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Anisotropic dynamos

Thierry Alboussiere, Kamel Drif and Franck Plunian

With materials of uniform and isotropic electrical conductivity, it is rather complicated to find a configuration suitable for dynamo action. Cowling and his anti-dynamo theorems are to blame for that. However, if we consider materials with anisotropic conductivity, we escape its conclusions and we can obtain dynamo action with a 2D planar velocity field or a dynamo with an axisymmetric magnetic field. We first consider a configuration of a plate of finite thickness sliding on top of another one. Both plates are made of an anisotropic material with two directions of large electrical conductivity and one direction of low electrical conductivity. With a suitable orientation of the anisotropic materials, we have been able to derive analytically the value of the critical magnetic Reynolds number for dynamo action. Interestingly, the derivation is quite elementary as the eigenvectors are expressed as the sum of four exponential functions. Secondly, we consider a cylindrical thick wall rotating inside another one, both with anisotropic electrical conductivity. This is just an axisymmetric version of our previous configuration and can produce an axisymmetrical magnetic field sustained by dynamo action.

Exciting news from the disc dynamo experiment with liquid metal contact

Raul Alejandro Avalos-Zuñiga, Janis Priede, Carla Elizabeth Bello-Morales, Juan Adrian Perez-Orozco

We present experimental new results from the homopolar disc dynamo facility constructed at CICATA-Queretaro in Mexico. The device consists of a flat, multi-arm spiral coil, which is placed above a fast-spinning metal disc and connected to the latter by sliding liquid-metal electrical contacts. Theoretically, self-excitation of the magnetic field was expected at the critical magnetic Reynolds number $\mathrm{Rm} \sim 36$, which corresponds to a critical rotation rate of about 8.3 Hz. We measured the magnetic field above the disc and the voltage drop on the coil for a rotation rate up to 6.7 Hz. We detected a strong amplification of the seed magnetic field so that the Lorentz force breaks the rotating disc. The initial amplification of the magnetic field was observed for a rotation rate around 5.8 Hz. The experimental results show dynamo effect for rotation rates below the predicted by the theoretical calculations. The liquid-metal of the outer contact degraded after some minutes of the operation losing its good conducting properties.

Experimental protoype of an AC MHD generator

Juan Adrian Perez-Orozco, **Raul Alejandro Avalos-Zuñiga**, and Sergio Cuevas Garcia

We present an experimental prototype of an AC MHD generator which uses liquid GaInSn as working fluid. The device consists of three parallel MHD transducers where the liquid metal oscillates harmonically with frequencies ranging from 0.3 to 2 Hz and amplitudes ranging from 5 to 25 mm. Each transducer is composed of a rectangular channel of 12 cm long, 15 mm width and 3 mm thick, and two parallel neodymium magnets with magnetic field intensity of 0.1 Tesla on their surfaces. The prototype is tested with an external load of the same internal resistance of the transducer, that is, for a load factor of 0.5. We measured the induced total current and voltage on the external load for several frequencies and amplitudes of the oscillating motion. The maximum value measured for the induced current was around 15 A with a total electrical power of around 10 mW. The measurements were compared with a simplified theoretical model of the AC MHD generator.

Simulations of decaying MHD turbulence in a flat duct

O. Zikanov, D. Krasnov, **T. Boeck**, and S. Sukoriansky

MHD turbulence in a duct emanating from a honeycomb section is studied via direct numerical simulations. The simulations explain the curious, experimentally observed high-amplitude velocity fluctuations that appear far downstream when the exit from the honeycomb is located within the magnetic field. They are caused by the large-scale quasi-two-dimensional structures forming in the flow at the initial stages of the decay and surviving the magnetic suppression. Turbulence properties and their spatial evolutions are also examined.

Sense or nonsense - Liquid Metal Batteries

Andris Bojarevics

We are trying to design an experimental model to check the "rotating wave" instability in a model someway similar to a liquid metal battery. The presentation would simply ask for ideas and "outsider" viewpoint.
Other point for open discussion – is there any sense to consider the liquid metal batteries as a commercially feasible solution since stored energy to weight factor is not too promising, efficiency of battery seems miserable?

Validation of the analytical criterion for MHD stability in aluminium cells and liquid metal batteries

Valdis Bojarevics and A. Tucs

Industrial aluminium electrolytic production cells are highly optimized for magnetic field and electric current distribution in order to avoid MHD instabilities, increase the current efficiency and to maintain a stable electrolytic process during normal operation. A deeper insight to the basic mechanisms of the MHD instability has the potential to unravel better ways to estimate the onset of instability using relatively simple analytical expressions suitable as engineering tools for the safe cell design. The majority of the previously published theoretical models are restricted to the case when the wave damping is completely neglected and the magnetic field is approximated as an average constant vertical magnetic field B_z. The assumption of inviscid fluid dynamics and the constant uniform magnetic field gives a very low value of the critical magnetic field, which is well below the average field observed in the real cells. The inclusion of the long gravity wave damping in the model similar to the aluminium cells was recently accomplished within a related problem of the MHD stability in large scale liquid metal batteries [1]. The derived criterion is applied to the previously published cases of theoretically derived MHD stability models and finally to the commercial cell where the detailed stability measurements are available [2]. The analytical criterion predictions are summarised for the most sensitive combination set of the interacting wave modes. For the case of the commercial Trimet cell the oscillation frequency 0.0254 Hz is observed in the experiment [2], which matches reasonably well to the numerically computed 0.0259 Hz, while the instability onset frequency according to the new analytical criterion is expected to be the result of the gravity mode $(1;1)+(2;0)$ interaction, giving the instability onset at 0.0253 Hz. The new criterion includes the dependence on the cell geometry (the horizontal aspect ratio, depth of the liquid layers), the electrical conductivities and densities of the liquids, and the magnetic field distribution.

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Experimental confirmation of additional magnetohydrodynamic pressure drop at junctions between electrically insulating flow channel inserts

L. Bühler, H.-J. Brinkmann, C.Koehly

In magnetohydrodynamic (MHD) liquid metal flows through electrically conducting pipes and ducts, flow-induced electric currents and resulting Lorentz forces are high since currents may shortcut along well-conducting walls. Electrically insulating flow channel inserts (FCI) decouple electrically the liquid metal flow from the well-conducting walls. This reduces currents and associated Lorentz forces that are responsible for the major contribution to pressure drop in ducts of liquid metal blankets for fusion reactors. Due to manufacturing restrictions, FCIs can be produced only in pieces of finite length, so that several samples have to be placed in series in the long channels of a blanket. This leads to the presence of gaps between the inserts, namely to local interruptions of the electrical insulation, thus providing local shortcuts for currents. A theoretical analysis of 3D MHD effects at junctions between FCIs shows strong modifications of velocity profiles and locally increased pressure gradients (presentation of theoretical work at previous MHD-Days). The present work focuses on the experimental confirmation of previous theoretical predictions. For experimental investigations of 3D effects at junctions between FCIs, a test section has been designed, manufactured and equipped with FCIs. Experiments have been performed in the MEKKA facility at the Karlsruhe Institute of Technology (KIT) using NaK as a model fluid. The present experimental study shows the benefits of FCIs for pressure drop reduction in fully developed flows and quantifies the deterioration of pressure drop reduction by the presence of uninsulated gaps between FCIs.

Acknowledgment: This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Towards a 2D acoustic travel time tomography in rotating flows

Fabian Burmann, Jerome Noir, and Andrew Jackson

Many common techniques in flow diagnostics rely on the presence of reflectors in the fluid, either for light or acoustic waves. These methods fail to operate when e.g. centrifugal or gravitational acceleration becomes significant, leading to a rarefaction of scatterers in the fluid, as for instance in rapidly rotating fluids. Such conditions will occur in the upcoming liquid sodium experiment SpiNaCh, currently under construction at ETH Zurich. In this study we present our first steps based on the well established time of flight principle (TOF) to perform velocity measurements in the absence of scattering particles. We compare two different acquisition approaches, a high end system based on lock in amplification and a low-cost system based on a commercialy available Texas Instruments evaluation board. A further goal of the project is the development towards a two dimensional time of flight tomography.

Large-scale oscillatory dynamos in rotating plane layer convection: understanding the mean electromotive force

P.J. Bushby, P.J. Käpylä, Y. Masada, A. Brandenburg, B. Favier, C. Guervilly, M.J. Käpylä

Focusing upon a model of compressible convection in a Cartesian domain, rotating about the vertical axis, I will describe numerical simulations of dynamo action in the rapidly rotating regime. Whilst the magnetic field is weak, the flow is dominated by a large-scale vortex. This large-scale flow is suppressed once the field becomes dynamically significant. The resultant dynamo has a strong, large-scale horizontal component which oscillates over long (ohmic) time-scales. I will discuss the underlying dynamo mechanism, focusing particularly upon determining the dominant contributions to the mean electromotive force. I will also describe the evolution of the kinetic and magnetic helicity in the system and the extent to which these quantities can be used to understand the dynamo.

