is a magnetic field-aligned electric field extending over the ion inertial length scale. The parallel electric field maintains quasineutrality by regulating the electron density, traps a large fraction of thermal electrons, and heats electrons in the parallel direction. Based on the expression for the electron phase-space density, equations of state provide a fluid closure for the electrons that relates the parallel and perpendicular pressures to the density and magnetic field strength. The resulting fluid model agrees well with fully kinetic simulations of guide-field reconnection, accurately predicting the electron temperature anisotropy. In addition, the equations of state impose strong constraints on the electron Hall currents and magnetic fields that develop during antiparallel reconnection. The model provides scaling laws for the Hall magnetic fields and predicts the magnitude of the current in the electron layer.

Three-dimensional simulations of the orientation and structure of reconnection X-lines

By: Schreier, R; Swisdak, M; Drake, JF; Cassak, PA

PHYSICS OF PLASMAS

Volume: 17 **Issue:** 11
Article Number: 110704
DOI: 10.1063/1.3494218
Published: NOV 2010

Abstract
This letter employs Hall magnetohydrodynamic simulations to study X-lines formed during the reconnection of magnetic fields with differing strengths and orientations embedded in plasmas of differing densities Although random initial perturbations trigger the growth of X-lines with many orientations, a few robust X-lines sharing an orientation consistent with the direction of maximal outflow speed, as predicted by Swisdak and Drake [Geophys Res Lett 34, L11106 (2007)] eventually dominate the system Reconnection in the geometry examined here contradicts the suggestion of Sonnerup [J Geophys Res 79, 1546 (1974)] that it occurs in a plane normal to the equilibrium current At late time, the X-lines' growth stagnates, leaving them shorter than the simulation domain

The effects of strong temperature anisotropy on the kinetic structure of collisionless slow shocks and reconnection exhausts. I. Particle-in-cell simulations

By: Liu, YH; Drake, JF; Swisdak, M

PHYSICS OF PLASMAS

Volume: 18 **Issue:** 6
Article Number: 062110
DOI: 10.1063/1.3601760
Published: JUN 2011

Abstract
A 2-D Riemann problem is designed to study the development and dynamics of the slow shocks that are thought to form at the boundaries of reconnection exhausts. Simulations are carried out for varying ratios of normal magnetic field to the transverse upstream magnetic field (i.e., propagation angle with respect to the upstream magnetic field). When the angle is sufficiently oblique, the simulations reveal a large firehose-sense (P-parallel to > P-perpendicular to) temperature anisotropy in the downstream region, accompanied by a transition from a coplanar slow shock to a non-coplanar rotational mode. In the downstream region the firehose stability parameter epsilon = 1 - mu(0)(P-parallel to - P-perpendicular to)/B-2 tends to plateau at 0.25. This balance arises from the competition between counterstreaming ions, which drive e down, and the scattering due to ion inertial scale waves, which are driven unstable by the downstream rotational wave. At very oblique propagating angles, 2-D turbulence also develops in the downstream region.

The effects of strong temperature anisotropy on the kinetic structure of collisionless slow shocks and reconnection exhausts. II. Theory

By: Liu, YH; Drake, JF; Swisdak, M

PHYSICS OF PLASMAS

Volume: 18 **Issue:** 9
Article Number: 092102
DOI: 10.1063/1.3627147
Published: SEP 2011

Abstract
Simulations of collisionless oblique propagating slow shocks have revealed the existence of a transition associated with a critical temperature anisotropy epsilon = 1 - mu(0)(P(parallel to) - P(vertical bar))/B(2) = 0.25 (Y.-H. Liu, J. F. Drake, and M. Swisdak, Phys. Plasmas 18, 062110 (2011)). An explanation for this phenomenon is proposed here based on anisotropic fluid theory, in particular, the anisotropic derivative nonlinear-Schrodinger-Burgers equation, with an intuitive model of the energy closure for the downstream counter-streaming ions. The anisotropy value of 0.25 is significant because it is closely related to the degeneracy point of the slow and intermediate modes and corresponds to the lower bound of the coplanar to non-coplanar transition that occurs inside a compound slow shock (SS)= rotational discontinuity (RD) wave. This work implies that it is a pair of compound SS/RD waves that bound the outflows in magnetic reconnection, instead of a pair of switch-off slow shocks as in Petschek's model. This fact might explain the rareness of in-situ observations of Petschek-reconnection-associated switch-off slow shocks.

