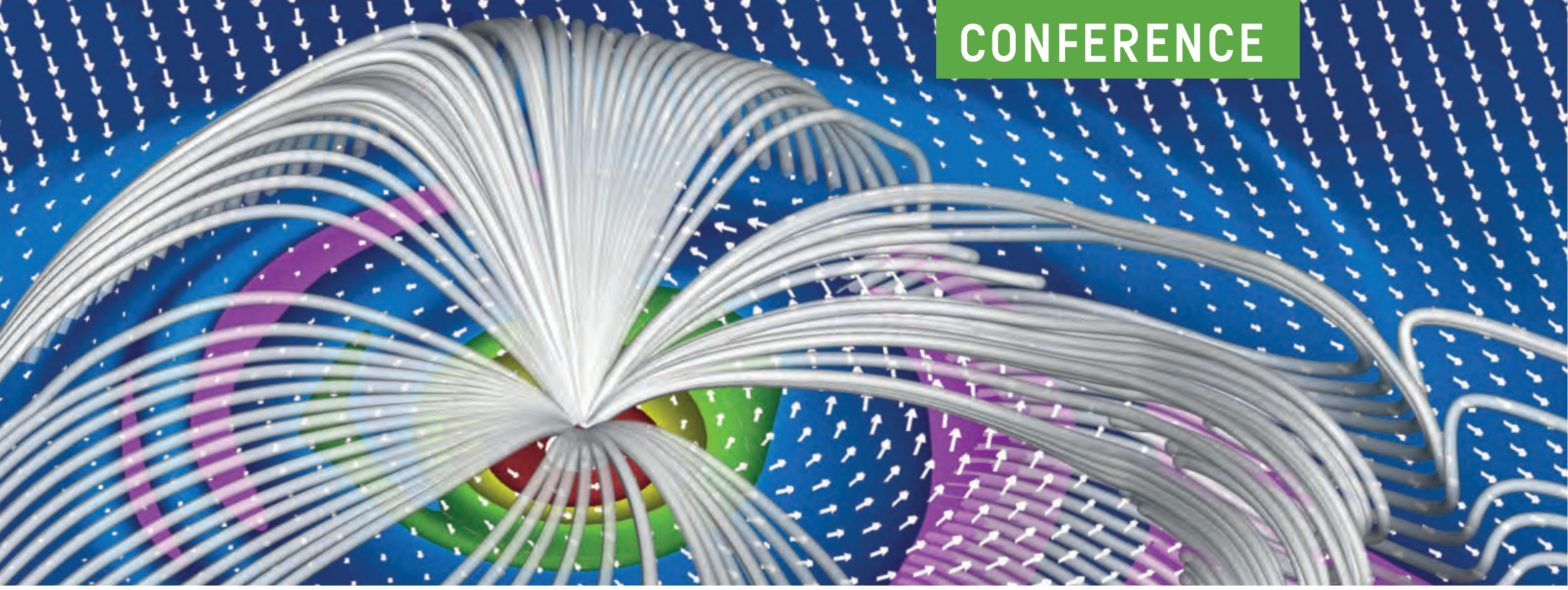

CONFERENCE

Numerical techniques in MHD simulations

August 16-18, 2017
University of Cologne, Germany

Abstract Booklet

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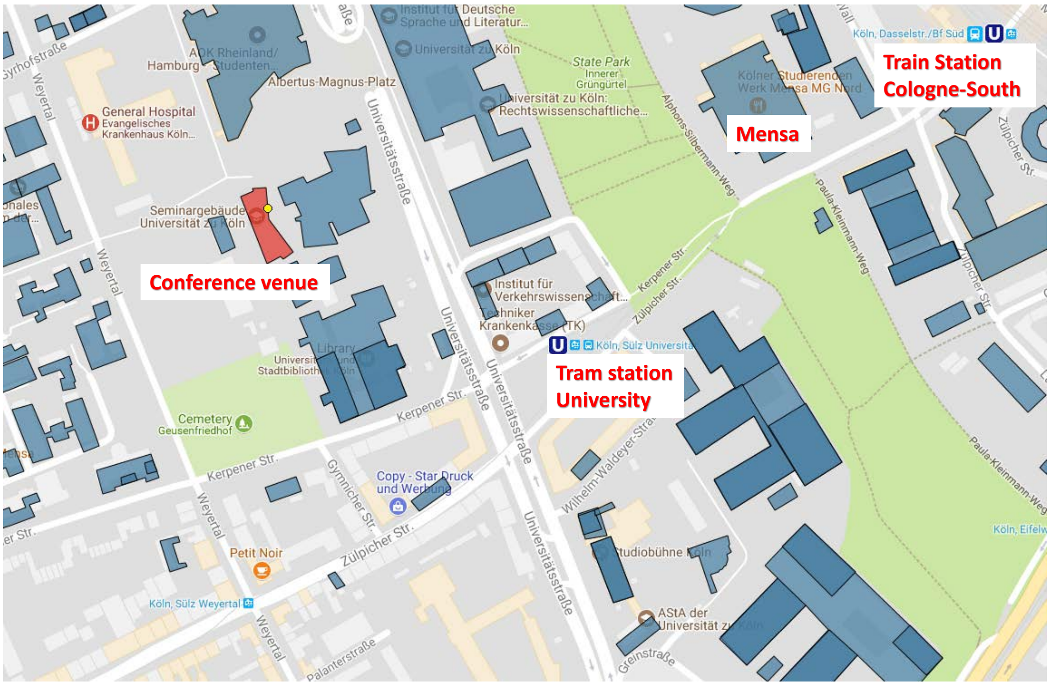
Numerical Techniques in MHD Simulations

Magnetohydrodynamic (MHD) simulations are an important tool to better understand the complex physics of astrophysical and geophysical plasma flows. As the frontiers are constantly pushed towards more accurate, faster and higher resolved simulations new mathematical approaches are needed to meet these goals. Therefore, the conference Numerical Techniques in MHD Simulations (MHD-SIM) focuses on recent developments of numerical techniques, models, and algorithms to address challenging science questions in computational space and astrophysics. Our conference covers various approaches to describe plasmas as a fluid, i.e., single fluid, multi-fluid and Hall-MHD approaches. The aim is to bring together researchers of several fields, such as applied mathematics, computer science, space science and astrophysics, in order to foster interdisciplinary discussions and to stimulate potential future collaborations.

Conference Venue and General Information

The conference takes place at the Universiy of Cologne's New Seminar Building (Universitätsstr. 37, building 106, see map below). Internet is available at the venue via eduroam; if you do not have eduroam access, please contact the local organizing committee. We will provide lunch tickets for the UoC's cafeteria (Mensa).