Parametric study of torus instability threshold

Jun Chen, Bernhard Kliem, Rui Liu

Utilizing the analytical model of Titov & Demomulin (1999) to set the current channel, we studied the thresholds of torus instability for a range of different geometries and external toroidal field strengths. There are 4 parameters that have been adjusted: radius of the current channel, footpoint distance of the current channel, strength of an line current under the photosphere, sunspot distance. Sunspots distance determines the distribution of decay index, then determines the torus stability threshold. We found that the decay index increases with the radius of the current channel, decreases with the strength of the line current, and does not significantly change with the footpoint distance of the current channel.

Subcritical convection driven dynamos at low Ekman number

Robert G. Cooper, Celine Guervilly, Paul J. Bushby

We study Cartesian, Boussinesq convection driven dynamos at rapid rotation (low Ekman numbers), focussing on subcritical dynamo action. We will present recent results where we aim to further explore the parameter space at Rayleigh numbers below the onset of convection, expanding the work of Stellmach & Hansen (2004). Supercritical dynamo action is able to generate a strong, large-scale magnetic field which we are then able to extend subcritically, sustaining dynamo action below convective onset.

Gauss linking number and magnetic helicity

Antonio Ferriz-Mas and Mitch Berger

The linking number or "Verschlingungszahl" is an integer invariant that describes the linking of two closed curves in 3-D space. It was introduced by Gauss in the form of a double line integral and it is one of the oldest topological results.
In this talk I will show, using Differential Geometry, that the linking number and Gauss' double line integral are at the heart of the definition of helicity, a key concept in Topological Fluid Mechanics with wide applications in solar magnetism.

Anisotropic beta effect in rotating magnetoconvection study

Enrico Filippi, Jozef Brestenský , and Tomáš Šoltís

The Earth's Fluid Core is driven into motion by buoyancy forces so strongly that the flow and field are turbulent, fluctuating on many length and time scales, as it is accepted by the most of geophysicists. This turbulence may cause some phenomena which influence the Core dynamics. The beta-effect, even an anisotropic one, is one possible result of the turbulence. So, it is very interesting to study how anisotropic diffusion phenomena work in the Geodynamo models or at least in linear Rotating Magnetoconvection models in horizontal plane layer with gravity and rotation axis in vertical direction and magnetic field in horizontal direction. In this regard in our models we introduce anisotropy at least into one diffusive coefficient (viscosity, thermal and magnetic diffusivity) in the simplest possible way. Corresponding anisotropic coefficients are diagonal tensors with two equal components different from the third one. All possible combinations of mixed isotropic and anisotropic diffusivities are studied and compared. Further, we analyze two distinct kinds of anisotropy, Stratification Anisotropy - SA, determined by direction of single gravity (buoyancy) force and Braginsky-Meytlis one BM, determined by two directions magnetic field and rotation axis. SA preserves and BM brakes a horizontal isotropy in the models. The system described by these models is prone to instabilities. We present in great depth only the stationary modes of instabilities. Arising modes of instabilities depend on input parameters. The BM anisotropy modes are very sensitive to parameters. The main result is that different anisotropy cases of diffusive coefficients may crucially affect the Geodynamo processes. We strongly believe that the results of these studies can be a challenge to prepare experiments to study more complex beta-effect than the isotropic one.

Non-linear non-localities in Babcock-Leighton dynamos, a solution to solar activity?

Yori Fournier, Rainer Arlt, Detlev Elstner

The solar dynamo is often attributed to the Babcock-Leighton mechanism in which magnetic flux tubes rise to the surface, turn into poloidal flux loops and eventually contribute to the global poloidal field of the Sun. However, in order to reproduce a solar-like butterfly diagram, such dynamos require low diffusivities at the bottom of the convection zone, and typically consider the rise of the flux tubes to be instantaneous. In this talk, we present mean-field Babcock-Leighton dynamos employing rise times obtained from direct numerical simulations of rising magnetic flux tubes. Found to be non-linearly depending on the large scale field, the rise time is introduced as a delay in the source term of the poloidal mean-field. The delay acts as a non-linear temporal non-locality. The parameter study we conducted led to the identification of an unknown dynamo regime which self-saturates, exhibits solar-like cycles and recovers the solar-like butterfly diagram in the diffusive regime.

Intermittency and multifractality of growth of weak magnetic fields in compressible turbulence

Itzhak Fouxon and Michael Mond

We study the amplification of small initial fluctuations of magnetic field by compressible turbulence. We stress that there are two types of intermittency of the growing field. One type is due to non-linear dependence of the growth exponent of the magnetic field on the order of the field moment. This corresponds to strongly inhomogeneous growth with non-constant growth exponent in space. This type of intermittency is present already in the incompressible case of zero Mach number where it is known in the regime of large magnetic Prandtl numbers. We demonstrate that this type of intermittency can become dramatic at finite compressibility of the flow where the field may decay almost everywhere and yet the magnetic energy grows due to rare regions of strong growth that disappear with time exponentially fast. We demonstrate that this type of intermittency must also occur at small Prandtl numbers since scaling exponent of the flow is a regular perturbation in the growth problem. We use the Kazantsev-Kraichnan model for the demonstration. Other type of intermittency holds only above a critical Mach number. The magnetic field can be written as a product of the natural measure and a growing vector amplitude field. The former is multifractal in the supersonic inertial range where eddy velocity of turbulence is faster than the speed of sound. The growing magnetic field has thus two-fold multifractality: the multifractality of its spatial support and the multifractality of distribution of growth exponents on that support. This phenomenon could not be captured by studies that consider only the pair-correlation function of the magnetic field. Finally we consider the impact of the sonic scale on the growth. That scale divides the inertial interval in two ranges. Below that scale the eddies are slower than sound and the growth is as in incompressible flow. In the supersonic range above that scale the growth is slowed by finite compressibility. The question then is what is the growth rate of the magnetic field in the whole inertial range. The above considerations point to difficulties in accurate experimental as well as numerical detection of the magnetic field structures.

MHD turbulence in spin-down flows of liquid metals

Peter Frick and I. Mizeva

Intense spin-down flows allow one to reach high magnetic Reynolds numbers in relatively small laboratory setups using moderate mass of liquid metals. The spin-down flow in toroidal channels was the first flow configuration used for studying dynamo effects in non-stationary flows. In this paper, we estimate the effect of small-scale dynamo in liquid metal spin-down flows realized in laboratory experiments (Denisov et al., JETP Letters, 88, 2008; Frick et al., PRL, 105, 2010; Noskov et al., PRE, 85, 2012). Our simulations confirm the conclusion that the dynamo effects observed in gallium experiments are weak - a slight burst of small-scale magnetic energy arises only at the highest available rotation velocity of the channel. In sodium flows, the induction effects are quite strong - an essential part of kinetic energy of sodium spin-down flows is converted into magnetic energy and dissipates due the Joule heat losses. We have extended our simulations beyond the capabilities of existing laboratory facilities and examined the spin-down flows at the channel rotation velocity above 50 rps. It has been found that 100 rps could be enough to reach the equipartition of magnetic and kinetic spectral power density at the lowest wave numbers (largest scales), whereas at 200 rps the intensity of the magnetic field becomes comparable to the intensity of velocity field fluctuations. We have also studied the influence of the magnetic Prandtl number on the efficiency of small-scale dynamo in spin-down flows. In the experimental flows, the small-scale dynamo remains in a quasi-kinematic regime, and magnetic energy is mainly dissipated at the same scale, wherein it is converted from kinetic energy. The real small-scale dynamo starts to operate at $\mathrm{Pm} > 0.0001$, and the inertial range of the magnetic energy spectrum appears. Thereupon the energy dissipation is postponed to a later time and smaller scales, and the peak of turbulent energy (both kinetic and magnetic) slightly increases with Pm.

An analytical example of the strong-field scaling regime for dynamo saturation

Basile Gallet, K. Seshasayana

I will present analytical examples of fluid dynamos that saturate through the action of the Coriolis and inertial terms of the Navier-Stokes equation. The flow is driven by a body force and is subject to global rotation and uniform sweeping velocity. The model can be studied down to arbitrarily low viscosity and naturally leads to the strong-field scaling regime for the magnetic energy produced above threshold: the magnetic energy is proportional to the global rotation rate and independent of molecular viscosity.

