Tutorial: Computational MHD

Gabor Toth

I will describe some of the major challenges of computational magnetohydrodynamics and various numerical methods to cope with them. In particular, adaptive grids and implicit time integration methods can improve the efficiency by orders of magnitude. I will also discuss the numerical aspects of various extensions of MHD: semi-relativistic, Hall, multi-ion, anisotropic pressure, radiative transport and heat conduction.

Tutorial: relativistic MHD

Rony Keppens

An introduction to the ideal MHD equations, generalized to (special) relativistic flow regimes is given, following the exposition of Chapter 21 in Advanced Magnetohydrodynamics (CUP, 2010). We highlight relativistic effects on linear wave modes in homogeneous plasmas. For nonlinear regimes, we summarize knowledge on relativistic MHD shocks, and discuss and demonstrate challenges met in relativistic MHD simulations.

3D MHD numerical simulations of EUV waves in rotating Active Regions

Mag Selwa

Recent STEREO observations enabled to study the structure and properties of EUV waves in more detail. Patsourakos & Vourlidas (2009) studied the basic 3D structure of a growing wave front finding it to have a dome-shaped structure that can be separated from an expanding CME. Later, Veronig et al. (2010) reported another observation of a dome-shaped large-scale coronal EUV wave. We investigate, by means of 3D MHD simulations, the formation of EUV waves as the result of the interaction of twisted coronal magnetic loops. The simulation is initialized with one or two dipoles anchored in the photosphere and performed under coronal (low beta) conditions. A kinematic rotational motion is applied to the central parts of the dipolar regions at the photosphere so that a flux tube within each dipole becomes twisted. Simulations are performed for the different magnetic field topologies leading to different contact angles during the magnetic reconnection process. We find that the twisting motion results in a dome-shaped structure followed by a dimming. However, the shape of the dome depends on the initial configuration (topology of the AR). We investigate the relation between the properties of the initiation mechanism and the characteristics of the resulting EUV waves.

Towards detailed prominence seismology: MHD equilibria and continuous MHD spectrum

Jan Willem Blokland

One of the most fascinating structures around the sun are prominences. These prominences are plasma filaments suspended by magnetic field against the gravitational force of the sun. These filaments can be 100 times cooler than the surrounding, the million degree coronal plasma, in which they are embedded. In the research area of prominence seismology the ultimate goal is to deduce the internal structure of a prominence using the observed oscillatory motions of the filaments by matching the detected frequencies, damping rates, and possibly spatio-temporal eigenstructure of the vibration modes. Up till now, idealized models, based on cylindrical flux tubes without gravity, have been used to study the prominences. These models have gain us deep insight and, for example, successfully explained the observed damping of global eigenoscillations.

However, it is yet unclear if it can all be generalized to more realistic prominences, where the magnetic shear, gravity, and pressure variations are play a role.

In this presentation we will discuss a generalization of these models by considering translational invariance prominence equilibria including magnetic shear, gravity and pressure variations. These equilibria are analyzed for their stability properties, with special attention to the continuous MHD spectrum. We will show that due to the presence of gravity gaps or even instabilities may appear in the continuous spectrum. The gaps are particular interesting because inside of them new global modes may occur. These global modes could provide us with important information of the internal structure of the prominence. Before investigating the possible appearance of global modes, detailed analysis of the continuous spectrum is required.

Formation of Solar Filaments by Steady and Nonsteady Chromospheric Heating

Chun Xia

We revisit the formation process of solar filaments. Theoretical analysis, as well as numerical simulations, established that cold plasma condensations can form in a magnetic loop subject to localized heating of the footpoints. We use grid-adaptive numerical solutions of the radiative hydrodynamic equations to parametrically investigate the filament formation process in a pre-shaped loop with both steady and nonsteady chromospheric heating. We demonstrate that the onset of thermal instability in our simulations obeys the linear instability criterion. As chromospheric plasma is evaporated into the corona, the thermal instability criterion becomes locally satisfied, subsequently driving the plasma condensation. The cold condensation formation can be divided into three stages, namely, a thermal rearrangement stage, a thermally unstable stage, and a kinematic stage. The onset time of the condensation follows roughly 2 hr or more after footpoint localized heating is effective, and the growth rate of the thread length varies from 800 km/hr to 4000 km/hr, depending on the amplitude and the decay length scale of the localized chromospheric heating. We show how single or multiple condensation segments may form in the coronal portion, and their repetitive formation, streaming, coalescence, and drainage down to the chromosphere. Moreover, we find that steady heating is not necessary to sustain the condensation. Once the condensation is formed, it can keep growing also when the localized heating ceases. We also show that the condensation remains stable under perturbations from p-mode waves.