The Conference Dinner will take place on Thursday evening (7 PM) at the Brauhaus Sünner im Walfisch. On Thurday afternoon, there will be free time for social program and sightseeing (e.g. a trip to the Cologne Cathedral or the Wallraf Museum, or a panorama boat tour at 16:30).



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Keynote Speakers

1 High order ADER schemes for a unified first order hyperbolic formulation of Newtonian continuum mechanics coupled with electro-dynamics

Author(s): Michael Dumbser
Affiliation: Laboratory of Applied Mathematics, University of Trento
Type: keynote presentation
Time: Thu, 13:30–14:15
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In this talk, we propose a new unified first order symmetric hyperbolic and thermodynamically compatible theory of Newtonian continuum mechanics coupled with electrodynamics. The model is able to describe the behavior of moving elasto-plastic dielectric solids as well as viscous and inviscid fluids in the presence of electro-magnetic fields. It is actually a very peculiar feature of the proposed PDE system that viscous fluids are treated just as a special case of elasto-plastic solids. This is achieved by introducing a strain relaxation mechanism in the evolution equations of the distortion tensor A, which in the case of purely elastic solids maps the current configuration to the reference configuration. The model also contains a hyperbolic formulation of heat conduction as well as a dissipative source term in the evolution equations for the electric field given by Ohm's law. Via formal asymptotic analysis we show that in the stiff limit, the governing first order hyperbolic PDE system with relaxation source terms tends asymptotically to the well-known viscous and resistive magnetohydrodynamics (MHD) equations, and to the compressible Navier-Stokes equations in the absence of electro-magnetic fields. The present work extends the unified first order hyperbolic model of Newtonian continuum mechanics recently proposed by Peshkov and Romenski (2016) to the more general case where the continuum is coupled with electro-magnetic fields. The governing PDE system is symmetric hyperbolic and satisfies the first and second principle of thermodynamics, hence it belongs to the so-called class of symmetric hyperbolic thermodynamically compatible systems (HTC), which have been studied for the first time by Godunov in 1961 and later in a series of papers by Godunov and Romenski. An important feature of the proposed model is that the propagation speeds of all physical processes, including dissipative processes, are finite. The model is discretized using high order accurate ADER discontinuous Galerkin (DG) finite element schemes with a posteriori subcell finite volume limiters and using high order ADER-WENO finite volume schemes. We show numerical test problems that explore a rather large parameter space of the model ranging from compressible Euler and Navier-Stokes flows over ideal MHD, viscous and resistive MHD to pure electro-dynamics and moving dielectric elastic solids in a magnetic field. We will also show applications of our ADER-DG framework to the ideal and resistive relativistic MHD equations.

2 Recent add-ons to the MPI-AMRVAC framework

Author(s): Rony Keppens, Chun Xia, Jannis Teunissen, Bart Ripperda, Oliver Porth, Ileyk El Mellah, Guo Yang
Affiliation: University of Leuven
Type: keynote presentation
Time: Thu, 9:00–9:45
E-Mail: Rony.Keppens@wis.kuleuven.be

I will present the current status of the MPI-AMRVAC framework, with particular attention to recent extensions that allow for challenging applications in solar and astrophysical contexts. The code has been restructured in a more modular Fortran style, and extended with many test cases for hydrodynamic and magnetohydrodynamic applications. For especially solar applications, we added a magnetofrictional module to compute nonlinear force-free field extrapolations from photospheric vector magnetogram data, that can be combined with hierarchically nested meshes. Moreover, MHD data can provide the electromagnetic field info to quantify charged particle motion, either by solving the full Lorentz equation of motion, or by adopting a guiding centre approximation. This can be used to address particle acceleration aspects in violently reconnecting MHD scenarios. The MHD module can split off a background magnetic field that can be potential, linear force-free, or even non-force-free in nature. The adaptive mesh refinement can exploit grid stretching in one coordinate direction, and we show some typical applications where this stretched AMR grid proves to be of real advantage.

3 Towards stable numerical schemes for magnetohydrodynamics and applications in astrophysics

Author(s): Christian Klingenberg
Affiliation: University of Würzburg

Type: keynote presentation
Time: Fri, 9:00–9:45

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In this lecture we would like to highlight the importance of certain features in devising an MHD algorithm that we find helpful with the stability of the code in applications. To this end we present a positivity preserving, entropy consistent numerical flux. This is being used in a finite volume code for ideal magnetohydrodynamics (MHD), which possesses excellent stability properties. Ingredients are: an approximate Riemann solver, extension to multidimensions via a Powell term, second order preserving positivity. The scheme's robustness is due to entropy stability, positivity and properly discretised Powell terms. Next we describe a discontinuous Galerkin method where these features have been introduced. Numerical implementations in various astrophysical codes will be shown. They show the overall stability of the these schemes.

4 MHD with particle methods — an overview of Smoothed Particle Magnetohydrodynamics

Author(s): Daniel Price
Affiliation: Monarch University
Type: keynote presentation
Time: Fri, 10:55–11:40
E-Mail: daniel.price@monash.edu

I will present an overview of the state-of-the-art in Smoothed Particle Magnetohydrodynamics, a mesh-free numerical method for solving the equations of MHD. I will discuss advantages and disadvantages of SPMHD, and some tricky issues, like how to enforce the $\text{div}B = 0$ constraint in particle methods, how to ensure numerical stability and how to implement non-ideal MHD. I will also present my 3D SPMHD code Phantom, which has been recently made public, and highlight some recent applications to star formation, tidal disruption events and spiral galaxies.

5 The University of Michigan MHD code: BATS-R-US

Author(s): Gabor Toth
Affiliation: University of Michigan
Type: keynote presentation
Time: Wed, 11:20–12:05
E-Mail: gtoth@umich.edu

This talk reviews the various physical equations and numerical techniques used in the University of Michigan's MHD code BATS-R-US. A key ingredient is the block-adaptive grid that provides an efficient method to resolve various spatial scales. In addition to the adaptive mesh refinement, the code allows generalized coordinates, for example spherical grids with stretched radial coordinate and also the "round cube" geometry that stretches the cartesian grid into a spherical shape. The grid blocks also provide an intermediate scale between the grid cells and the full computational domain that allow for various adaptive numerical algorithms. For example, we can employ explicit or implicit time stepping; a 2nd order or a 5th order scheme; ideal or Hall MHD etc. on a block-by-block basis. Since each grid block has a logically uniform grid and is on a single processor, these hybrid schemes are relatively simple to implement. I will discuss how load balancing can be achieved on massively parallel computers when the blocks employ different schemes with different computational cost. A large variety of spatial and temporal discretizations are available that provide flexibility to address the challenges of different applications. In addition to the wide range of numerical techniques, BATS-R-US also contains a wide variety of system of equations from hydrodynamics, ideal, resistive, semi-relativistic, Hall and multi-ion MHD, anisotropic ion pressure, multi-fluid closure with separate electron and ion fluids, viscosity, heat conduction, radiative transfer in the multi-group diffusion approximation. Finally, time permitting, I will discuss how this general MHD code can be coupled to other models, in particular Particle-in-Cell codes, which result in the MHD with Embedded PIC (MHD-EPIC) algorithm that can solve global problems while treating local phenomena, like reconnection, kinetically.