Formation of secondary islands during magnetic reconnection

By: Drake, JF; Swisdak, M; Schoeffler, KM; Rogers, BN; Kobayashi, S

GEOPHYSICAL RESEARCH LETTERS

Volume: 33 **Issue:** 13
Article Number: L13105
DOI: 10.1029/2006GL025957
Published: JUL 13 2006

Abstract
Full particle simulations are presented that suggest that the strength of an ambient guide magnetic field controls whether magnetic reconnection, once it is established, remains steady or becomes bursty. Specifically during anti-parallel (component) reconnection the electron current layers that form near the magnetic x-line are short (long) and therefore stable (unstable) to the formation of secondary magnetic islands. The implications for understanding magnetic reconnection and the formation of Flux Transfer Events at the magnetopause are discussed.

Orientation of the reconnection X-line

By: Swisdak, M; Drake, JF

GEOPHYSICAL RESEARCH LETTERS

Volume: 34 **Issue:** 11
Article Number: L11106
DOI: 10.1029/2007GL029815
Published: JUN 7 2007

Abstract
[1] We propose a criterion for identifying the orientation of the X-line when two regions of plasma with arbitrary densities, temperatures, and magnetic fields undergo reconnection. The X-line points in the direction that maximizes the (suitably-defined) Alfven speed characterizing the reconnection outflow. For many situations a good approximation is that the X-line bisects the angle formed by the magnetic fields.

Cited: 26

Evidence for collisionless magnetic reconnection at Mars

By: Eastwood, JP; Brain, DA; Halekas, JS; Drake, JF; Phan, TD; Oieroset, M; Mitchell, DL; Lin, RP; Acuna, M

GEOPHYSICAL RESEARCH LETTERS

Volume: 35 **Issue:** 2
Article Number: L02106
DOI: 10.1029/2007GL032289
Published: JAN 19 2008

Abstract
Using data from Mars Global Surveyor (MGS) in combination with Particle-In-Cell (PIC) simulations of reconnection, we present the first direct evidence of collisionless magnetic reconnection at Mars. The evidence indicates that the spacecraft passed through the diffusion region where reconnection is initiated and observed the magnetic field signatures of differential electron and ion motion - the Hall magnetic field - that uniquely indicate the reconnection process. These are the first such in-situ reconnection observations at an astronomical body other than the Earth. Reconnection may be the source of Mars' recently discovered auroral activity and the changing boundaries of the closed regions of crustal magnetic field.

Cited: 28

Development of a turbulent outflow during electron-positron magnetic reconnection

By: Swisdak, M; Liu, YH; Drake, JF

ASTROPHYSICAL JOURNAL

Volume: 680 **Issue:** 2 **Pages:** 999-1008
DOI: 10.1086/588088
Published: JUN 20 2008

Abstract

The mass symmetry between the two species in electron-positron (pair) plasmas has interesting consequences for collisionless magnetic reconnection, because the Hall term, which plays a crucial role in supporting fast reconnection in electron-proton plasmas, vanishes. We perform kinetic simulations of pair reconnection in systems of various sizes, show that it remains fast, and identify the reason why this occurs. For sufficiently large systems a Weibel-like temperature anisotropy instability develops in the outflow from the X-point that causes the current layer to broaden and form a Petschek-like open outflow. We discuss the parameter regimes in which pair reconnection should be fast and the implications for astrophysical pair plasmas.

Cited: 22

Evidence and theory for trapped electrons in guide field magnetotail reconnection

By: Egedal, J; Fox, W; Katz, N; Porkolab, M; Oieroset, M; Lin, RP; Daughton, W; Drake, JF

JOURNAL OF GEOPHYSICAL RESEARCH-SPACE PHYSICS

Volume: 113 **Issue:** A12
Article Number: A12207
DOI: 10.1029/2008JA013520
Published: DEC 10 2008

Abstract

A previous analysis of electron distributions measured in situ by the Wind spacecraft has revealed that electrons were trapped in the electromagnetic geometry of the reconnection event encountered in the deep magnetotail. In this paper we develop a detailed theory that can account for the main anisotropic features of the electron distributions associated with trapping in reconnection. The analysis shows that electron trapping in electric fields is generic in reconnection, as it is required in order to maintain the condition of quasineutrality. In addition to the spacecraft data, evidence of trapping in numerical simulations is also presented. Trapping is effective in eliminating free-streaming electrons along magnetic fields and thereby reduces parallel electron currents. Its importance for fast reconnection is discussed and emphasized by observations in a laboratory plasma.