Hall MHD turbulence and the solar wind

Sebastien Galtier

Hall MHD is a theoretical paradigm that captures both the MHD behavior at long wavelength and some of the plasma kinetic effects that become important at small-scales due to the decoupling between electron and ion flows. In this talk I will review recent results about heating and wave interactions in Hall MHD turbulence based on analytical and numerical studies. I will explain why this model is relevant to reach a first understanding of solar wind turbulence.

Experiments and simulations on the magnetized spherical Couette problem

Ferran Garcia Gonzales and Frank Stefani

Experiments on the magnetized spherical Couette system are presently being carried out at Helmholtz-Zentrum Dresden-Rossendorf (HZDR). A liquid metal (GaInSn) is confined within two differentially rotating spheres and exposed to a magnetic field parallel to the axis of rotation. Bifurcation diagrams for rotating waves, obtained with continuation methods when only the magnetic field is increased, are presented. This allows us to carefully investigate the time-scales of the nonlinear saturation of the radial jet, return flow, and shear layer instabilities, as found in previous studies. In addition, modulated rotating waves, obtained at secondary bifurcations, are exhaustively studied by means of direct numerical simulations, with main focus on their spatio-temporal symmetries. We find that at moderate differential rotation the modulated rotating waves give rise to several types of chaotic flows, but only for the radial jet instability. With this study we reveal how the flow patterns and time-scales depend on the magnetic field, reproducing thus different physical situations of the HZDR experiments.

Is there a stably-stratified layer in Jupiter? Some constraints from global dynamo models

Thomas Gastine, Johannes Wicht, Lucia Duarte

The Juno spacecraft is currently orbiting Jupiter. Newly available data reveal a complex magnetic field morphology. The dominant dipolar component is accompanied by strong magnetic flux patches and a narrow field belt in the equatorial region. The gravitational sounding also indicates that the fierce surface zonal jets extend thousand kilometers below the cloud level. Those are key signatures of the intricate Jovian internal dynamics.
Jupiter's internal structure comprises an outer layer filled with a mixture of molecular hydrogen and helium where the zonal flows are thought to be driven; and an inner region where hydrogen becomes metallic and dynamo action is expected to sustain the magnetic field. Several recent

ab-initio calculations suggest a more complicated structure with a small intermediate region in which helium and hydrogen would become immiscible.
Integrated dynamical models of Jupiter's internal dynamics encompass several key features of the Jovian structure: an electrical conductivity that strongly varies with radius and transport properties that are relatively close to ab-initio calculations. Those models are quite successful in reproducing many features of the observed Jovian magnetic field. In particular, we attribute the generation of the large-scale dipolar component to a deep-seated distributed dynamo action, while the equatorial belts are formed thanks to the shearing of the poloidal field by the main equatorial jet.
Despite those achievements, 3-D calculations are currently not able to sustain multiple jets as observed on the gas giants. This may indicate that some key physical ingredient is still missing in the current models. To go beyond those limitations, I will present new calculations in which the effects of the hydrogen-helium immiscibility is incorporated by the means of a stably-stratified intermediate layer. I will show that for a sufficient degree of stratification high-latitude jets start to develop in contrast with the fully-convective existing models.

Numerical simulations for the DRESDYN precession dynamo

André Giesecke, Tobias Vogt, Thomas Gundrum, and Frank Stefani

More than 100 years ago, Henri Poincaré in his pioneering study showed that the inviscid base flow in a precessing spheroid is described by a constant vorticity solution, the spin-over mode. Since then there have been repeated discussions whether the geodynamo is driven (or at least influenced) by precession. More recently, precession has also been considered as an important mechanism for the explanation of the ancient lunar dynamo.
Experiments with precessing fluids in cylindrical and in spherical geometry showed that precession indeed is an efficient mechanism to drive substantial flows even on the laboratory scale without making use of propellers or pumps. A precession dynamo experiment is currently under construction within the project DRESDYN (DREsden Sodium facility for DYNamo and thermohydraulic studies) at Helmholtz-Zentrum Dresden-Rossendorf (HZDR) in which a precession driven flow of liquid sodium will be used to drive dynamo action.
Here we address related numerical and experimental examinations in order to identify parameter regions where the onset of magnetic field excitation will be possible. Preliminary kinematic dynamo models using a prescribed flow field from hydrodynamic simulations, exhibit magnetic field excitation at critical magnetic Reynolds numbers around $\mathrm{Rm_c} \approx 430$, which is well within the range of the planned liquid sodium experiment. Our results show that large scale inertial modes excited by precession are able to excite dynamo action when their structure is sufficiently complex, i.e. the forcing is sufficiently strong. More advanced models that take into account the container's finite conductivity show that boundary conditions may play an important role, but the critical magnetic Reynolds number will still be achievable in the planned experiment.

Magnetically-driven oceans in Jovian moons

Christophe Gissinger and Ludovic Petitdemange

During the last decades, data from Galileo space missions has provided strong evidence of subsurface liquid oceans on several moons of Jupiter [1-3]. More recently, observations of water vapor erupting from the ice crust of Europa added more support for the existence of an ocean of salty water beneath the surface of the moon [4,5]. But these observations have also raised many unanswered questions regarding the oceanic motions generated under the ice, or the mechanisms keeping the water in a liquid state. By means of direct numerical simulations of Europa's interior and comparison with observations, we show here that Jupiter's magnetic field has a major influence on the global dynamics of Europa's ocean, and may play a significant role in the heat budget of Jovian moons. We demonstrate that the time-varying magnetic field of the host planet generates a strong retrograde oceanic jet at the equator, while ohmic heating is significantly stronger at the poles, in agreement with the presence of chaos terrain at low latitudes whereas vapor plumes are preferentially found in the polar regions of Europa [6].

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The effect of weak magnetic and thermal diffusion on magnetic buoyancy instability

Marek J. Grądzki and Krzysztof A. Mizerski

Magnetic buoyancy instability in weakly resistive and thermally conductive plasma is an important mechanism of magnetic field expulsion in astrophysical systems. It is often invoked, e.g., in the context of the solar interior. Here, we revisit a problem introduced by Gilman: the short-wavelength linear stability of a plane layer of compressible isothermal and weakly diffusive fluid permeated by a horizontal magnetic field of strength decreasing with height. In this physical setting, we investigate the effect of weak resistivity and weak thermal conductivity on the shortwavelength perturbations, localized in the vertical direction, and show that the presence of diffusion allows to establish the wavelength of the most unstable mode, undetermined in an ideal fluid. When diffusive effects are neglected, the perturbations are amplified at a rate that monotonically increases as the wavelength tends to zero. We demonstrate that, when the resistivity and thermal conduction are introduced, the wavelength of the most unstable perturbation is established and its scaling law with the diffusion parameters depends on gradients of the mean magnetic field, temperature, and density. Three main dynamical regimes are identified. Our analytic results are backed up by a series of numerical solutions. The two-dimensional interchange modes are shown to dominate over three-dimensional ones when the magnetic field and/or temperature gradients are strong enough.

Correlations and energy transfer in compressible isothermal and adiabatic MHD turbulence

Philipp Grete

Compressibility, magnetic fields and turbulence are all thought to be important factors to varying degrees in many astrophysical processes and terrestrial experiments. However, our understanding of their joint effect even in it's simplest description, i.e., compressible magnetohydrodynamic turbulence, is still scarce. One step towards a more comprehensive picture is a better understanding of the governing energy dynamics, e.g., looking at the interplay between kinetic and magnetic energy via different mediators such as advection, magnetic tension or magnetic pressure. Here, we present an extension of established shell-to-shell energy transfer analysis methods to the compressible MHD regime. We apply this analysis to numerical simulations in the subsonic and supersonic regime. This allows us to illustrate how varying degrees of compressibility influence the energy dynamics within and between kinetic and magnetic energy reservoirs. For example, we show that compression acts against a magnetic energy cascade (scale-local magnetic to magnetic energy transfer). Moreover, we present how magnetic tension becomes overall less important with increasing sonic Mach number. Finally, we show how different correlations, for example, the observationally relevant correlation between density and magnetic field strength, are affected by different equations of state.

Interfacial wave dynamics in liquid metal batteries

Gerrit Maik Horstmann, Norbert Weber, Tom Weier

Liquid metal batteries (LMBs) are discussed today as a cheap grid scale energy storage, as required for the deployment of fluctuating renewable energies. LMBs incorporate stratified three-layer fluid systems consisting of two liquid metal electrodes separated by a thin molten salt electrolyte. Due to the large electrical conductivities of the liquid metals, LMBs can be highly susceptible to become unstable by MHD interactions of induced or external magnetic fields with internal cell currents. In particular, interfacial instabilities, widely known from aluminum reduction cells (ARCs), have emerged as to be crucial for the operational safety. In this talk I will introduce a purely hydrodynamical wave experiment allowing to mimic Lorentz force-driven interfacial wave motion as it can be present in ARC and LMB models. A cylindrical container filled with two or three inmiscible liquids is placed on a shaking table prescribing circular translations. The resulting centripetal force can excite exactly the same rotational wave mode in the system that is commonly induced by interfacial MHD instabilities. While the instability mechanism itself is not captured by the experiments, different practically important aspects of responding wave dynamics can be studied. The talk will focus on three different issues: viscous damping, contact line dynamics and three-layer interfacial wave coupling. All these effects are still far from being understood in the context of interfacial MHD instabilities but can largely affect stability onsets and the evolving wave dynamics.