6 Skew-Symmetric Splitting and Stability of High Order Central Schemes

Author(s): H.C.Yee[1] and Björn Sjögreen[2], and Dmitry Kotov[3]
Affiliation: [1]NASA Ames Research Center, Moffett Field CA94035; [2]Multid Analyses AB, Odinsgatan 28, Göteborg, Sweden
Type: keynote presentation
Time: Wed, 9:45–10:30
E-Mail: [1]Helen.M.Yee@nasa.gov, [2]Bjorn.Sjogreen@multid.se, [3]kotov-d-v@yandex.co

Skew-symmetric splittings of the inviscid flux derivative for high order central schemes are studied and developed to improve their numerical stability without added high order numerical dissipation for long time wave propagations and long time integration of compressible turbulent flows. For flows containing discontinuities and multiscale turbulence fluctuations the Yee & Sjogreen [6] and Kotov et al. [5, 4] high order nonlinear filter approach is utilized in conjunction with the skew-symmetric form of high order central schemes. Due to the incomplete hyperbolic nature of the conservative ideal magnetohydrodynamics (MHD) governing equations, not all of the skew-symmetric splittings for gas dynamics can be extended to the ideal MHD. For the MHD the Ducros et al. [2] variants are constructed. In addition, four formulations of the MHD are considered: (a) the conservative MHD, (b) the Godunov/Powell non-conservative form, (c) the Janhunen MHD with magnetic field source terms [3], and (d) a MHD with source terms of [1]. The different formulation of the equations in conjunction with the variants of Ducros et al. type skew-symmetric splitting will be shown to have a strong effect on the stability of non-dissipative approximations. Representative test cases for both smooth flows and problems containing discontinuities for the ideal MHD are included. The results illustrate the improved stability by using the skew-symmetric splitting as part of the central base scheme instead of the pure high order central scheme.

[1] Brackbill, J.U., Barnes, D.C.: The effect of nonzero $\nabla \cdot B$ on the numerical solution of the magnetohydrodynamics equations. J. Comput. Phys. 35, 426-430 (1980).
[2] Ducros, F., Laporte, F., Soulères, T., Guinot, V., Moinat, P., Caruelle, B.: High-order uxes for conservative skew-symmetric-like schemes in structured meshes: application to compressible ows: J. Comput. Phys. 161, 114-139 (2000).
[3] Janhunen, P.: A Positive conservative method for MHD based on HLL and Roe methods. J. Comput. Phys. 160, 649-661 (2000).
[4] Kotov, D.V., Yee, H.C., Wray, A.A., Sjögreen, B., Kritsuk, A.G.: Numerical disipation control in high order shock-capturing schemes for LES of low speed flows. J. Comput. Phys. 307, 189-202 (2016).
[5] Kotov, D.V., Yee, H.C., Wray, A.A., Sjögreen, B.: High order numerical methods for dynamic SGS model of turbulent flows with shocks. Commun. Comput. Phys. 19, 273-300 (2016).
[6] Yee, H. C., Sjögreen, B.: High Order Filter Methods for Wide Range of Compressible Flow Speeds. Proceedings of the ICOSAHOM09, June 22-26, 2009, Trondheim, Norway.

Invited Speakers

7 MHD simulations of the gas giants' magnetospheres

Author(s): Emmanuel Chané, J. Saur, R. Keppens, S. Poedts
Affiliation: University of Leuven
Type: invited talk
Time: Thu, 9:45–10:15
E-Mail: Emmanuel.Chane@kuleuven.be

Using the MPI-AMRVAC code, we perform global one-fluid MHD simulations of the interactions between the solar wind and the magnetospheres of Jupiter and Saturn. In contrast to other MHD models for planetary magnetospheres, our model incorporate the magnetosphere-ionosphere coupling by explicitly including the ionosphere within the MHD simulation domain. In the ionosphere, the plasma velocity is affected by the collisions with the atmospheric neutral particles. The neutral particles have a given constant velocity and temperature, and the ion-neutral collision frequency is fixed in the ionosphere. These collisions accelerate the ionospheric plasma, which then rotates almost rigidly with the planet. By introducing collisions with the neutral particles in the ionosphere, we also allow magnetospheric electrical current systems to close in the ionosphere (because the collisions generate the Perdersen and Hall conductivities necessary to close the currents). The coupling between the ionosphere and the magnetosphere makes the whole magnetosphere rotate: it rotates rigidly close to the planet and it sub-corotates on larger L-shells. We then use our model to perform numerical experiments and to study: how the solar wind ram pressure influences the aurorae, how the magnetodisk is influenced by the strength of the interplanetary magnetic field, and how the magnetopause influences the plasma circulation.

8 Background/residual decomposition for the magnetic field in MHD simulations using a time-dependent B0 - application to Saturn-like and Uranus-like magnetospheres

Author(s): L. Griton, F. Pantellini
Affiliation: LESIA - Observatoire de Paris - PSL/CNRS
Type: invited talk
Time: Wed, 16:10–16:40
E-Mail: lea.griton@obspm.fr

We present 3D magnetohydrodynamics (MHD) simulations (on a spherical grid) of the interaction of the solar wind with a fast rotating magnetized planet. We adapted the MPI-AMRVAC code to allow for any possible orientation of spin and magnetic axis using a background/residual decomposition of the magnetic field. MHD equations have been rewritten to allow time-dependent (and possibly non-potential) background magnetic field. The Saturn-like and Uranus-like cases are briefly discussed. We present in particular the effects of rotation on the configuration of the planet-connected magnetic field lines and on the flow pattern.

9 Implementation of energy dependent transport of cosmic rays in PIERNIK MHD code

Author(s): Michal Hanasz & Mateusz Ogrodnik
Affiliation: Centre for Astronomy, Nicolaus Copernicus University
Type: invited talk
Time: Thu, 10:15–10:45
E-Mail: mhanasz@umk.pl

Cosmic rays (CR) gain increasing attention in the studies of the dynamics and evolution of the interstellar medium. I am going to present a new implementation of energy-dependent propagation of CR electrons and protons in PIERNIK MHD code. The overall propagation of cosmic rays is described by energy-dependent diffusion-advection equation, including adiabatic cooling and synchrotron losses of CR electrons. We assume a piecewise power-law, isotropic CR distribution function and apply a conservative, finite volume-type propagation of CR gas in momentum space. The core of the algorithm is based on Miniati's (Computer Physics Communications 141, 17, 2001) implementation of CR energy spectrum evolution and on our own implementation of anisotropic, magnetic field-aligned diffusion and advection of CRs on a spatial grid. I will present test problems for the recently developed algorithm to demonstrate specific effects the energy-dependent propagation of CR electrons produced in SN remnants.