Cited: 31

Nonlinear Development of Streaming Instabilities in Strongly Magnetized Plasma

By: Che, H; Drake, JF; Swisdak, M; Yoon, PH

PHYSICAL REVIEW LETTERS

Volume: 102 **Issue:** 14
Article Number: 145004
DOI: 10.1103/PhysRevLett.102.145004
Published: APR 10 2009

Abstract
The nonlinear development of streaming instabilities in the current layers formed during magnetic reconnection with a guide field is explored. Theory and 3D particle-in-cell simulations reveal two distinct phases. First, the parallel Buneman instability grows and traps low velocity electrons. The remaining electrons then drive two forms of turbulence: the parallel electron-electron two-stream instability and the nearly perpendicular lower-hybrid instability. The high velocity electrons resonate with the turbulence and transfer momentum to the ions and low velocity electrons.

Cited: 19

Formation of a localized acceleration potential during magnetic reconnection with a guide field

By: Egedal, J; Daughton, W; Drake, JF; Katz, N; Le, A

PHYSICS OF PLASMAS

Volume: 16 **Issue:** 5
Article Number: 050701
DOI: 10.1063/1.3130732
Published: MAY 2009

Abstract
Magnetic reconnection near the surface of the sun and in the Earth's magnetotail is associated with the production of highly energetic electrons. Direct acceleration in the reconnection electric field has been proposed as a possible mechanism for energizing these electrons. Here, however, we use kinetic simulations of guide-field reconnection to show that in two-dimensional (2D) reconnection the parallel electric field, E(parallel to) in the reconnection region is localized and its structure does not permit significant energization of the electrons. Rather, a large fraction of the electrons become trapped due to a sign reversal in E(parallel to), imposing strict constraints on their motions and energizations. Given these new results, simple 2D models, which invoke direct acceleration for energizing electrons during a single encounter with a reconnection region, need to be revised.

Cited: 19

Reconnecting Magnetic Fields

By: Burch, JL; Drake, JF

AMERICAN SCIENTIST

Volume: 97 **Issue:** 5 **Pages:** 392-399
Published: SEP-OCT 2009

Energetic protons, radionuclides, and magnetic activity in protostellar disks

By: Turner, NJ; Drake, JF

ASTROPHYSICAL JOURNAL

Volume: 703 **Issue:** 2 **Pages:** 2152-2159
DOI: 10.1088/0004-637X/703/2/2152
Published: OCT 1 2009

Abstract
We calculate the location of the magnetically inactive dead zone in the minimum-mass protosolar disk, under ionization scenarios including stellar X-rays, long- or short-lived radionuclide decay, and energetic protons arriving from the general interstellar medium, from a nearby supernova explosion, from the disk corona, or from the corona of the young star. The disk contains a dead zone in all scenarios except those with small dust grains removed and a fraction of the short-lived radionuclides remaining in the gas. All the cases without exception have an "undead zone" where intermediate resistivities prevent magneto-rotational turbulence while allowing shear-generated large-scale magnetic fields. The mass column in the undead zone is typically greater than the column in the turbulent surface layers. The results support the idea that the dead and undead zones are robust consequences of cold, dusty gas with mass columns exceeding 1000 g cm(-2).

The impact of microscopic magnetic reconnection on pre-flare energy storage

By: Cassak, PA; Drake, JF

ASTROPHYSICAL JOURNAL LETTERS

Volume: 707 **Issue:** 2 **Pages:** L158-L162
DOI: 10.1088/0004-637X/707/2/L158
Published: DEC 20 2009

Abstract
It is widely accepted that magnetic reconnection releases a large amount of energy during solar flares. Studies of reconnection usually assume that the length scale over which the global (macroscopic) magnetic field reverses is identical to the thickness of the reconnection site. However, in spatially extended high-Lundquist number plasmas such as the solar corona, this scenario is untenable; the reconnection site is microscopic and embedded inside the macroscopic current set up by global fields. We use numerical simulations and scaling arguments to show that embedded effects on reconnection could have a profound influence on energy storage before a flare. From large-scale high-Lundquist number resistive magnetohydrodynamics simulations of reconnection with a diffusion region on a much smaller scale than the macroscopic current sheet, we find that the generation of secondary islands is governed by the local magnetic field immediately upstream of the diffusion region rather than the (potentially much larger) global field. This diminishes the production of secondary islands and leads to a thicker diffusion region than those predicted using the global field strength. Such considerations are crucial for understanding the onset of solar eruptions and how energy accumulates before such eruptions. We argue that if reconnection with secondary islands is fast, the energy storage times before an eruption are too small to explain observations. If reconnection with secondary islands remains slow, embedded effects cause the diffusion region to begin far wider than kinetic scales, so energy storage before a flare can occur while collisional (Sweet-Parker) reconnection with secondary islands proceeds.