The Adaptive Implicit MHD Code HiFi: Computational fluid modeling of magnetized plasmas in laboratory and space

Vyacheslav (Slava) Lukin

We will describe the methods and underlying principles used in the development of the two- and three-dimensional implicit spectral element multi-fluid HiFi code. Ongoing work towards achieving scalability of this implicit PDE solver framework beyond several thousand processors for MHD equations will be discussed. Several examples of past and present applications of the HiFi code to modeling of laboratory and solar plasmas, with particular emphasis on the coupling between small and global scales, will be demonstrated.

Understanding Solar Coronal EUV and X-Ray Emission: Comparing MHD Models with Observations

Zoran Mikic

Advanced MHD models with a sophisticated description of energy flow offer the opportunity to predict emission of EUV and X-ray radiation in the solar corona. We will describe how an MHD model with parallel thermal conduction, radiation loss, empirical coronal heating, and Alfven wave acceleration is used to simulate coronal EUV and X-ray emission. Comparing such simulated emission with observations provides a very sensitive constraint on coronal heating models.

MHD Simulations of Solar System Plasmas

Tamas Gombosi and the CSEM team
The University of Michigan, Ann Arbor

The Center for Space Environment Modeling (CSEM) at the University of Michigan has developed a multiphysics simulation capability to simulate solar system plasmas extending from the low solar corona to the outer edges of the heliosphere. This talk will focus on the the simulation results obtained with this capability. Particular examples will include the simulation of the two-state solar wind, coronal mass ejections, the solar wind interaction with Earth, other planets and comets.

General Relativistic Magnetohydrodynamic Simulations of Binary Neutron Stars

Bruno Giacomazzo

In several astrophysical scenarios the presence of very compact objects, such as neutron stars and black holes, is combined with strong magnetic fields. Therefore the numerical solution of the full set of General Relativistic Magnetohydrodynamics (GRMHD) equations is often required. After briefly describing the fully GRMHD code Whisky, I will report on some recent results obtained using Whisky in simulating equal-mass binary neutron star systems during the last phases of inspiral, merger and collapse to a black hole surrounded by an hot and magnetized torus. I will in particular describe how magnetic fields can affect the gravitational wave signal emitted by these sources and their possible role in powering short gamma-ray bursts.

Waves and instabilities in rotating tokamak plasmas

Willem Haverkort

Toroidal rotation can have a significant impact on the waves and instabilities in a tokamak plasma. Within the framework of ideal MHD, a stability criterion is derived for localized interchange modes clustering below the Alfvén continuum. Numerical calculations of the linearized MHD equations show that above a critical Mach number, rotation induces stable global Alfvén modes. Because of their sensitivity to the Mach number, these modes may provide an extension to MHD-spectroscopy by giving information on the rotational velocity.

On the non-linear evolution of the magnetorotational instability

Martin Pessah

The magnetorotational instability (MRI) is considered a key process for driving efficient angular momentum transport in astrophysical disks. Understanding its non-linear saturation constitutes a fundamental problem in modern accretion disk theory. The large dynamical range in physical conditions in accretion disks makes it challenging to address this problem only with numerical simulations. I will discuss the results of recent work analyzing the idea that (secondary) parasitic instabilities are responsible for the saturation of the MRI. This approach enables us to explore dissipative regimes that are relevant to astrophysical and laboratory conditions that lie beyond the regime accessible to current numerical simulations. I will argue that the “saturation” amplitude obtained within this framework provides an estimate of the magnetic field that can be generated by the MRI before the secondary instabilities suppress its growth significantly. I will show that Kelvin-Helmholtz and tearing modes are responsible for saturation at high and low Elsasser numbers, respectively. Several features of numerical simulations designed to address the saturation of the MRI in accretion disks surrounding young stars and compact objects can be interpreted in terms of these findings.