10 Modern understanding of MHD turbulence: theory and implications

Author(s): Alex Lazarian
Affiliation: University of Wisconsin-Madison
Type: invited talk
Time: Fri, 12:40–13:10
E-Mail: lazarian@astro.wisc.edu

I am going to challenge the folklore notion about MHD turbulence being a mess. I will show that MHD turbulence has well defined scalings and these scalings can be used to solve many astrophysical problems. I will discuss both balanced and imbalanced MHD turbulence, the connection of turbulence and magnetic reconnection, the problem of cosmic ray acceleration as well as propagation of cosmic rays and heat. From the point of view of MHD turbulence I shall address the issues of subdiffusion and superdiffusion that has important implication for the transport of both heat and energetic particles. Finally, I shall briefly discuss how turbulence properties can be obtained from observations.

11 GAMERA – The New Magnetospheric Code

Author(s): John Lyon; Binzheng Zhang (HAO/NCAR) Kareem Sorathia (JHU/APL) Slava Merkin (JHU/APL) Mike Wiltberger (HAO/NCAR) Lars Daldorff (JHU/APL)
Affiliation: Dartmouth College
Type: invited talk
Time: Wed, 12:05–12:35
E-Mail: lyon@tinman.dartmouth.edu

The Lyon-Fedder-Mobarry (LFM) code has been a main-line magnetospheric simulation code for 30 years. The code base, designed in the age of memory to memory vector machines,is still in wide use for science production but needs upgrading to ensure the long term sustainability. In this presentation, we will discuss our recent efforts to update and improve that code base and also highlight some recent results. The new project GAMERA, Grid Agnostic MHD for Extended Research Applications, has kept the original design characteristics of the LFM and made significant improvements. The original design included high order numerical differencing with very aggressive limiting, the ability to use arbitrary, but logically rectangular, grids, and maintenance of $nablacdotvecB = 0$ through the use of the Yee grid. Significant improvements include high-order upwinding and a non-clipping limiter. One other improvement with wider applicability is an improved averaging technique for the singularities in polar and spherical grids. The new code adopts a hybrid structure - multi-threaded OpenMP with an overarching MPI layer for large scale and coupled applications. The MPI layer uses a combination of standard MPI and the Global Array Toolkit form PNL to provide a lightweight mechanism for coupling codes together concurrently. The single processor code is highly efficient and can run magnetospheric simulations at the default CCMC resolution faster than real time on a MacBook pro. We have run the new code through the Athena suite of tests, and the results compare favorably with the codes available to the astrophysics community. LFM/GAMERA has been applied to many different situations ranging from the inner and outer heliosphere and magnetospheres of Venus, the Earth, Jupiter and Saturn. We present results from the simulation of the Kelvin-Helmholtz instability at the Earth, Jupiter, and Saturn. For the Earth we show that the simulation agrees with the theoretical growth rates for compressive K-H. In the outer planets the rotation of the magnetosphere is an important component of the resulting structure.

12 Combined Global NLFFF simulations and MHD simulations

Author(s): Paolo Pagano, Duncan Mackay, Stefaan Poedts
Affiliation: University of St Andrews
Type: invited talk
Time: Wed, 14:50–15:20
E-Mail: pp25@st-andrews.ac.uk

Magnetic flux rope ejections are considered the main progenitor of Coronal Mass Ejections (CMEs) from the Solar Corona where flux ropes are often rapidly ejected after a long period of stable equilibrium. These two contrasting time scales present a major problem for modelling actual configurations on the Sun. To tackle this we couple the Global Non-Linear Force-Free Field (GNLFFF) model - tailored to describe the slow magnetic evolution of the corona - with 3D MHD simulations - a general approach and can effectively model a fast flux rope ejection. We will present two applications of the coupling and explain how we construct a solar atmosphere around the coupled magnetic field configuration in each case. In the first application we focus on the global scale, where we model magnetic flux rope ejections in the global corona. In the second application we use this technique to model a magnetic flux rope ejection observed on August, 2nd 2011 and describe the early stage of the following CME. This application aims to show the potential of the technique when applied to a time series of magnetically complex active regions where the small scale and internal structuring are essential to describe the dynamic evolution along with the relaxation mantaining the complexity and non-potentiality of the magnetic field.

13 The Applicability of MHD to Describe a Collisionless Plasma Like the Solar Wind

Author(s): Daniel Verscharen
Affiliation: University of New Hampshire
Type: invited talk
Time: Wed, 9:15–9:45
E-Mail: daniel.verscharen@unh.edu

The fast solar wind is a collisionless plasma flow that typically exhibits non-equilibrium features in its distribution function. This observation suggests that the action of binary Coulomb collisions is insufficient to create a low-order closure of the velocity-moment hierarchy. Therefore, it appears reasonable to assume that a kinetic description is necessary whereas low-moment fluid descriptions such as magnetohydrodynamics (MHD) break down. We compare observations of the polarization properties of large-scale compressive fluctuations in the solar wind with predictions from MHD and kinetic theory. Surprisingly, MHD predicts these fluctuations more accurately than kinetic theory, even at times of low collisionality. We conjecture that some mechanism, which still remains to be identified, suppresses fluctuations in higher moments of the distribution function. This collisionless mechanism, therefore, takes over the role of collisions in the closure of the moment hierarchy. We discuss anti-phase-mixing in a turbulent background as well as the heat-flux suppression through fluctuating-moment effects as potential candidates for such a mechanism. Although further studies are necessary, our results imply a physics-based justification for the application of MHD to model collisionless plasmas like the solar wind.