A statistical model of magnetic islands in a current layer

By: Fermo, RL; Drake, JF; Swisdak, M

PHYSICS OF PLASMAS

Volume: 17 **Issue:** 1
Article Number: 010702
DOI: 10.1063/1.3286437
Published: JAN 2010

Abstract
This letter describes a statistical model of the dynamics of magnetic islands in very large current layers that develop in space plasma. Two parameters characterize the island distribution: the flux Sigma contained in the island and the area A it encloses. The integrodifferential evolution equation for this distribution function is based on rules that govern the small-scale generation of secondary islands, the rates of island growth, and island merging. The numerical solutions of this equation produce island distributions relevant to the magnetosphere and solar corona. The solution of a differential equation for large islands explicitly shows the role merging plays in island growth.

A magnetic reconnection mechanism for the generation of anomalous cosmic rays

By: Drake, JF; Opher, M; Swisdak, M; Chamoun, JN

ASTROPHYSICAL JOURNAL

Volume: 709 **Issue:** 2 **Pages:** 963-974
DOI: 10.1088/0004-637X/709/2/963
Published: FEB 1 2010

Abstract
The recent observations of the anomalous cosmic ray (ACR) energy spectrum as Voyager 1 and Voyager 2 crossed the heliospheric termination shock have called into question the conventional shock source of these energetic particles. We suggest that the sectored heliospheric magnetic field, which results from the flapping of the heliospheric current sheet, piles up as it approaches the heliopause, narrowing the current sheets that separate the sectors and triggering the onset of collisionless magnetic reconnection. Particle-in-cell simulations reveal that most of the magnetic energy is released and most of this energy goes into energetic ions with significant but smaller amounts of energy going into electrons. The energy gain of the most energetic ions results from their reflection from the ends of contracting magnetic islands, a first-order Fermi process. The energy gain of the ions in contracting islands increases their parallel (to the magnetic field B) pressure p(parallel to) until the marginal fire-hose condition is reached, causing magnetic reconnection and associated particle acceleration to shut down. Thus, the feedback of the self-consistent development of the energetic ion pressure on reconnection is a crucial element of any reconnection-based, particle-acceleration model. The model calls into question the strong scattering assumption used to derive the Parker transport equation and therefore the absence of first-order Fermi acceleration in incompressible flows. A simple one-dimensional model for particle energy gain and loss is presented in which the feedback of the energetic particles on the reconnection drive is included. The ACR differential energy spectrum takes the form of a power law with a spectral index slightly above 1.5. The model has the potential to explain several key Voyager observations, including the similarities in the spectra of different ion species.

Magnitude of the Hall fields during magnetic reconnection

By: Le, A; Egedal, J; Daughton, W; Drake, JF; Fox, W; Katz, N

GEOPHYSICAL RESEARCH LETTERS

Volume: 37
Article Number: L03106
DOI: 10.1029/2009GL041941
Published: FEB 11 2010

Abstract
In situ observation of the Earth's magnetosphere has identified Hall magnetic fields as a key signature of collisionless magnetic reconnection. The inflow portion of the reconnection diffusion region is further characterized by strong electron pressure anisotropy. These two features are tightly linked in a quantitative model, which is verified using fully kinetic simulations. The model predicts the Hall field strength and the maximum electron pressure anisotropy as functions of the upstream ratio of electron fluid and magnetic pressures