Current challenges in modelling stellar magnetic fields

Moira Jardine

Magnetic fields appear to be ubiquitous in almost all types of stars, but the nature of these fields and their role in influencing the structure and evolution of the star and its environment can vary significantly. Recent advances in spectropolarimetry have revealed the diversity of stellar magnetic fields and have presented modellers with some interesting challenges. In this talk I will review these results and illustrate the role that advances in MHD modelling can make in tackling the most significant science questions for stellar magnetic fields.

Magnetically-dominated relativistic jets.

Serguei Komissarov

Relativistic jets are often produced in black hole-accretion disk systems, like active galactic nuclei, gamma-ray bursters, and X-ray binaries. It is widely believed that magnetic fields play the key role in their dynamics and emission. In recent years we have seen a significant progress in this area, facilitated by the advances in computer simulations. Yet, there are still many unresolved issues. In this talk, I will review various aspects of the physics of relativistic magnetically-dominated jets, including their generation, collimation, and acceleration, as well as the likely mechanisms of dissipation, which ultimately determine their observed characteristics.

Numerical sunspot models: From sunspot fine structure to the scale of active regions

Matthias Rempel

Over the past few years, MHD simulations with realistic equation of state and radiative transfer have evolved to the point, at which entire sunspots can be resolved sufficiently to capture details of sunspot fine structure. In this talk I will summarize recent developments and will focus with more detail on three aspects: 1) Fine structure of sunspot penumbrae, 2) larger scale flows surrounding sunspots, and 3) flux emergence and sunspot formation.

Shock refraction as a Riemann problem

Peter Delmont

We study the classical problem of planar shock refraction at an oblique density discontinuity, separating two gases at rest, in planar ideal (magneto)hydrodynamics. In the hydrodynamical case, 3 signals arise and the interface becomes Richtmyer-Meshkov unstable due to vorticity deposition on the shocked contact. In the magnetohydrodynamical case, on the other hand, when the normal component of the magnetic field does not vanish, 5 signals will arise. The interface then typically

remains stable, since the Rankine-Hugoniot jump conditions in ideal MHD do not allow for vorticity deposition on a contact discontinuity.
We present an exact Riemann solver based solution strategy to describe the initial self similar refraction phase. Using grid-adaptive MHD simulations, we show that after reflection from the top wall, the interface remains stable.

Resonant absorption in coronal loops

Jaume Terradas

Resonant absorption is a candidate to explain the strong damping of transverse loop oscillations. In this talk the focus is on the time-dependent aspects of this damping mechanism. We solve the linear and nonlinear MHD equations using different equilibrium models. The process of mode conversion is first described using a simple one-dimensional cylindrical magnetic tube in the linear regime. The time-dependent results are linked with the eigenmode calculations. Then, the nonlinear MHD equations are solved for more realistic loop models. We show the development of a shear instability at the tube boundary and we discuss the possible effects of this instability on the process of resonant absorption.

Magnetohydrodynamic instabilities of current-carrying jets

Alfio Bonanno

Magnetohydrodynamic instabilities can be responsible for the formation of structures with various scales in astrophysical jets. In this talk the stability properties of equilibrium configuration containing both azimuthal and axial field of subthermal strength will be discussed. It will be argued that in the presence of azimuthal and axial magnetic fields the jet is always unstable to non-axisymmetric perturbations. In particular the fate of the most unstable modes will be studied by means of non-linear global 3D-simulations.

Multi-fluid MHD: applications in solar and space physics

Leon Ofman

In solar and space plasmas often more than a single ion species plays an important role in the dynamics of the plasma. For example, in the solar wind He++ ions carry significant fractions of solar wind momentum. Moreover, multiple ions can play an important role in energetic processes in heliospheric plasma. The remote sensing diagnostic of plasma parameters in the corona often relies on low-abundance heavy ion line emission such as Fe or O. The simplifying assumpitions of single fluid MHD break down in multi-ion plasma when collisons are infrequent, resulting in differentiation between the ion species. Multi-fluid equations provide the next level of approximation that can capture the physics of the relevant multi-ion processes. The multi-fluid model equations and the simplifications in the low frequency (MHD) regime applicable to solar wind plasma will be discussed. Application of the equations to solar and space plasma will be reviewed, and the results of recent multifluid computations of slow solar wind in coronal streamers validated by comparison with observations will be presented.