Contributor Talks

14 Numerical investigation of the laminar-turbulent transition in magnetized spherical Couette flow

Author(s): Lalaoua Adel, Merah Abdelkrim, University M'Hamed Bougra of Boumerdes/ Algeria. Aiche Celia, Faculty of Mechanical Engineering and Process Engineering/ University of Sciences and Technology Houari Boumedienne / Algeria. Naitbouda Faycal, Faculty of Technology/ University of Bejaia/Algeria.
Affiliation: Faculty of Technology, University AbdErrahmane Mira of Béjaïa
Type: contributor talk
Time: Thu, 11:35–11:55
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The stability and transition of a flow evolves in an annulus between two concentric rotating spheres, known as spherical Couette flow, present a great importance in the field of fluid dynamics and has a fundamental interest in the planetary atmosphere, accretion discs and oceanic circulations. If the fluid is taken as an electrically conducting, and a magnetic field is imposed, termed MHD spherical Couette flow, the flow patterns and the map of the transition from laminar flow to turbulence can be drastically changed. This flow problem offers the possibility of exploring a wide variety of instabilities and plays an important role to understand the geophysics and astrophysics phenomena as well as to study the dynamics of the Earth's outer core. In this work, the flow of an electrically conducting fluid in an annulus between two concentric rotating spheres subjected to a dipolar magnetic field is investigated numerically. The outer sphere is stationary while the inner one rotates freely about a vertical axis passing through its center. The spherical shell is completely filled with liquid sodium. The numerical studies are performed for the medium gap width β=0.18, and carried out for a wide range of Hartmann number, Ha, from 0 up to 5000. Both inner and outer spheres are considered insulating walls. Computations for the onset of Taylor vortices in spherical Couette flow without an imposed magnetic field show a good agreement with the previous works. It is established that the imposed magnetic field radically alters the flow structures leading to significant topological changes on the flow patterns. In particular, we found that depending on the magnetic field imposed, the basic state consists of either a shear layer or a counter-rotating jet and both becoming thinner and thinner for increasingly strong imposed fields, but with the jet also becoming stronger.

15 Magnetohydrodynamic simulations of Io's and Europa's plasma interaction

Author(s): Aljona Blöcker, University of Cologne; Joachim Saur, University of Cologne

Affiliation: Institute of Geophysics and Meteorology, University of Cologne

Type: contributor talk

Time: Wed, 17:00–17:20

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We apply a three-dimensional magnetohydrodynamic (MHD) model to study the influence of inhomogeneities in Io's and Europa's atmosphere, as, for example, volcanic plumes and water vapor plumes, on the moons' plasma interaction with the Jovian magnetosphere. In our model we have included collisions between ions and neutrals, plasma production and loss due to electron impact ionization, and dissociative recombination, the ionospheric Hall effect, and electromagnetic induction in a subsurface water ocean at Europa. The insulating nature of the surface is described in the numerical model with the nonconducting boundary condition derived by Duling et al. [2014] ensuring that there is no radial electric current. To solve the set of MHD equations, we apply a modified version of the publicly available ZEUS-MP MHD code using spherical geometry. We present a systematic study of the plasma interaction when a local inhomogeneity in the neutral density is present within a global atmosphere. We show that an inhomogeneity near the north or south pole affects the plasma interaction in a way that a pronounced north-south asymmetry is generated. We find that an Alfvén winglet develops within the main Alfvén wing on that side where the inhomogeneity is located. Furthermore, we compare our model results with the measured magnetic field data from different flybys of the Galileo spacecraft.

16 Discontinuous Galerkin schemes for Magneto-Hydrodynamics

Author(s): M. Bohm, A. Winters, G. Gassner, G.B. Jacobs
Affiliation: Mathematisches Institut Universität zu Köln
Type: contributor talk
Time: Thu, 14:35–14:55
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In this presentation the ideal MHD equations are solved by an explicit Discontinuous Galerkin Spectral Element Method (DGSEM). Since high order approximations of non-linear conservation laws are prone to oscillations in regions with strong shocks or contact discontinuities, special attention is paid to shock capturing strategies. Concerning this matter two different approaches are discussed: Smoothing these shocked regions by adding an appropriate amount of artificial viscosity and limiting the interpolating polynomial by a local filter matrix. For both approaches theoretical derivations of the necessary modifications to the scheme are demonstrated and validated by numerical results.

17 Power Modeling of a MHD Faraday type generator

Author(s): Fabiano Carvalho de Castro Sene, Alessandro Goedtel, Marcelo Favoretto Castoldi
Affiliation: Federal Technological University of Paraná - UTFPR

Type: contributor talk
Time: Thu, 12:15–12:35

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Due to the increasing of energetic demand in the world, appears the necessity to improve the aspects about the research in alternative sources to supply new loads and new markets to help or even substitute the conventional energy sources in a possible case of saturation. Therefore, converging to this side, one of the alternative energy sources that still can be improved is the Magnetohydrodynamic Power Generation. Materialized in the early 1960's, but without great progress because of the little knowledge about electrical properties of the gas, magnetohydrodynamic for energetical supply kept being developed for highly specific use. But, with the development of new fluids and decreasing temperature of melting for some metal alloys, the tendencies of changing plasma as work fluid for another fluid has become a good choice. Beyond this, conditions of flow and power modelling, for computational methods, as will be shown, were improved and wait to be tested experimentally to prove magnetohydrodynamic power generator as a reliable choice to operate in effective power supply conditions.

18 Ideal GLM-MHD: About the novel entropy-consistent nine-wave magnetic field divergence diminishing ideal magnetohydrodynamics equations

Author(s):	Dominik Derigs (PH1), Andrew R. Winters (MI), Gregor J. Gassner (MI), Stefanie Walch-Gassner (PH1)
Affiliation:	I. Physikalisches Institut, Universität zu Köln, Germany (PH1), Mathematisches Institut, Universität zu Köln, Germany (MI)
Type:	contributor talk
Time:	Fri, 10:05–10:25
E-Mail:	derigs@ph1.uni-koeln.de

The applications of ideal magnetohydrodynamics (MHD) are ubiquitous in science and engineering. Accordingly, the design of numerical schemes for the approximation of this particular set of hyperbolic conservation laws has undergone extensive development. In this work, we describe the derivation of the first entropy-consistent, magnetic field divergence diminishing ideal MHD system which minimizes errors in the divergence-free constraint of the magnetic field by construction. Its unique selling point is that it does not require any “on-top” divergence cleaning mechanisms. We present our new system both in continuous as well as discrete space, where the latter can directly be used for an implementation in numerical schemes for ideal MHD. Our scheme is conservative in mass, momentum and total energy and is entropy stable. Entropy stable algorithms have the benefit that the scheme is nearly isentropic in smooth parts of the flow, i.e. low dissipation, enhancing the resolution of the numerical solution in these regions. The scheme is guaranteed to generate entropy, i.e. dissipate, near discontinuities. Thus, the scheme follows the fundamental physics of thermodynamics by design.