The vector direction of the interstellar magnetic field outside the heliosphere

By: Swisdak, M; Opher, M; Drake, JF; Bibi, FA

ASTROPHYSICAL JOURNAL

Volume: 710 **Issue:** 2 **Pages:** 1769-1775
DOI: 10.1088/0004-637X/710/2/1769
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Abstract
We propose that magnetic reconnection at the heliopause (HP) only occurs where the interstellar magnetic field points nearly anti-parallel to the heliospheric field. By using large-scale magnetohydrodynamic (MHD) simulations of the heliosphere to provide the initial conditions for kinetic simulations of HP reconnection, we show that the energetic pickup ions downstream from the solar wind termination shock induce large diamagnetic drifts in the reconnecting plasma and stabilize non-anti-parallel reconnection. With this constraint, the MHD simulations can show where HP reconnection most likely occurs. We also suggest that reconnection triggers the 2-3 kHz radio bursts that emanate from near the HP. Requiring the burst locations to coincide with the loci of anti-parallel reconnection allows us to determine, for the first time, the vector direction of the local interstellar magnetic field. We find it to be oriented toward the southern solar magnetic pole.

Fast radial basis function interpolation via preconditioned Krylov iteration

By: Gumerov, NA; Duraiswami, R

SIAM JOURNAL ON SCIENTIFIC COMPUTING

Volume: 29 **Issue:** 5 **Pages:** 1876-1899
DOI: 10.1137/060662083
Published: 2007

Abstract
We consider a preconditioned Krylov subspace iterative algorithm presented by Faul, Goodsell, and Powell (IMA J. Numer. Anal. 25 (2005), pp. 1 - 24) for computing the coefficients of a radial basis function interpolant over N data points. This preconditioned Krylov iteration has been demonstrated to be extremely robust to the distribution of the points and the iteration rapidly convergent. However, the iterative method has several steps whose computational and memory costs scale as O(N(2)), both in preliminary computations that compute the preconditioner and in the matrix-vector product involved in each step of the iteration. We effectively accelerate the iterative method to achieve an overall cost of O(N logN). The matrix vector product is accelerated via the use of the fast multipole method. The preconditioner requires the computation of a set of closest points to each point. We develop an O(N logN) algorithm for this step as well. Results are presented for multiquadric interpolation in R(2) and biharmonic interpolation in R(3). A novel FMM algorithm for the evaluation of sums involving multiquadric functions in R(2) is presented as well.

Fast multipole methods on graphics processors

By: Gumerov, NA; Duraiswami, R

JOURNAL OF COMPUTATIONAL PHYSICS

Volume: 227 **Issue:** 18 **Pages:** 8290-8313
DOI: 10.1016/j.jcp.2008.05.023
Published: SEP 10 2008

Abstract
The fast multipole method allows the rapid approximate evaluation of sums of radial basis functions. For a specified accuracy, epsilon, the method scales as O(N) in both time and memory compared to the direct method with complexity O(N-2), which allows the solution of larger problems with given resources. Graphical processing units (GPU) are now increasingly viewed as data parallel compute coprocessors that can provide significant computational performance at low price. We describe acceleration of the FMM using the data parallel GPU architecture. The FMM has a complex hierarchical (adaptive) structure, which is not easily implemented on data-parallel processors. We described strategies for parallelization of all components of the FMM, develop a model to explain the performance of the algorithm on the GPU architecture; and determined optimal settings for the FMM on the GPU. These optimal settings are different from those on usual CPUs. Some innovations in the FMM algorithm, including the use of modified stencils, real polynomial basis functions for the Laplace kernel, and decompositions of the translation operators, are also described. We obtained accelerations of the Laplace kernel FMM on a single NVIDIA GeForce 8800 GTX GPU in the range of 30-60 compared to a serial CPU FMM implementation. For a problem with a million sources, the summations involved are performed in approximately one second. This performance is equivalent to solving of the same problem at a 43 Teraflop rate if we use straightforward summation.

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Generation of whistler waves by a rotating magnetic field source

By: Karavaev, AV; Gumerov, NA; Papadopoulos, K; Shao, X; Sharma, AS; Gekelman, W; Gigliotti, A; Pribyl, P; Vincena, S
PHYSICS OF PLASMAS
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Article Number: 012102
DOI: 10.1063/1.3274916
Published: JAN 2010

Abstract
The paper discusses the generation of polarized whistler waves radiated from a rotating magnetic field source created via a novel phased orthogonal two loop antenna. The results of linear three-dimensional electron magnetohydrodynamics simulations along with experiments on the generation whistler waves by the rotating magnetic field source performed in the large plasma device are presented. Comparison of the experimental results with the simulations and linear wave properties shows good agreement. The whistler wave dispersion relation with nonzero transverse wave number and the wave structure generated by the rotating magnetic field source are also discussed. The phase velocity of the whistler waves was found to be in good agreement with the theoretical dispersion relation. The exponential decay rate of the whistler wave propagating along the ambient magnetic field is determined by Coulomb collisions. In collisionless case the rotating magnetic field source was found to be a very efficient radiation source for transferring energy along the ambient magnetic field lines.