Dynamo action in rapidly rotating convection with no inertia

David Hughes

It is generally believed that the Earth's dynamo operates in the strong field regime, in which the nature of the convection is very different to that in the absence of magnetic field. That said, accessing the strong field regime computationally has proven difficult. Here we consider dynamos driven by rotating convection in which inertia is neglected, but viscous terms are retained. This system supports both weak and strong field dynamos, which can be analysed by exploiting the linearity (with no inertia) of the momentum equation. We also address the issue of Taylor's constraint and how closely this is satisfied in a system with ostensibly small viscosity.

Torsional waves in the Earth's core in the presence of topography at the boundary

Dominique Jault, F. Gerick, and J. Noir

Both geostrophic and quasi-geostrophic flows have been shown to arise naturally in simulations of the geodynamo outside the cylindrical surface tangent to the inner core. They can be continued from the Earth's core surface to its interior. Dynamically consistent depth-averaged equations can be derived from a three-dimensional Lagrangian by restricting the fluid elements to move in columns. For axisymmetric bodies, conservation of angular momentum (when the boundary is electrically insulating and stress-free) results from the invariance of the Lagrangian under rotational symmetry. In the geophysical case, torsional waves, which are akin to Alfvén waves, have been shown to carry angular momentum. In a spherical shell, torsional waves consist exclusively of geostrophic motions. In the presence of topography at the boundary, the net torque exerted by the geostrophic pressure on the solid container is zero. We will show, however, that when the fluid volume is not symmetrical with respect to the rotation axis, torsional waves also involve non geostrophic motions. As a result, in the course of the propagation of these waves, the fluid pressure exerts a torque on the container and there is exchange of angular momentum between the fluid and the solid.

2D MHD simulations of oscillations excited by plasmoids during magnetic reconnection

Petr Jelinek and Marian Karlicky

Using the FLASH code, which solves the full set of the two-dimensional (2-D) non-ideal (resistive) time dependent magnetohydrodynamic (MHD) equations, we study processes during the magnetic reconnection in a vertical gravitationally stratified current sheet. We show that during these processes, which correspond to processes in solar flares, plasmoids are formed due to the tearing mode instability of the current sheet. These plasmoids move upwards or downwards along the vertical current sheet, and some of them merge into larger plasmoids. We study the density and temperature structure of these plasmoids and their time evolution in details. It is also shown that the merging process of plasmoid with the flare arcade is a complex process as presented by complex density and temperature structures of the oscillating arcade. Moreover, all these processes are associated with magnetoacoustic waves produced by the motion and merging of plasmoids.

Semi-global convection-driven dynamos with Kramers opacity law

Petri Käpylä

We present first results from three-dimensional, rotating, magnetohydrodynamic (MHD), simulations of stratified convection in a semi-global wedge geometry applying a Kramers-type opacity law. Earlier Cartesian studies indicated that the depth of the convection zone is not a priori fixed in models with the Kramers opacity law as it is sensitive to temperature and density. Furthermore, a substantial portion of the convective zone is stably stratified according to the Schwarzschild criterion [1,2].
The stably stratified layers can be helpful in breaking the Taylor-Proudman balance in simulations to yield more realistic rotation profiles [3]. Another possible effect is a kinetic helicity inversion that can change the propagation direction of the latitudinal dynamo wave [4].
The new rotating MHD simulations in spherical coordinates produce stably stratified, yet convective, layers in the deep parts of the convection zone, similar to the previous non-rotating hydrodynamic models in Cartesian geometry [5]. The rotation profiles show clear deviations from the Taylor-Proudman state altough they are also sensitive to thermodynamic boundary conditions [6]. We find that the dynamo solutions are sensitive to subtle changes to the hydrodynamics such that quasi-stationary and oscillatory solutions are realized with relatively small changes in the depths of the convection zone and stably stratified layers.

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Large Scale vortices in tilted rotating convection

Mouloud Kessar, Celine Guervilly, David W. Hughes, E. Kersale

The JUNO probe has been providing us with astonishing pictures and datas from Jupiter over the last few years. One can easily spot large scale vortices near the poles. Recent work (Guervilly et al, JFM, 2014) has been able to perform simulations of rotating Rayleigh-Benard convection exhibiting large scale vortices (LSV). They found that for a given Taylor number, those LSV can exist at the pole only for a range of Rayleigh numbers. More recently, they have studied the influence of aspect ratio on those LSV. They found out that even a small breaking of symmetries could lead to the loss of LSV.
Another way to break symmetries would be to introduce an angle between the rotation and the gravity axis. In a study based on the Boussinesq approximation von Hardenberg et al (PRL 2015) have performed simulations showing the absence of LSV at the equator. One could wonder how far away from the pole the LSV can be observed. Chan (Astronomical Notes 2007) have resorted to a fully compressible code to perform simulations of tilted rotating convection. LSV were observed away from the pole. The also managed to obverse large scale anti-cyclonic events, where Guervilly et al (JFM, 2014) were able to observe only cyclonic large scale events. To have a more accurate understanding of the behaviour of LSV, we have started to study the influence of the introduction of an angle between the rotation and gravity axis on those LSV under a Boussinesq approximation. We started from one of Guervilly et al, JFM, 2014 configuration, and performed simulations for different angles. At $\pi/8$ and $\pi/4$ away from the pole, we can still observe LSV, similar to the ones observed at the pole. So far, no large scale anti-cyclonic events were found. When reaching $3\pi/8$ away from the pole, the LSV have disappeared, but jets are clearly visible.

Determination of the level of Magnesium in a Titanium reduction reactor

Ruslan Khalilov, N. Krauter, F. Stefani, P. Frick, A. Pavlinov, I. Kolesnichenko, A. Teimurazov

Titanium is produced by the reduction of titanium chloride with reactive metals such as magnesium. This process is called the Kroll method. Magnesium reduction of titanium chloride proceeds in a reactor filled with liquid magnesium and placed in a special furnace. Liquid titanium is supplied from the top to the liquid magnesium surface where the exothermic reaction of titanium reduction takes place. This reaction produces sponge titanium which sinks down to the bottom of the reactor. Technological difficulty that arises in this case concerns the control of the level of magnesium level during the entire titanium reduction process. Induction measurement of the level of magnesium in a reactor is a complicated problem because the effectiveness of traditional measurement techniques decreases due to the formation of titanium sponge rings (garnissage) in the reactor. In this paper, we present a new method for determining the level of magnesium with the aid of the available equipment for reduction titanium. The proposed approach takes into account the presence of sponge rings with unknown geometry and conductivity (garnissage) and offers a solution to the inverse problem using the search table method based on the numerical solution of the induction problem with several tens of thousands combinations of parameters. We describe the results of numerical studies and laboratory experiments aimed to simulate the above mentioned process.

Instead of the reactor, we used a stainless steel pipe embraced by the system of coils. Reactor geometry and arrangement of generating and measuring coils were given on a reduced scale. Liquid magnesium of different heights was represented by an aluminum cylinder. As a garnissage, we used rings made of the materials having different electrical conductivity and located on the internal surface of the pipe. The frequency of the current in the coils varied so that the depth of magnetic field penetration could be changed. Experiments allowed us to evaluate the measurement accuracy and the sensitivity of the proposed method to systematic and random noise.

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Singular diffusionless limits of double-diffusive instabilities in MHD

Oleg Kirillov

We study local instabilities of a differentially rotating viscous flow of electrically conducting incompressible fluid subject to an external azimuthal magnetic field. In the presence of the magnetic field, the hydrodynamically stable flow can demonstrate non-axisymmetric azimuthal magnetorotational instability (AMRI) both in the diffusionless case and in the double-diffusive case with viscous and ohmic dissipation. Performing stability analysis of amplitude transport equations of short-wavelength approximation, we find that the threshold of the diffusionless AMRI via the Hamilton-Hopf bifurcation is a singular limit of the thresholds of the viscous and resistive AMRI corresponding to the dissipative Hopf bifurcation and manifests itself as the Whitney umbrella singular point. A smooth transition between the two types of instabilities is possible only if the magnetic Prandtl number is equal to unity, $\mathrm{Pm} = 1$. At a fixed Pm non equal to unity, the threshold of the double-diffusive AMRI is displaced by finite distance in the parameter space with respect to the diffusionless case even in the zero dissipation limit. The complete neutral stability surface contains three Whitney umbrella singular points and two mutually orthogonal intervals of self-intersection. At these singularities, the double-diffusive system reduces to a marginally stable system which is either Hamiltonian or parity-time-symmetric.