19 Wind accretion in Super Giant X-ray Binaries

Author(s): Ileyk EL MELLAH, Jon SUNDQVIST, Rony KEPPENS
Affiliation: KU Leuven - CmPA
Type: contributor talk
Time: Fri, 12:00–12:20
E-Mail: ileyk.elmellah@kuleuven.be

X-ray emission associated to accretion onto compact objects such as neutron stars displays important levels of photometric and spectroscopic time-variability. When the accretor orbits a Supergiant star, it captures a fraction of the supersonic radiatively-driven wind which forms shocks in its vicinity. The amplitude and stability of this gravitational beaming of the flow conditions the mass accretion rate responsible, in fine, for the X-ray luminosity of those Supergiant X-ray Binaries and Super Fast X-ray Transients. The capacity of this low angular momentum inflow to form a disc-like structure before being truncated by the neutron star magnetosphere remains at stake. We developed a synthetic model of mass transfer in Supergiant X-ray Binaries which couples the launching of a radiatively-driven wind accordingly to the stellar parameters, the orbital evolution of the streamlines in a modified Roche potential and the accretion process. We show that the shape of the permanent flow is entirely determined by a limited number of degrees of freedom : the mass ratio, the filling factor, the Eddington factor and the alpha force multiplier. Provided scales such as the orbital period are known, we can trace back the observables to evaluate the mass accretion rates, the accretion mechanism (stream or wind-dominated) and the shearing of the inflow, tracer of its capacity to form a disc around the accretor. The influence of each degree of freedom is discussed and sets of fundamental parameters of interest are determined. This model also provides self-consistent outer boundary conditions for multi-scales 3D hydrodynamical simulations centered around the neutron star, in-between the accretion and the magnetosphere scales. Coupled to state-of-the-art numerical simulations of the wind of isolated massive stars by Jon Sundqvist et al (publication in prep), it enables us to investigate the impact of physically-derived clumpiness on the mass and angular momentum accretion rates, for different orbital separations. We follow the clumps through the shock, as they get more and more ionized and enter the neutron star magnetosphere.

20 The Theoretical Foundation of 3D Alfv'en Resonances

Author(s): Tom Elsden, Andrew Wright
Affiliation: University of St Andrews
Type: contributor talk
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Time Dependent Solutions Abstract: The coupling of fast and Alfv'en magnetohydrodynamic (MHD) waves is of fundamental interest in astrophysical plasmas. Under certain conditions, Alfv'en waves can be resonantly excited by fast mode waves, resulting in a localised accumulation of energy in the plasma. In the solar community this is often referred to as resonant absorption, while in the magnetospheric community it's known as field line resonance. These processes have applications in coronal heating and in magnetospheric dynamics. Alfv'en resonances are reasonably well understood in 1D and 2D, but not so in 3D. We present a theoretical way of understanding the structure of Alfv'en resonances in 3D, which is corroborated by 3D MHD simulations.

21 Towards fast high-order MHD for astrophysics in the AREPO code

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I present our latest developments on MHD schemes for the cosmological hydrodynamical simulation code AREPO. The code implements finite volume solvers for hydrodynamics and MHD, and can operate on two major types of grids: either a fully dynamic quasi-Lagrangian unstructured Voronoi mesh, or an octree-based adaptive mesh refinement (AMR) grid. The moving mesh solver is based on a second-order unsplit Godunov scheme. For AMR grids, we implemented a higher-order discontinuous Garlerkin (DG) hydrodynamics solver, which we have extended to MHD based on locally divergence-free basis functions. I discuss some challenges to achieve a robust and efficient implementation of MHD that can be applied to astrophysical problems, with a focus on the DG implementation. Finally, I highlight some key aspects of achieving high computational efficiency with DG on modern CPU architectures.

22 Mesh generation and resistive MHD simulations for plasmas in fusion devices with a parallel 3D DGSEM framework

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The main goal of the numerics department at IPP is to design algorithms to study the physical behavior of magnetic confinement fusion (MCF) devices. Two main torus-shaped designs for plasma confinement are distinguished, the Tokamak with an axisymmetric field and the Stellarator with a fully 3D field. Instabilities of the plasma, triggered by the interaction between the strong magnetic field and density and temperature gradients, can change, deteriorate or even break the confinement (Freidberg, 2014). The simplest model to study the linear growth and the non-linear interaction of these plasma instabilities is described by the resistive one-fluid MHD equations. The MHD simulation starts from a non-trivial steady state of the ideal MHD equations, representing an equilibrium between gas pressure and magnetic pressure. Then the equilibrium is disturbed and instabilities grow and interact and can either saturate or lead to a breakdown. The equilibrium is computed by specifically designed equilibrium solvers, e.g. VMEC (Hirshman, van Rij and Merkel, 1986) for Stellarators. First, we show how the three-dimensional high order meshes for Tokamak and Stellarator configurations are generated. Since the magnetic field is very strong, the behavior of the equations is highly anisotropic. Hence, to reduce resolution requirements toroidally (in field direction), the mesh and the boundaries should be aligned with the magnetic field, given by the equilibrium state. The open-source tool (*https://github.com/fhindenlang/hopr*) is used to generate the mesh, consisting of unstructured and curved hexahedral elements, also allowing for 2/1 and 4/1 non-conforming element interfaces. The 3D simulations have substantial resolution requirements, both toroidally and poloidally (plane perpendicular to the field) and need to be run in parallel. We employ the highly efficient Discontinuous Galerkin Spectral Element Method (DGSEM) citeblack1999 implemented in parallel in the *https://github.com/project-fluxo/fluxo* solver, which was developed at IAG in Stuttgart (Hindelang et al., 2012) and extended at IPP in Garching and at MI in Cologne. The solver exhibits high parallel efficiency both for weak and strong scaling. We will discuss some details of the implementation and also show benchmark simulations of MHD instabilities.

23 On the resolution requirements for modelling molecular gas formation

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The simulations investigate the formation of molecular clouds in two different models: (i) the colliding flows of the warm neutral medium and (ii) supersonic, driven turbulence in cubic pieces of the ISM with periodic boundary conditions. The simulations have been carried out with a modified version of the Eulerian AMR code FLASH 4, into which additional physical processes have been implemented. In addition to magneto-hydrodynamics and turbulence, diffuse radiative transfer and two (optional) chemical networks that treat the formation of molecular hydrogen and CO as well as non-equilibrium cooling and heating effects have been included. The project studies the numerical and physical resolution required to reach a converged picture of molecular gas formation using these two typical setups. In both the scenarios, the resolution study for the two employed chemical networks (a simpler and a slightly more complex one) have been carried out to test if the findings are general.