Consistent wave heating for solar wind MHD models

Jens Kleimann

The interaction of outward-traveling Alfvén waves with the interplanetary medium has been identified as a major heating agent for the solar wind. After a short review of the concept and its physical description, I shall discuss recent attempts to incorporate this effect into self-consistent MHD models of the inner heliosphere.

Bayesian Magnetohydrodynamic Seismology of Coronal Loops

Inigo Arregui

Current magnetohydrodynamic seismology inversion techniques using both theoretical and observed wave properties in coronal structures show a number of limitations, such as the obtention of infinite number of solutions that equally well reproduce observed wave properties. We perform a Bayesian parameter inference in the context of resonantly damped transverse coronal loop oscillations that aims to overcome these limitations. The forward problem is solved in terms of parametric results for kink waves in one-dimensional flux tubes in the thin tube and thin boundary approximations. This reduces the problem to solving two analytic algebraic equations for the period and damping of kink oscillations. For the inverse problem, we adopt a Bayesian approach to infer the most probable values of the relevant parameters, for given observed periods and damping times, and to extract their confidence levels. The posterior probability distribution functions are obtained by means of Markov Chain Montecarlo simulations, incorporating observed uncertainties in a consistent manner. We find well localized solutions in the posterior probability distribution functions for two of the three parameters of interest, namely the Alfven travel time and the transverse inhomogeneity length-scale. The obtained estimates are consistent with previous classic inversion results, but the method enables us to additionally constrain the transverse inhomogeneity length-scale and to estimate real error bars for each parameter. These results can serve to improve our current estimates of unknown physical parameters in coronal structures and to test the assumed theoretical model(s).

Opportunities and Challenges in Supercomputing

Lukas Arnold

Computer simulations have become an important tool in various scientific fields, but in many cases, computing resources – hardware and software -- are limiting factors in terms of required numerical resolution and/or simulated timescales. Large-scale supercomputing facilities offer new possibilities to overcome the hardware limitations by providing computing time to scientific researchers. On the software side, it has traditionally been to the users to develop algorithms which are capable of efficiently utilizing the facility's systems. However, there is an increasing need to assist users in form of e.g. workshops, individual advisors, and community support. This talk will focus on benefits of large-scale simulations as well as the corresponding programming challenges. A brief overview of modern hardware and programming techniques, support activities, as well as forthcoming calls for computing resources will be given.

Plasma and Field Configurations Around Black Holes Interface Between MHD Theory, Transport Processes and Self Organization

Bruno Coppi

After presenting the ideal MHD theory of two and tri-dimensional plasma structures around compact objects (e.g. black holes), general issues concerning the significance of the ideal MHD approach, as a start to describe both laboratory and astrophysical plasmas at the macroscopic level, are discussed.
Some of these issues arise from the necessity to combine the results from this approach with those of known plasma transport theories that can reproduce realistic profiles of relevant parameters such as temperatures, plasma current densities, particle densities and flow velocities. The need to consider self-organization processes (for instance, represented by the so-called principle of “profile consistency”) in this context is pointed out.
Another set of issues arises from the fact that in important regimes associated with astrophysical objects, in the domain of X-ray and γ-ray astronomy, the particle distributions in momentum space are far from thermal. Then phase space analyses, beyond the fluid approach, have to be undertaken.