Pressure-driven 3D liquid metal MHD flow in a dual-coolant lead lithium blanket

V. Klüber, L. Bühler, C. Mistrangelo

In a future fusion DEMOnstration power reactor, so-called blankets foreseen as plasma facing components, are supposed to extract heat, shield neutron radiation and breed the fuel component tritium, which is essential for the fusion reaction. The dual coolant lead lithium (DCLL) blanket concept deploys relatively high liquid metal velocities through blanket ducts for efficient heat removal. The movement of the electrically conducting fluid in the strong magnetic field that confines the fusion plasma induces electric currents, which are responsible for strong Lorentz forces, high magnetohydrodynamic (MHD) pressure drop, and substantial modifications of velocity profiles compared to conventional hydrodynamic flow.
In order to support design activities of DCLL blankets, 3D MHD liquid metal flows are investigated by finite volume techniques for one representative blanket segment. The derived numerical model takes into account that electric currents may close along the conductive duct wall. In a first series, simulations have been performed for pressure driven forced flow up to fusion relevant conditions in terms of Hartmann and Reynolds numbers. Numerical results confirm that with increasing magnetic field the flow behaves as being quasi inertialess and inviscid with a major balance of forces between pressure and Lorentz force.
The presented results should be considered as a first step in a series of comprehensive analyses. Future work will take into account in addition volumetric heating, buoyancy effects and oblique magnetic fields.

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Liquid metal flow in channel with helical magnetic field

Ilia Kolesnichenko, S. Mandrykin, R. Khalilov, P. Frick

Interactions of the magnetic field with the turbulent flow of a conducting fluid, characterized by a significant level of helicity, play a key role in many MHD dynamo models. Most mean-field dynamo models include the so-called alpha-effect, which is the generation of an electromotive force directed along the large-scale magnetic field in the turbulent flow with nonzero hydrodynamic helicity. The resulting current is aligned with the applied magnetic field, and the total magnetic field becomes helical. We study the opposite case, where the conducting fluid flows in a helical magnetic field. It is assumed that the magnetic field with nonzero current helicity can generate the vorticity directed along the velocity vector in the flow of the conducting fluid, thus producing the hydrodynamic helicity. Our aim is to prove this phenomenon experimentally, which is why this particular setup configuration was chosen. It consists of cylindrical MHD channel, in which the helical magnetic field is generated by a special magnetic system. The magnetic system is a set of copper rods with passing electric current and Helmholtz coils. For this configuration of the MHD channel a numerical study was performed, which has shown that in the case when the conducting fluid flows through the region with the magnetic field with non-zero current helicity there occurs azimuthal velocity component of the flow, whose hydrodynamic helicity becomes non-zero. In one of the MHD channel configurations the electro-vortex flow arises. It was studied both numerically and experimentally as a separate task. With help of an ultrasonic Doppler velocimeter, the velocity profiles of gallium alloy flow were obtained for different electric current values and for different locations of the sensors. It is shown that electro-vortex flow appears in all considered ranges of the electric current. The flow velocities are relatively low, but the flows themselves are non-stationary at all considered parameters. The characteristics of fluctuations are determined depending on the applied current. Based on these results, an MHD channel has been designed and manufactured. It is planned to be embedded into the sodium loop for further experimental research.

This study was supported by the project RSF–18–41–06201.

Disruption of an Isolated Vortex by the Magnetic Flux Expulsion

Todor Kondic, Stephen Griffiths, David Hughes

A vortex in an electrically conducting fluid may organise magnetic fields, via stretching and reconnection, in highly unstable configurations characterised by magnetic stresses strong enough to disrupt, or even destroy the original vortex. This process of "flux expulsion" is investigated in the context of two-dimensional incompressible MHD using direct numerical simulations of an isolated, decaying vortex threaded by an, initially, homogeneous magnetic field. Depending on the magnetic Reynolds number and the magnitude of the initial magnetic field, three types of behaviour are identified: the kinematic regime that accurately follows the Weiss (1966) prescription, a transitional regime in which vortices are disrupted to a varying degree and a fully nonlinear regime when the vortical motion is completely destroyed by small-scale instability. Furthermore, it is demonstrated that the scaling derived by Mak et al. (2017) captures well the mechanics of the transition to the fully disrupted regime.

The turbulent magnetic pressure in rotating convection

Manfred Küker and Günther Rüdiger

The Negative Magnetic Pressure Instability has been proposed as an alternative mechanism to the rise of magnetic fluxtubes caused by buoyancy. It is based on the circumstance that the turbulent contribution to the magnetic pressure can be negative under certain circumstances. We have carried out box simulations of rotating convection to study the conditions for the existence of this effect in rotating convection with a vertical background magnetic field.

Discretization of Navier-Stokes equations with spectral methods

A. Bergeon, **Joris Labarbe**, F. Muller

The major difficulty of integrating the Navier-Stokes equation for incompressible flows in primitive variables comes from velocity-pressure coupling through incompressibility. The method we use is a so-called splitting method that splits a time step and allows decoupling velocity and pressure calculation problems. To spatially discretize the fields, we have used a spectral method in which the fields are approximated by a high order interpolant through the Gauss-Lobatto-Legendre points in the two directions.
We use the code to investigate by direct numerical simulation the onset of double diffusive convection in two-dimensional enclosures driven by opposing horizontal temperature and concentration gradients with a particular focus on the formation of (stable) spatially localized solutions.

MHD heat transfer of liquid metals

I. A. Belyaev, **Yaroslav Listratov**, E. V. Sviridov, V. G. Sviridov

Nuclear power plants and hybrid thermonuclear reactors with molten salt and liquid metal are currently considered as priority areas of nuclear energy. The development and creation of such installations is constrained, among other things, by insufficient study of the heat of hydraulic characteristics of coolants in the conditions of combined effects of high heat fluxes and magnetic fields, which leads to an overestimated conservatism and a decrease in the efficiency and economy of the proposed solutions. The direct study of full-scale objects is impossible, so the studies are carried out both by numerical simulation and using experimental laboratory facilities with model fluids. In recent years, an automated experimental complex RK-3 (HELMEF) was created, on which the conditions close to the tokamak reactor were realized: the presence of strong magnetic fields, high homogeneous and heterogeneous heat flows, different mutual orientations of the magnetic field, gravity, flow directions. Complex experimental and numerical data on three-dimensional temperature fields, temperature fluctuation characteristics in a wide range of operating parameters are obtained. As a result of the data analysis, it is possible to determine the area of existence of quasi-periodic temperature fluctuations in heat exchangers, to estimate the potential effect of temperature inhomogeneities on the structure as a whole, and to develop engineering methods for taking into account the effect of MHD heat exchange effects necessary for the design of elements of promising energetics devices.

This work was supported by RSF project 14-50-00124.

New axisymmetric helical magnetorotational instability in dissipative rotating flows with positive shear

George Mamatsashvili, F. Stefani, R. Hollerbach, G. Rüdiger

We present a new type of axisymmetric magnetorotational instability which is capable of destabilizing viscous and resistive magnetized flows with radially increasing angular velocity. Using short-wavelength WKB approach, supported by 1D linear stability calculations in Taylor-Couette flow, we show that this instability works only when a combination of axial and azimuthal magnetic fields is applied and when the magnetic Prandtl number is different from one. It might have grave consequences for the stability of the equator-near parts of the solar tachocline, and for the dynamo action in this region.

Inverse cascade of magnetic helicity in MHD turbulence

Melissa D. Menu, S. Galtier, L. Petitdemange

We investigate the impact of a solid-body rotation Ω_0 on the large-scale dynamics of an incompressible magnetohydrodynamic turbulent flow in presence of a background magnetic field B_0. Three-dimensional direct numerical simulations are performed in a periodic box, at unit magnetic Prandtl number and with a forcing at intermediate wavenumber $k_f = 20$. When Ω_0 is aligned with B_0 (tilt angle = 0), inverse transfer is found for the magnetic spectrum at $k < k_f$. The strength of this transfer changes with the Rossby number, the polarisation of the fluctuations and with the tilt angle. These properties are understood as the consequence of an inverse cascade of hybrid helicity which is an inviscid/ideal invariant of this system when $\Omega_0 = 0$. Hybrid helicity emerges, therefore, as a key element for understanding rotating dynamos. Implication of these findings on the origin of the alignment of the magnetic dipole with the rotation axis in planets and stars will be discussed.