24 The non-linearity of the cross-polar cap potential during high solar wind driving: GUMICS-4 results

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It is well known that the Earth's ionospheric cross-polar cap potential (CPCP) saturates as a response to the solar wind driver especially when the level of driving is high and the interplanetary magnetic field (IMF) is oriented southward. Moreover, recent studies have shown that the upstream Mach number may be an important factor in the saturation effect. We use the Grand Unified Magnetosphere-Ionosphere Coupling Simulation (GUMICS-4) and artificial solar wind data to mimic weak and strong driving in order to study the CPCP response to a wide range of IMF magnitudes (3.5 nT – 30 nT) and upstream Alfven Mach number values (1.2 – 22). A total of five simulations were executed with different IMF magnitude in each run and identical gradually increasing solar wind plasma flow speed from 350 km/s to 750 km/s in 100 km/s steps every one hour. This study contributes to explaining processes leading to the CPCP non-linear response to the solar wind driver and, most importantly, in which part of the system the nonlinearity arises.

25 3D CFD study of the MHD liquid sodium flow between two rotating conical cylindes system

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This purpose is about 3D numercial study of MHD liquid sodium flow in conical Taylor-Couette System, with the conical cylinders taken to be perfect electrically insulatings. The liquid sodium is contained in the uniform gap between a stationary outer cone and an inner rotating one of constant angular velocity. We consider that the top and bottom end-plates are rigid and the cone's wall is a no-slip boundary. The continuity and incompressible three-dimensional Navier-Stokes equations are solved with finite volume method. We investigate the effect of an axial magnetic field on flow pattern. For considred Taylor number and Hartmann number values, we analyze the velocity profiles, Taylor-vortex flow and Ekman-Hartmann cell.

26 EUHFORIA: a solar wind and CME evolution model

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We present the latest state-of-the-art update of the new physics-based forecasting-targeted inner heliosphere model EUHFORIA ('EUropean Heliospheric FORecasting Information Asset') that we are developing. EUHFORIA consists of a coronal model and a magnetohydrodynamic (MHD) heliosphere model with CMEs. The aim of the baseline coronal model is to produce realistic plasma conditions at the interface radius r = 0.1 AU between the two models thus providing the necessary input to the time-dependent, three-dimensional MHD heliosphere model. It uses GONG synoptic line-of-sight magnetograms as input for a potential (PFSS) field extrapolation of the low-coronal magnetic field coupled to a current sheet (CS) model of the extended coronal magnetic field. The plasma variables at the interface radius are determined by employing semi-empirical considerations based on the properties of the PFSS+CS field such as the flux tube expansion factor and distance to nearest coronal hole. The heliosphere model computes the time-dependent evolution of the MHD variables from the interface radius typically up to 2 AU. Coronal mass ejections (CMEs) are injected at the interface radius using a hydrodynamic cone-like model using parameters constrained from fits to coronal imaging observations. In order to account for the modification of the heliosphere due to the presence of earlier CMEs, the standard run scenario includes CMEs launched five days prior to the start of the forecast, while the duration of the forecast extends up to seven days. In addition to presenting results of the modeling, we will highlight our on-going efforts to advance beyond the baseline in the forecasting pipeline. In particular we discuss the performance of the novel magnetized CME flux-rope models. We also mention our plans for the application of a time-dependent coronal model as well as modeling the transport of solar energetic particles (SEPs) in the heliosphere, and discuss the tests with solution AMR (Adaptive Mesh Refinement) for the background wind and the evolution of magnetized CME clouds and shock waves.

27 MHD control of non-equilibrium high-speed flow

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MHD shock wave control is a concept that has several possible applications in aircraft design, but requires extensive numeric and experimental research to be realized. This study aims at developing a comprehensive open-source toolkit for the numerical modeling of interaction between magnetic field and hypersonic flow. OpenFOAM CFD toolbox is chosen as a framework for the development. Magnetohydrodynamical capabilities have been added to an existing hypersonic solver. The underlining hypersonic solver utilizes Park's two-temperature model, based on Navier-Stokes-Fourier equations with separate trans-rotational and vibro-electronic energy modes. The reasons for the introduction of second temperature into the model are caloric and chemical non-equilibrium that is characteristic for the studied flow regimes. The distinction between different modes of temperature of different species can play a significant role in estimating the intensity of MHD interaction, which is illustrated by comparing numerical results of a single- and two-temperature model-based simulation. Electrical conductivity of 11-species air in hypersonic flow is calculated using electron-heavy particle collisions data. Weakly ionized air flow control around a wedge has been simulated to estimate the potential effect of MHD control system on shockwave configuration. The differences in calculated shock front shape between the flow in absence and in presence of magnetic field are compared to equivalent experimental data. The potential of MHD flow control for both re-entry capsules and hypersonic scramjets has been numerically investigated. Key differences between the two cases have been outlined. The study provides a foundation for future developments of a comprehensive simulation tool for MHD hypersonic flow interaction.

28 MHD Boundary Conditions at Electrically Non-Conductive Bodies

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The interaction of planetary bodies with their surrounding magnetized plasma can often be described within the magnetohydrodynamic (MHD) framework. This description requires boundary conditions for the plasma mass and energy density, the plasma velocity and the magnetic field. Many planetary bodies have electrically non-conductive surfaces, which do not allow electric current to penetrate their surfaces. Magnetic boundary conditions, which consider that the associated radial electric current at the planetary surface is zero are difficult to implement because they include the curl of the magnetic field. Here we review appropriate magnetic boundary conditions, which we derived in Duling et al. 2014. The method is based on a decomposition of the magnetic field in poloidal and toroidal parts. We find that the toroidal part of the magnetic field needs to vanish at the surface of the insulator. For the spherical harmonics coefficients of the poloidal part we derive a Cauchy boundary condition, which also matches a possible intrinsic field by including its Gauss coefficients. Thus we can additionally include planetary dynamo fields as well as time-variable induction fields within electrically conductive subsurface layers. We implement this boundary condition in the MHD code ZEUSMP using spherical geometry. We apply it to a model for the plasma interaction around Jupiter's moon Ganymede. Our model also includes a consistent set of boundary conditions for the other MHD variables density, velocity and energy. With this model we can describe Galileo spacecraft observations in and around Ganymede's mini-magnetosphere very well. Duling S., J. Saur & J. Wicht, (2014), J. Geophys. Res., 119, doi:10.1002/2013JA019554

29 Numerical Modelling of Stealth Solar Eruptions

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Coronal Mass Ejections (CMEs) are huge expulsions of magnetized plasma from the Sun into the interplanetary medium. A particular class of CMEs are the so-called stealth CMEs, i.e., solar eruptions that are clearly distinguished in coronagraph observations, but that are not associated with clear signatures close to the Sun, such as solar flares, coronal dimmings, EUV waves, or post-flare loop arcades. Observational studies show that quite often (about 60%) stealth CMEs are preceded by another CME whose solar origin could be identified. In order to determine the triggering mechanism for stealth CMEs we are using the MPI-AMRVAC code developed at KU Leuven. As initial condition, we consider a multi-polar magnetic field constituted by three magnetic arcades embedded in a globally bipolar magnetic field. This configuration results in the formation of a coronal null point, i.e., a location where the magnetic field goes to zero. These are locations where current sheets are formed and magnetic reconnection can develop. Starting from this configuration, we simulate consecutive CMEs, where the first one is driven through shearing motions at the solar surface and the second is a stealth eruption. We analyse the parameter range that allows the stealth CME to occur, which will lead to a better understanding of its triggering mechanism and improve the forecasting of the geomagnetic impact of stealth eruptions.