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Magnetohydrodynamic Spectroscopy: Unraveling the dynamics of plasma on all scales from the laboratory to the Universe

Hans Goedbloed

The continuing effort of harnessing nuclear fusion energy from magnetically confined plasma and the super-abundance of magnetized plasma in the visible Universe call for a unifying theoretical description. It is a great pleasure to realize that the equations of magnetohydrodynamics (MHD) enable this by being scale-independent: the scales of length, mass and time (entering through the Alfv´en speed) may be divided out. Consequently, the macroscopic dynamics of this enormous variety of plasma objects may be described by the same equations! Thus, MHD spectroscopy for the determination of the structure of tokamaks from the spectrum of MHD waves could be developed in full analogy with helioseismology for the determination of the interior structure of the Sun from the spectrum of sound oscillations [1]. To exploit this analogy for the description of other astrophysical objects, like stellar coronae and winds or accretion disks and jets about black holes, and actually also for the description of modern tokamaks, two stumbling blocks had to be removed:
(a) Most MHD spectroscopy to date has been based on the assumption of a static background equilibrium. It is evident that there are no such plasmas in astrophysics;
(b) In the remaining small set of analyses, where this assumption was more adequately replaced by that of a stationary equilibrium flow, the complexity of the problem was characterized as due to non-selfjointness of the occurring operators.
The large gap between the appearance of our first and our second volume on MHD [2] is partly due to our mental struggle to counter the latter, wide spread, superstition. This was accomplished by realizing that the relevant operators are self-adjoint, expressing energy conservation, but that the eigenvalue problem is nonlinear. New tools were developed to deal with this nonlinearity. In this tutorial, the new theory of MHD spectroscopy of stationary plasma equilibria will be presented in enough detail to enable young researchers to exploit the new tools.

[1] J.P. Goedbloed and S. Poedts, Principles of Magnetohydrodynamics; with Applications to Laboratory and Astrophysical Plasmas (Cambridge University Press, 2004), Section 7.2.4.
[2] J.P. Goedbloed, R. Keppens and S. Poedts, Advanced Magnetohydrodynamics; with Applications to Laboratory and Astrophysical Plasmas (Cambridge University Press, 2010).

An Unsplit Staggered Mesh (USM) MHD solver in FLASH3

Dongwook Lee

We present a new, publicly available unsplit staggered mesh (USM) magnetohydrodynamics (MHD) scheme for the solution of compressible MHD flows in multi-spatial dimensions in FLASH3. The code provides solutions on uniform and adaptive mesh refinement (AMR) grids on parallel computing architectures, preserving the divergence-free constraint of the magnetic fields using the constrained transport (CT) method. The USM solver incorporates various implementations including different types of reconstruction methods (e.g., first-order Godunov, second-order MUSCL-Hancock, third-order PPM, and fifth-order WENO), and different choices of Riemann solvers (e.g., local Lax-Friedrichs, HLLE, HLLC, HLLD, Marquina, and Roe).

High order conservative finite difference schemes for computational MHD

Petros Tzeferacos

We discuss and compare 3rd and 5th order accurate finite difference schemes for the numerical solution of the compressible ideal MHD equations in multiple spatial dimensions. In the presented schemes, four different reconstruction techniques were explored, namely the recently improved versions of the weighted essentially non-oscillatory (WENO) schemes, a fifth order monotonicity preserving (MP) scheme as well as slope-limited polynomial reconstruction. Opting for a cell centered numerical formulation and therefore avoiding the added complexities of a staggered mesh, the divergence-free condition is enforced using the hyperbolic/parabolic ansatz of Dedner et al. (J. Comput. Phys. 175 (2002) 645-673). The resulting family of conservative explicit schemes is robust, cost effective and easy to implement; smooth flows are accurately described, avoiding "clipping" effects at smooth extrema, whereas discontinuous features are sharp and non-oscillatory.

Working on an Osher scheme for MHD

Bram van Es

In gasdynamics, the Osher scheme is called a smooth wine with underlying complexity and high proof content compared to other illustrious schemes such as the Roe-scheme and the Van Leer scheme. It has this special place on the 'wine card' for several reasons; it has continuous differentiability, consistent boundary treatment, and the closest similarity to the Godunov scheme. For these reasons an application of the Osher scheme to MHD is being investigated.

The role of magnetic fields in stellar evolution

Vincent Duez

Rotational mixing, playing a major role in distributing angular momentum and chemical elements inside the stars, can be severely influenced by the presence of magnetic fields. For example, chemically peculiar Ap stars exhibit long rotational periods and always display large-scale organized magnetic fields, inferred to be of fossil origin (either from a primordial seed magnetic field, or from a dynamo having occured during the convective pre-main-sequence phase). In this context, is is important to determine stable magnetic configurations in order to implement their effects in stellar evolution codes. I will here briefly show how a variational method allows us to provide an analytical model for such equilibria and then how 3D MHD, "star-in-a-box" simulations are used to test their stability.