Evolution of magnetic field structures in nonlinear MHD dynamos

Daniel Miller

ABC flows are an exact solution to the MHD equation of motion. As such they provide an ideal testing ground for examining changes to the magnetic field during the saturation process. In this seminar I compare how the saturation process affects magnetic field structures in dynamos with and without stagnation points in their forcing.

Mean field dynamo mechanisms in highly conducting fluids

Krzysztof Mizerski

It is well known that a field of random waves in a fluid of non-zero resistivity is capable of exciting a large-scale magnetic field through creation of an electromotive force (EMF) which leads to exponential growth of magnetic energy until the growing Lorentz force reacts back upon the wave field, leading to a saturated state. For highly conducting plasma it is generally found that kinematic fast-dynamos with finite growth rate in the limit of vanishing resistivity, have a pathological structure, non-differentiable wherever they are non-zero; the applicability of fast-dynamo theory to natural physical systems is then questionable. Here we relax the standard simplifying assumptions of stationarity and homogeneity of the background turbulence and introduce new fast-dynamo mechanisms, fully dynamic, that are incorporating the back reaction of the Lorentz force on the flow (hitherto scarcely considered), for which the growing magnetic field remains smooth during the whole dynamo process. This results from a random superposition of waves, perturbed by the magnetic field. Particularly effective are the interactions of 'beating' waves (close-frequency waves) and nonlinear effects in the mean electromotive force leading to very fast amplification of the mean magnetic field. The instability driving and interactions of viscously decaying waves are often vital for fast dynamo action and increase the effectiveness of the herewith introduced and investigated fast dynamo mechanisms. The theory has the potential to be applied to the dynamo generation of magnetic fields in the ionised gas of the early universe, both before and during the process of galaxy formation. In such a plasma, the resistivity is extremely low, giving characteristic diffusion times many orders of magnitude greater than the age of the entire universe and hence negligible. Nevertheless the large-scale galactic magnetic fields and fields of galaxy clusters are observed, thus non-resistive dynamo mechanisms are strongly desirable in this context.

Electro-Vortex flow in Liquid Metal Batteries

Caroline Nore, P. Ziebell Ramos, W. Herreman, L. Cappanera, J.-L. Guermond, N. Weber

We use our multiphase MHD solver SFEMaNS [1-3] to study the generation of flows in (cylindrical) liquid metal batteries due to the Electro-Vortex-Flow (EVF) phenomenon, i.e. the interaction of a non-uniform current with the magnetic field that it generates. First, we discuss the typical intensity and structure of the axisymmetric flow in a liquid metal column covered by many previous studies. After that, we focus on EVF in liquid metal batteries. We discuss the deformation of the electrolyte-liquid metal interfaces caused by EVF and we characterize how EVF helps in mixing the bottom alloy layer.

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The role of fluid flow in heat and mass transport in Liquid Metal Batteries

Paolo Personnettaz, Steffen Landgraf, Michael Nimtz, Norbert Weber, and Tom Weier

Liquid metal batteries (LMBs) are suggested as a promising energy storage technology. An LMB is a three liquid layers concentration cell: two liquid metal electrodes are divided by a molten salt electrolyte. The relatively simple composition and geometry, the occurrence of multi-physics phenomena and the completely liquid nature of the active material have made the LMB an interesting candidate for continuum mechanics studies, ranging from magnetohydrodynamics to transport phenomena, such as Marangoni convection. The cell is in fact subject to a simultaneous transport of charge, heat, mass and momentum together with electrochemical reactions. The fluid flow can be beneficial if it is able to enhance the mixing at the electrolyte interfaces, thereby preventing the formation of intermetallic solid phases. However, a vigorous flow can also be detrimental to the safe operation of the battery, leading to short circuit induced by the rupture of the thin electrolyte layer. In our work the attention is focused on the role of fluid flow in heat and mass transport. Thermally driven convection is investigated in a three layer Li||Bi LMB with an extended version of the VOF solver multiphaseInterFOAM. A relevant flow is discovered in the pure negative electrode, however it is too weak to deform the liquid interface. Moreover mass transfer is studied in the positive electrode with a single-phase CFD solver. The presence of solutal convection is numerically confirmed during the charge of the cell. The flow structures and the effects on cell efficiency are presented, the modeling limitations and the future developments are discussed.

Simulations of convectively-driven stellar dynamos in a stratified spherical shell

Ludovic Petitdemange and R. Raynaud

Observations of low-mass stars reveal a variety of magnetic field topologies ranging from large-scale, axial dipoles to more complex magnetic fields. At the same time, three-dimensional spherical simulations of convectively driven dynamos reproduce a similar diversity, which is commonly obtained either with Boussinesq models or with more realistic models based on the anelastic approximation, which take into account the variation of the density with depth throughout the convection zone. Nevertheless, a conclusion from different anelastic studies is that dipolar solutions seem more difficult to obtain as soon as substantial stratifications are considered. We aim at clarifying this point by investigating in more detail the influence of the density stratification on dipolar dynamos. Stellar dynamos require a complex description of convective motions. Studying this problem numerically remains challenging as the realistic parameter regime is extreme by computational standards. The fluid properties are also characterized in part by the Prandtl number $\mathrm{Pr} = \nu/\kappa$ where ν is the kinematic viscosity and κ is the thermal diffusion. In stars, this number is extremely low, $\mathrm{Pr} < 10^{-3}$. The influence of Pr on the convective motions at the heart of the dynamo is not well understood since most numerical studies are limited to $\mathrm{Pr} = 1$. We rely on a systematic parameter study that allows us to clearly follow the evolution of the stability domain of the dipolar branch as the density stratification and Pr are changed. The impact of both on the dipole collapse is discussed and compared to previous results. In addition, our study allows us to highlight the influence of two important effects, i.e. the rotation period of low-mass stars (with a convective envelope) and their magnetism on the brightness distribution at their surface (gravity darkening).

Plasma column rotation profile control using emissive electrodes

Nicolas Plihon, Victor Desangles, Guillaume Bousselin

Experimental studies of MHD processes at moderate magnetic Prandtl numbers require the use of highly ionized plasmas as electrically conductive medium. A detailed characterization of the control of the rotation profile of a moderately magnetized plasma column (1 m in length, 10 cm in diameter) using large emissive electrodes will be presented. We will show how the shear profile and the velocity amplitude may be controlled using current injection from large emissive cathodes. Extensive plasma parameter measurements allow to compute plasma viscosity and resistivity. These figures show the existence of regimes with magnetic Reynolds numbers of order 0.1.

Torsional Alfvén waves in a dipolar magnetic field: experiments and simulations

Zahia Tigrine, Henri-Claude Nataf, Nathanaël Schaeffer, Philippe Cardin and **Franck Plunian**

Eight years after their discovery in the Earth's core (Gillet et al, 2010), we report on the first experimental evidence of torsional Alfvén waves. In the DTS experiment, a volume of 40 liters of liquid sodium is contained between two spherical shells, a copper inner sphere of radius $R_{\rm in} = 74$ mm and a stainless steel outer sphere of radius $R_{\rm out} = 210$ mm. Both spheres can rotate independently around a common vertical axis. The inner sphere shells a strong permanent magnet. Measured in the equatorial plane, the intensity of the nearly dipolar magnetic field falls from 175 mT at $R_{\rm in}$ to 8 mT at $R_{\rm out}$.
Rotating both the inner and outer spheres at the same frequency f, the Alfvén waves are produced by applying a sudden jerk to the inner sphere. Two cases are reported, without and with global rotation, corresponding respectively to $f = 0$ Hz and $f = 15$ Hz. We measure the propagation of the wave with magnetometers inside a sleeve. It takes only a few hundredths of a second for the wave to travel from the inner to the outer sphere. In order to decipher the behavior of the waves, we perform numerical simulations with the XSHELLS software, using the same parameters as in the experiment, except for the fluid viscosity.
We identify subtle differences in the magnetic field records that differentiate non-torsional from torsional Alfvén waves. We also document differences in the surface electrical potentials linked to the geostrophic nature of fluid velocities when global rotation is present. Though the Alfvén waves are far from being ideal due to their strong dissipation, the experiment reveals interesting properties of fundamental MHD phenomena.

Convection and magnetoconvection in a rotating tangent cylinder

Alban Potherat, K. Aujogue, B. Sreenivasan, F. Debray

We present an experimental study of rotating magnetoconvection in a geometry reproducing the configuration of the Earth's tangent cylinder. The experiment is conducted in a transparent electrolyte subjected to a very high magnetic field. This makes it possible to map the flow by means of Particle Image Velocimetry. We first show that without magnetic field, the confinement exerted by the Taylor-Proudman constraint above the heated "core" leads the convection to behave in many ways as if real walls were present. In particular wall-modes are observed. We then show that imposing a magnetic field changes some of the features of the convection (such as its lengthscale) but that wall modes are still observed. When the convection is about 10 times critical, the magnetoconvection shows a small number of slightly-off-centre anticyclonic vortices.