30 Entropy Conservation, Stability, and Numerical Partial Differential Equations

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We outline the mathematical entropy analysis of the ideal magnetohydrodynamic (MHD) equations. The discussion on the continuous level highlights the strong link between entropy conservation and the divergence-free condition on the magnetic fields, $\nabla \cdot \vec{B} = 0$. With a particular non-conservative added to the system, proportional to the divergence-free condition, it is possible to guarantee entropy conservation. The entropy analysis is then mimicked on the discrete level in the context of finite volume methods to create a numerical approximation that remains consistent to the second law of thermodynamics. The entropy conservative numerical flux acts as a baseline approximation to which dissipation is added. Special attention is paid to the construction and evaluation of the dissipation term, at some mean state, in order that the numerical approximation remains robust for a wide variety of flow configurations. So, entropy is conserved in the semi-discrete approximation for continuous solutions and dissipates for discontinuous solutions. We use several standard numerical tests to demonstrate the theoretical findings.

31 Axial magnetic field effect on silicon melt

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Time: Thu, 11:55–12:15

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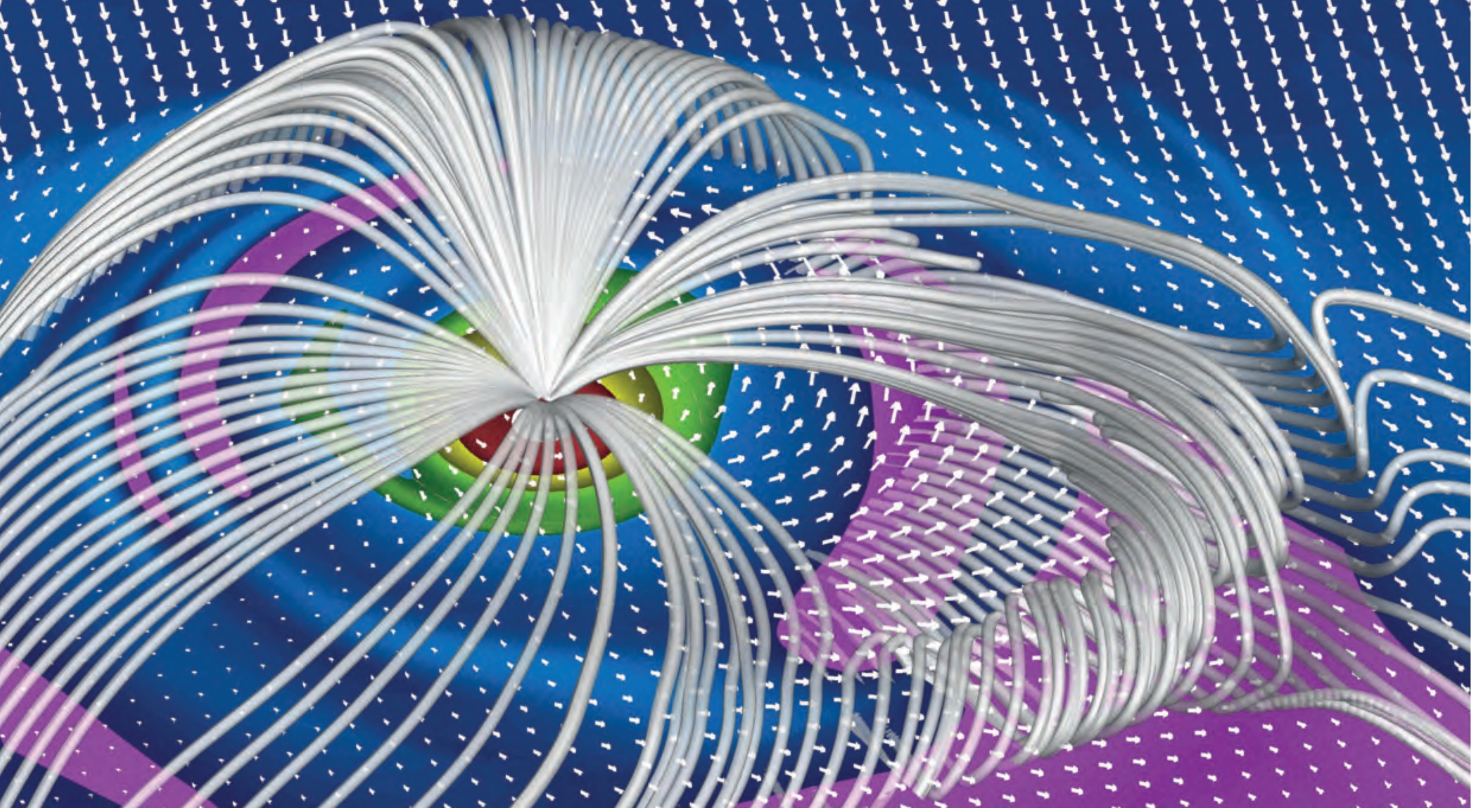
The effect of axial magnetic field of different intensities on melt and temperature field in a silicon melt is investigated. The melt flow and temperature are described by the three-dimensional time-dependent MHD equations of momentum and heat conservation taking into account the Boussinesq approximation for an incompressible Newtonian fluid. The influence of the steady magnetic field is considered by the Lorentz force intensity in the Navier–Stokes equations. In addition to the steady, uniform magnetic field produced by a solenoid an induced magnetic field is produced by an electric current in the melt. The characteristic ratio of the induced magnetic field to the applied one is the magnetic Reynolds number, $R_m = \mu_m \sigma U L$, where μ_m and σ are the magnetic permeability and the electrical conductivity of the silicon melt respectively, U is a typical velocity scale and L is a typical length scale associated with the velocity field. R_m is significantly small than unity. The induced magnetic field can thus be neglected and the induction equation reduces to the same form as in a fluid at rest.

A gradual increasing of the axial magnetic field intensity constitutes an efficient mains to avoid thermal shocks within the silicon melt. A critical axial magnetic field strength is found to be sufficient to ensure flow, temperature fields homogenization accompanied by a considerable weakening of buoyancy cell intensity.



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