3D Numerical Simulations of Torsional Alfven Waves

Viktor Fedun & Robert Erdelyi

Recent high-resolution ground-based observations provide clear evidence for the existence of oscillations driven by magnetic twist in solar flux tubes. These torsional oscillations are associated with Alfven waves. It is of particular interest to study the excitation and propagation of torsional Alfven waves into the upper, magnetised atmosphere because they can channel photospheric energy into the corona. Here we examine numerically the direct propagation of such torsional waves, driven at the foot-point of a solar magnetic flux tube, into a three-dimensional magnetised atmosphere representing the gravitationally stratified solar atmosphere between the photosphere and low corona. The simulations are based on fully compressible ideal magneto-hydrodynamical modelling. The model solar atmosphere is constructed based on realistic temperature and density stratification derived from VAL IIIF, and is most suitable perhaps for a bright magnetic network element or magnetic pore.
We discuss how torsional phosphoric motion can excite Alfven and other types of MHD waves that reach the upper parts of the solar atmosphere. Finally, we briefly discuss the observational signatures of these waves.

Signatures of synchrotron radiation from the relativistic jet base

Oliver Porth

We show the results of large scale axisymmetric simulations of two-component jet acceleration in special relativistic magnetohydrodynamics. Within one parsec from the accretion disk, the component dominated by Poynting flux accelerates to relativistic velocities $\Gamma \sim 8$ but is still far from equipartition. Thermal acceleration of the inner component saturates quickly after the sonic point but is delimited to $\Gamma \sim 3$ by the amount of enthalpy available in the modeled black hole corona.
In the near-stationary end-state, we solve the polarized Synchrotron radiation transport incorporating self-absorption and (internal) Faraday rotation. With mock-observations of the parsec scale jet base in radio and sub-mm wavelength we obtain observational signatures of the model. These comprise radio maps, spectra, polarization structure (revealing spin direction), frequency dependent depolarization, core shift and Faraday rotation measure. We also specify the detectability of such features depending on the available resolution, predicting the discovery of rotation measure gradients with the advance of space-VLBI and mm-VLBI featuring resolutions of 100 Schwarzschild radii.
The presented work represents a complete toolbox to test the present diagnostics used in radio observations of AGN cores.

Implications of Maxwell's Equations for Plasma Problems

Allen H. Boozer
Columbia University

Maxwell's equations provide model-independent solutions to important plasma problems: (1) The separation between neighboring magnetic field lines generically increases exponentially with distance along a line--even for curl-free magnetic fields. Given a magnetic field in a system of finite length, the exponentiation of neighboring lines, *exp(N)*, can be defined field line by field line and *N* evolves as the field evolves. When *N>1*, even simple changes to the field, such as a twist, tend to give a parallel current density that scales as $\mu_0 j_{||}/B \sim (L/a^2) exp(3N)$, where *L* is the length scale along the lines for a twist of a radian and *a* is the system scale across the magnetic field lines. For $N \sim 10$, non-ideal effects must occur because $j_{||}/B$ becomes large and fractal across the field lines, which gives a natural trigger for reconnection. (2) When the medium through which a current flows cannot support forces, $j_{||}/B$ must be constant along the magnetic field. In the solar photosphere, the density drops exponentially with a scale height of about 40km. The magnetic field has a vertical scale of order 1000 times longer, so the number of current carriers becomes insufficient, and a runaway distribution of electrons must form, which would look like a corona. (3) In an evolving magnetic field in a torus distant currents that tend to drive magnetic islands on the surfaces on which the magnetic field lines close on themselves. In an ideal evolution, delta function currents arise on these surfaces to prevent islands from opening, but a comparable current must also flow in a narrow, but finite width, channel about these surfaces.