Cited: 5

Gyrokinetic statistical absolute equilibrium and turbulence

By: Zhu, JZ; Hammett, GW

PHYSICS OF PLASMAS

Volume: 17 **Issue:** 12
Article Number: 122307
DOI: 10.1063/1.3514141
Published: DEC 2010

Abstract

A paradigm based on the absolute equilibrium of Galerkin-truncated inviscid systems to aid in understanding turbulence [T.-D. Lee, Q. Appl. Math. 10, 69 (1952)] is taken to study gyrokinetic plasma turbulence: a finite set of Fourier modes of the collisionless gyrokinetic equations are kept and the statistical equilibria are calculated; possible implications for plasma turbulence in various situations are discussed. For the case of two spatial and one velocity dimension, in the calculation with discretization also of velocity v with N grid points (where N + 1 quantities are conserved, corresponding to an energy invariant and N entropy-related invariants), the negative temperature states, corresponding to the condensation of the generalized energy into the lowest modes, are found. This indicates a generic feature of inverse energy cascade. Comparisons are made with some classical results, such as those of Charney-Hasegawa-Mima in the cold-ion limit. There is a universal shape for statistical equilibrium of gyrokinetics in three spatial and two velocity dimensions with just one conserved quantity. Possible physical relevance to turbulence, such as ITG zonal flows, and to a critical balance hypothesis are also discussed.

Noncurvature-driven modes in a transport barrier

By: Rogers, BN; Dorland, W

PHYSICS OF PLASMAS

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Article Number: 062511
DOI: 10.1063/1.1928250
Published: JUN 2005

Abstract

Transport barriers that form in both the edge and interior regions of high temperature magnetically confined discharges are characterized by steep plasma gradients, strong ExB and diamagnetic flows, and varying levels of magnetic shear. This study addresses the linear stability of such configurations in the context of a simple slab model using both analytic calculations as well as numerical simulations from the gyrokinetic GS2 code. Three linear modes of potential importance are found: the Kelvin-Helmholtz instability, the tertiary mode, and a nonlocal drift wave instability. Each mode is unstable only in the presence of nontrivial spatial variations in either the ExB flow and/or the plasma gradients. The strongest conclusion of this study is that the drift wave mode may be an important driver of anomalous transport in the edge region of magnetic confinement devices. Two other weaker conclusions that warrant further study are as follows: (1) the Kelvin-Helmholtz instability may be associated with edge-localized modes or edge transport and (2) the tertiary mode can potentially limit the radial growth of a transport barrier.

Discrete particle noise in particle-in-cell simulations of plasma microturbulence

By: Nevins, WM (Nevins, WM); Hammett, GW (Hammett, GW); Dimits, AM (Dimits, AM); Dorland, W (Dorland, W); Shumaker, DE (Shumaker, DE)

PHYSICS OF PLASMAS

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Abstract

Recent gyrokinetic simulations of electron temperature gradient (ETG) turbulence with the global particle-in-cell (PIC) code GTC [Z. Lin et al., Proceedings of the 20th Fusion Energy Conference, Vilamoura, Portugal, 2004 (IAEA, Vienna, 2005)] yielded different results from earlier flux-tube continuum code simulations [F. Jenko and W. Dorland, Phys. Rev. Lett. 89, 225001 (2002)] despite similar plasma parameters. Differences between the simulation results were attributed to insufficient phase-space resolution and novel physics associated with global simulation models. The results of the global PIC code are reproduced here using the flux-tube PIC code PG3EQ [A. M. Dimits et al., Phys. Rev. Lett. 77, 71 (1996)], thereby eliminating global effects as the cause of the discrepancy. The late-time decay of the ETG turbulence and the steady-state heat transport observed in these PIC simulations are shown to result from discrete particle noise. Discrete particle noise is a numerical artifact, so both these PG3EQ simulations and, by inference, the GTC simulations that they reproduced have little to say about steady-state ETG turbulence and the associated anomalous heat transport. In the course of this work several diagnostics are developed to retrospectively test whether a particular PIC simulation is dominated by discrete particle noise.