Instabilities of a liquid metal - electrolyte interface caused by local magnetic fields

A. Wiederhold and **Christian Resagk**

We report about a two-fluid experiment where the behavior of a liquid metal/electrolyte interface is studied. This experiment is a simplified model of a liquid metal battery (LMB) which is a promising device with regard to energy storage and grid stabilization. LMBs generally consist of two liquid metal layers and an electrolyte layer which lies between them. Because hydrodynamic stable interfaces are a key factor for the operation of a LMB, interface deflections caused by local magnetic field, which occures during current flow through the LMB were investigated.

Inverse and direct cascades in geostrophic turbulence

Maxim Reshetnyak and O. Pokhotelov

As is known, the alpha effect in the dynamo theory is responsible for the generation of the large-scale magnetic fields by turbulence. In terms of cascade phenomena, this corresponds to the inverse cascade of the energy, when the energy of small-scale motions is transformed into the energy of a large-scale magnetic field. However, inverse energy cascade exists even in a simpler systems without a magnetic field. Thus, in 2D turbulence, two cascades are simultaneously observed: the inverse cascade of kinetic energy and the direct cascade of enstrophy [1]. The inverse cascade of kinetic energy is also observed in 3D rotating turbulence, where instead of the cascade of enstrophy, a cascade of the kinetic helicity, which is also direct, is considered [2]. At the moment, a large number of confirmations of this phenomenon have appeared both in numerical simulations [2] as well as in a physical experiment [3]. We present an analogue of the Fjortoft theorem for

3D rapidly rotating turbulence [4], which gives a simple explanation of the both cascades in the rapidly rotating turbulence. The considered regimes are typical for the planetary cores and rapidly rotating convective zones of the stars.

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Dynamo action of magnetized Taylor-Couette flows

Günther Rüdiger and Manfred Schultz

The stability of conducting Taylor-Couette flows with quasi-Kepler rotation law is considered if it contains a toroidal magnetic field due to a homogeneous axial electric current between the cylinders ("z-pinch"). Such MHD flows are unstable against nonaxisymmetric perturbations which transport angular momentum and originate electromotive force. If both degenerated modes are excited with the same power then the α effect vanishes and a "Tayler-Spruit dynamo" cannot work in cylindrical Couette flows. The equilibrated solutions, however, do not consist of equal mixtures of both modes. If only one mode is excited then the Tayler instability produces a finite α effect. Even in this case we find with a new axially unbounded dynamo model that neither an α^2 dynamo nor an $\alpha\Omega$ dynamo can operate. For an α^2 dynamo the naturally existing helicity of the pinch is by far too low and for an $\alpha\Omega$ dynamo the required rotation rates are so high that the pinch-type instability is totally suppressed by the rapid rotation.

Probing the Earth's core dynamics through geomagnetic data assimilation

Sabrina Sanchez and Johannes Wicht

The geodynamo is a complex nonlinear system operating in the Earth's core, which can be solely observed through its magnetic field at and above the Earth's surface. Although direct data of the surface geomagnetic field are only available for the past four centuries, indirect observations from paleomagnetic records provide insights on the field over much longer time scales. These observations are often affected by errors induced either by experimental and dating uncertainties, or problems in separating the contributions of the different field sources. Estimating the deep core dynamics from such noisy surface data is a challenging dynamical inverse problem, which can be supported by prior information from dynamo simulations and tackled within a data assimilation framework. The Ensemble Kalman Filter (EnKF) provides an interesting approach to the data

assimilation problem, given the high-dimensionality and nonlinear character of the geodynamo system. Within this approach, the error covariance necessary for the propagation of information from observable to hidden parts of the system is provided by an ensemble of dynamo models. In this talk, we will explore different aspects of geomagnetic data assimilation within an EnKF approach, beginning with synthetic experiments. We investigate, for instance, the stability of the assimilation, the resolution of the recovered flow structure and the predictability of the magnetic field forecasts. These analyses can provide important insights for the interpretation of the assimilation of geophysical data, such as geomagnetic field models based on modern or paleomagnetic observations. In particular, we focus on the possibility of retrieving information on the depth extent and longevity of the planetary scale gyre observed in core flow models, as well as predicting the long term evolution of the core's magnetic field, including specific features such as the South Atlantic Anomaly.

Precessing spheres: flows and dynamo at low viscosity

David Cebron, Raphael Laguerre, Jerome Noir, and **Nathanael Schaeffer**

Precession of planets or moons affects internal liquid layers by driving flows, instabilities and possibly dynamos. However, there is no systematic study of these flows in the spherical shell geometry relevant for planets, turning any extrapolation to celestial bodies to pure speculation. We have run more than 900 simulations of fluid spherical shells affected by precession, to systematically study basic flows, instabilities, turbulence, and magnetic field generation.
We obtain an analytical estimate of the viscous dissipation. We propose theoretical onsets for hydrodynamic instabilities. We propose a scaling law for the relative intensity of the turbulence, which decreases with decreasing viscosity.
We extend previous precession dynamo studies towards lower viscosities, at the limits of today's computers. In the low viscosity regime, precession dynamos rely on the presence of large-scale vortices, and the surface magnetic fields are dominated by small scales. Interestingly, intermittent and self-killing dynamos are observed.

Symmetry breaking of azimuthal magnetorotational instability caused by thermal boundary conditions

Martin Seilmayer

The first evidence of azimuthal magnetorotaional instability was given some years ago by Seilmayer et al. (2014). A Taylor Couette Setup, filled with liquid metal, was exposed to magnetic field $B_\varphi \sim r^{-1}$. The necessary current was supplied by a large frame of copper rods which caused a residual $m = 1$ field disturbance. This imperfection caused a stationary dominant background flow. Since then, several changes took place to circumvent external asymmetries and influences. The main improvement was the symmetric current return path which eliminates the $m = 1$ background flow and reduces stray fields.

Now the AMRI wave is mainly located at the top of the cylinder, which is surprising since the theoretical prediction allows a symmetric wave with $m = \pm 1$ configuration. However, the wave component from below is missing. Recent work indicate that thermal convection could be a possible source of symmetry breaking. We present experimental results which give evidence to the strong dependency on thermal boundary conditions which affect AMRI action in the volume.

Turbulent saturation of the dynamo instability

Kannabiran Seshasayanan, Basile Gallet, Alexandros Alexakis

While the saturated magnetic energy is independent of viscosity in dynamo experiments, it remains viscosity dependent in state-of-the-art 3D direct numerical simulations (DNS). Extrapolating such viscous scaling laws to realistic parameter values leads to an underestimation of the magnetic energy by several orders of magnitude. The origin of this discrepancy is that fully 3D DNS cannot reach low enough values of the magnetic Prandtl number Pm. To bypass this limitation and investigate dynamo saturation at very low Pm, we focus on the vicinity of the dynamo threshold in a rapidly rotating flow: the velocity field then depends on two spatial coordinates only, while the magnetic field consists of a single Fourier mode in the third direction. We perform numerical simulations of the resulting set of reduced equations for Pm down to 2×10^{-5}. This parameter regime is currently out of reach to fully 3D DNS. We show that the magnetic energy transitions from a high-Pm viscous scaling regime to a low-Pm turbulent scaling regime, the latter being independent of viscosity. The transition to the turbulent saturation regime occurs at a low value of the magnetic Prandtl number, $\mathrm{Pm} < 10^{-3}$, which explains why it has been overlooked by numerical studies so far.

A transition from laminar to a turbulent dynamo

Jan Simkanin, Juraj Kyselica

Many numerical geodynamo models are laminar although the outer Earth's core occurs in the state of high developed convection. This is mainly due to numerical reasons. We present transitions from laminar to turbulent dynamos, with focus on the way these transitions are influenced by viscous and thermal diffusive processes. In all the cases, the dynamos are driven by the temperature gradient between upper and lower boundaries, as is typical for many geodynamo models. As expected, transitions from dipolar to quadrupolar and multipolar dynamos are observed as well as transitions from the large-scale columnar to the small-scale velocity flows. For laminar dynamos at low Prandtl numbers, toroidal components of velocity and magnetic fields dominate over the poloidal ones, while the situation is reversed for turbulent dynamos, i.e. the poloidal components of velocity and magnetic fields dominate over the toroidal ones. When the Prandtl number equals unity, toroidal flows dominate over poloidal ones for both laminar and turbulent dynamos, while toroidal and poloidal components of the magnetic field are comparable for both laminar and turbulent dynamos. For laminar dynamos, Ohmic dissipation dominates over the viscous dissipation, while for the turbulent dynamos viscous dissipation dominates over the Ohmic dissipation. One could wonder why our magnetic Reynolds numbers and Elsasser numbers are large. This is due to small magnetic diffusion used in our computations.