Requirements on localized current drive for the suppression of neoclassical tearing modes

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Abstract. A heuristic criterion for the full suppression of an NTM was formulated as $\eta_{\rm NTM} \equiv j_{\rm CD,max}/j_{\rm BS} \geq 1.2$ [Zohm et al., *J. Phys. Conf. Ser.*, **25** 234 (2005)], where $j_{\rm CD,max}$ is the maximum in the driven current density profile applied to stabilize the mode and $j_{\rm BS}$ is the local bootstrap current density. In this work we subject this criterion to a systematic theoretical analysis on the basis of the generalized Rutherford equation. Taking into account only the effect of $j_{\rm CD}$ inside the island, a new criterion for full suppression by a minimum applied total current is obtained in the form of a maximum allowed value for the width of the driven current, $w_{\rm dep}$, combined with a required minimum for the total driven current in the form of $w_{\rm dep}\eta_{\rm NTM}$, where both limits depend on the marginal, and saturated island sizes. These requirements can be relaxed when additional effects are taken into account, such as a change in the stability parameter Δ' from the current driven outside the island, power modulation, the accompanying heating inside the island, or when the current drive is applied preemptively. When applied to ITER scenario 2, the requirement for full suppression either the 3/2 or 2/1 NTM becomes $w_{\rm dep} \lesssim 5$ cm and $w_{\rm dep}\eta_{\rm NTM} \gtrsim 5$ cm in agreement with [Sauter *et al.*, *Plasma Phys. Control. Fusion*, **52** 025002 (2010)]. Optimization of the ITER ECRH Upper Port Launcher design towards minimum required power for full NTM suppression requires an increase in the toroidal injection angle of the lower steering mirror of several degrees compared to its present design value, while for the upper steering mirror the present design value is close to the optimum.

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Non-linear MHD simulations of Edge Localised Modes in tokamaks

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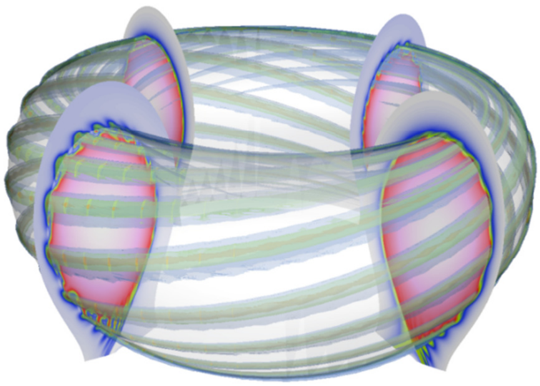
Edge Localised Modes (ELMs) are MHD instabilities commonly observed in plasmas in the H-mode confinement regime. The instability, a ballooning mode, is driven by the large pressure gradient at the edge of the H-mode plasmas. In present day tokamaks, ELMs cause large but mostly tolerable heat fluxes to the plasma facing components. In ITER, it is predicted that the ELM induced heat fluxes are such that they may lead to enhanced erosion and a reduced lifetime of the plasma facing components. Control of the amplitude of ELMs will be thus essential for meeting ITER’s mission. Although some progress has been made in ELM control methods applicable to ITER, there are still many open questions on the physics of ELMs and on ELM control methods.

The non-linear MHD code JOREK has been developed with the application to model ELMs as the main motivation. The simulation domain includes both the closed and open field lines, including the x-point. The poloidal plane is discretised using cubic Bezier finite elements aligned with the magnetic flux surfaces. Fourier harmonics are used in the toroidal direction. The time evolution is fully implicit.

The 3D non-linear MHD simulations of ELMs show several features that are, at least qualitatively, in agreement with experimental observations such as the expulsion of filaments and the fine-structure in the energy deposited on the divertor target by ELMs. Modelling of ELM control by the injection of frozen deuterium pellets indicates that the over-pressure generated by the pellet is the cause for the destabilisation of an ELM-like instability.



Coupling the fluid and the kinetic approach to handle multiple scale problems in space weather problems

Giovanni Lapenta
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The need to handle the coupling between microscopic and macroscopic processes in plasma physics is ubiquitous. The wide difference in mass between electrons and ions and the great change in time and space scales between large-scale magnetohydrodynamic processes and small-scale kinetic effects pose a great challenge to the simulation of plasma physics problems.

The traditional approach has been to try to derive reduced models of the full first principle physics model and solve them considering only the scales of interest. The approach decouples the simulation of small scales and large scales and uses different methods to treat both. The classic example is anomalous resistivity that is used as a tool to summarise in resistive MHD models the presence of kinetic microinstabilities. We present a different point of view, based on using first principle methods for each scales, relying on coupling different physics apporaches for each scale, fluid for the macroscopic and kinetic for the microscopic.

A new EC funded project has been initiated, SWIFF (swiff.eu) to study new methods for micro-macro coupling in space physics. Swiff encompasses 7 centers in 5 european countires and is coordinated by Giovanni Lapenta at the Katholieke universiteit Leuven. The centers involved are: the Katholieke Universiteit Leuven and the Belgian Institute for Space Aeronomy in Belgium, the Università di Pisa and the Astronomical Observatory of Turin in Italy, the Københavns Universitet in Denmark, the Astronomical Institute of the Academy of Sciences of the Czech Republic and the University of St Andrews in Scotland, UK.

An overview of the activities of the SWIFF project will be presented and the focus will go towards the methods planned for study the coupling of different fluid models and of fluid models with kinetic models. The latter aspect will be discussed in light of the implicit moment model. The approach relies on numerical methods that can effectively average the smallest scales within a correct kinetic treatment while focusing on large-scale structures. After describing the approach, we present a few specific examples.

Magnetic Reconnection, Field Line Topology, and Stellar X-ray Emission

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Rapid and ultra-rapid reconnection of magnetic fields occurs where the magnetic stresses squeeze the plasma out from between two oppositely directed field components. The resulting dissipation of magnetic field heats the ambient plasma, sometimes explosively. The question is the relation of rapid reconnection to the field line topology. To investigate the topological connection, consider a uniform magnetic field extending in the z-direction through an incompressible nonresistive fluid from the end plate $z = 0$ to the end plate $z = L$. Introduce a bounded continuous incompressible fluid motion that interlaces the field lines while preserving the connection of every line of force from $z = 0$ to $z = L$. Then clamp the footpoints of the field at both endplates and release the fluid throughout $0 < z < L$, allowing the field to relax to the lowest available energy state, i.e. static equilibrium. Solution of the equilibrium equation $\nabla\times\boldsymbol{B}=\alpha\boldsymbol{B}$ shows only a limited class of field line topologies among the continuous solutions. However, the physics of tethered field lines indicates that all interlacing topologies have equilibrium solutions, from which it follows that almost all interlacing field line topologies form surfaces of tangential discontinuity as the magnetic stresses drive them to equilibrium. That is to say, almost all field line topologies provide rapid reconnection.

It is observed that most of the X-ray emission from the Sun comes from plasma trapped in bipolar magnetic fields, with both ends anchored in the photospheric turbulence. Hence the field lines are continually interlaced and active in relaxing to form current sheets and rapid reconnection. The resulting dissipation appears to be the principal heat source creating the X-ray corona.

MHD spectroscopy on tokamaks

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Abstract

Various types of MHD modes driven by energetic particles and by thermal plasma are routinely detected in present-day tokamaks. Measurements of these instabilities are used to solve the inverse problem of identifying the plasma parameters using the dependence of the MHD spectrum observed on equilibrium parameters. This technique called MHD spectroscopy [1] allows an effective acquisition of data without significant external perturbations applied to the plasma. Energetic particle driven modes of the Alfvén frequency range, TAE and Alfvén Cascade (AC) eigenmodes represent the most valuable ingredient in the MHD spectroscopy, due to their relatively low amplitudes and multiplicity [2]. Experimental results from the Joint European Torus (JET) tokamak are reviewed showing the use of MHD spectroscopy for evolution of the $q(r,\ t)$-profile, determining some parameters of energetic particle population, assessing D:T concentration, developing internal transport barriers [3], and diagnosing L-H transitions. Main diagnostics used in the MHD spectroscopy on tokamaks are reviewed and their performances compared: external Mirnov coils, interferometry and reflectometry, and multi-channel ECE. Possible use of the MHD spectroscopy in burning ITER plasmas is discussed.

[1] J.P. Goedbloed et al., PPCF **35** (1993) B277

[2] S.E. Sharapov et al., Phys. Lett. **A289** (2001) 127

[3] S.E. Sharapov et al., Nucl. Fusion **46** (2006) S868