Magnetic energy growth in the subcritical Kazantsev model

Dmitry Sokoloff, E.Yushkov, A.Lukin

We study a growth of average magnetic field in a mirror-symmetrical Kazantsev turbulent flow near the dissipative scales. Main attention is directed to a subcritical regime, when current concepts expect a dynamo energy exponential decrease. We show that instead of damping, the fast enough energy increase can be revealed, for example, in dynamo processes supported by the large-scale magnetic fields. We calculate the corresponding longitudinal correlation function and demonstrate that it tends to a stationary solution with width of localization inversely proportional to the square of magnetic Reynolds numbers and with amplitude depending on the closeness of these numbers to the critical meaning. We present a local generation effect without any external support predicted in 1956 by Zeldovich. Numerically solving the initial-boundary Kazantsev problem on the nonuniform grids, we simulate this process by implicit schemes and discuss the possible consequences for subcritical dynamo physics.

A Tayler-Spruit type model of a tidally synchronized solar dynamo

Frank Stefani, André Giesecke, Norbert Weber, and Tom Weier

We consider a solar dynamo model of Tayler-Spruit type whose Ω-effect is conventionally produced by a solar-like differential rotation but whose α-effect is assumed to be periodically modulated by planetary tidal forcing. This resonance-like effect relies on the tendency of the current-driven Tayler instability to produce intrinsic helicity oscillations which can be synchronized by periodic tidal perturbations. Specifically, we focus on the 11.07 years alignment periodicity of the tidally dominant planets Venus, Earth, and Jupiter, whose empirical synchronization with the solar dynamo is illustrated. The typically emerging dynamo modes are dipolar fields, oscillating with a 22.14 years period or pulsating with a 11.07 years period, but also quadrupolar fields with corresponding periodicities. In the absence of any constant part of α, we prove the subcritical nature of this periodic Tayler-Spruit type dynamo. Phase coherent transitions between dipoles and quadrupoles, which are reminiscent of the observed behaviour during the Maunder minimum, can be easily triggered by long-term variations of dynamo parameters. Further interesting features of the model are the typical second intensity peak and the intermittent appearance of reversed helicities in both hemispheres.

Cross helicity sign reversals in the dissipative scales of magnetohydrodynamic turbulence

V. Titov, **R. Stepanov**, N. Yokoi, M. Verma, and R. Samtaney

We perform direct numerical simulations of MHD turbulence with energy and cross helicity injections at large scales. In the dissipation range, we observe a significant level of the relative cross helicity, as well as reversal of cross helicity as we traverse from large scales to small scales. We found that small scale isolated cross helicity structures at the reversal scale are well correlated with anisotropic current sheets. We demonstrate that the scenario for reconnection of magnetic field is realized under conditions of homogeneous isotropic forced MHD turbulence.

A novel modeling for massive stellar evolution with magnetism

Koh Takahashi, Norbert Langer

About 10% of massive main-sequence stars possess strong magnetic fields on their surfaces, and the magnetic massive stars may be progenitors of strongly magnetized neutron stars known as magnetors. However, the evolution of magnetic fields in stellar interiors remains a big open question for the stellar evolution theory. We are developing a new stellar evolution code which is capable to follow a long-timescale evolution of stellar magnetism. Because of the far different timescales between the MHD and the evolutionary times, high degree of simplification in the modeling is inevitable. First, we assume that the configuration of the stellar magnetism can be approximated by axially symmetric toroidal + poloidal components, which explicitly have only a radial dependence. Then the evolution of the two component magnetic field is described by the mean-field dynamo equation. The new formalism includes the effects of alpha-dynamo, which characterizes the magnetic amplification in a helical flow that may be developed in a convective region in the star, as well as omega-dynamo, which results from large scale shear in the rotation flow. We will present our preliminary results and discuss how the model can be verified by observations. We welcome candid comments and discussions with MHD specialists.

About different MHD-approximations in the simulation of the electrovortex flow

Igor Teplyakov, D. Vinogradov, Yu. Ivochkin

Electrovortex flow (EVF) is formed as a result of interaction between the non-uniform electric current passing through the liquid metal and the own magnetic field of this current [1]. Such flows significantly affect many processes in mechanical engineering (electro-welding) and electrometallurgy (electroslag remelting [2], various electric melting furnaces). In particular, electrovortex flow determines the hydrodynamic structure in the baths of DC-arc furnaces, which are increasingly used in the industry [3]. In an axisymmetric system, without the influence of external axial magnetic fields, EVF develops which has the shape of a toroidal vortex. The influence of the axial external magnetic field leads the azimuthal swirl of the flow. Often problems associated with the calculation of the electrovortex flow are carried out using the so-called electrodynamic approximation, according to which the effect of the motion of the liquid under the action of electric current in the liquid can be neglected [4]. The electromagnetic force is being calculated only basing on the current density distribution and the self-magnetic field calculated earlier. In the present system, external axial magnetic field leads to intense rotation due to the swirl effect, so that the electrodynamic approximation is probably not applicable. The present paper is devoted to the investigation of applicability of the different magnetohydrodynamic approximations in calculations of the electrovortex flow of the liquid metal in the external magnetic field. Experiments on velocity measurements were carried out at the setup consisting of the hemispherical container filled with In-Ga-Sn. An electric current passed through the liquid metal. The magnetic field was created by a solenoid coiled around a container. The azimuthal velocity was measured by the change in the position of the hydrogen bubbles released by the contact of the metal with the acid. The calculation of the velocity field was carried out in the electrodynamic, non-inductive approximation, and the complete MHD problem was solved with the magnetic field recalculation. As a result of the calculations, the limits of applicability of the approximations under conditions of external magnetic field effects were obtained.

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Determining the depth of Jupiter's dynamo region

Yue-Kin Tsang and Chris Jones

An important issue in planetary dynamo is to determine the dynamo radius, defined as the depth at which dynamo action starts. For the Earth, the dynamo radius is at the core-mantle boundary where the electrical conductivity abruptly drops to virtually zero inside the mantle. If we adopt the hypothesis that magnetic energy is evenly distributed over different scales, i.e. different spherical harmonic degrees, near the transition point because of the turbulence there, the location of the core-mantle boundary can be accurately estimated from the Lowes-Mauersberger spectrum, a quantity computed from magnetic measurement on the Earth's surface. The recent Juno mission have measured Jupiter's surface magnetic field to high accuracy. So one may hope to estimate the depth of Jupiter's dynamo using the Lowes-Mauersberger spectrum. However, unlike the Earth, the conductivity inside Jupiter falls off smoothly as one approaches the planetary surface from below. Can a dynamo radius still be defined? If so, can it be estimated from surface magnetic measurement? Is magnetic energy evenly distributed over different scales inside Jupiter? We investigate these questions using a numerical model of Jupiter.

Effects of turbulent pumping and turbulent diffusion on magnetic buoyancy instability in the Solar tachocline

Daniela Weston, David Hughes, Steven Tobias

Magnetic buoyancy has been suggested as a probable mechanism for the rise of flux tubes through the solar convection zone to emerge as the structures we observe at the surface. The large scale of these structures, however, implies that rising flux interacts with the effects of the small-scale, turbulent convection in the region through which they pass in such a way as to preserve the large scale variation. With this motivation, we consider the linear stability of a horizontal layer to magnetic buoyancy, as a model for the region of the solar tachocline. We assume a turbulent region in the upper part of the layer and a non-turbulent region below. The effects of turbulent convective motion are captured via the turbulent pumping and turbulent diffusion effects implied by mean field dynamo theory. We produce a self-consistent equilibrium state given these effects, and solve for linear perturbations to this state. We consider the effects of parameter changes and of the vertical profiles of the turbulent effects on the growth rate, horizontal scale, and vertical variation of perturbations. We find that for stronger turbulent effects in the upper part of the layer, 2D interchange modes are preferred over 3D modes. We also apply the turbulent pumping and turbulent diffusion preferentially to larger horizontal scales, in light of the assumption of mean field turbulence. However, we find that the primary effect of the turbulent pumping and diffusion on stability for our parameters is via their influence on the initial equilibrium field gradient, as opposed to their action directly on the perturbations.

Cyclic solutions and anti-solar differential rotation: can a Parker Dynamo Wave explain them?

Mariangela Viviani, Jörn Warnecke, M. J. Käpylä, and Petri Käpylä

Numerical simulations are the primary tool to understand the dynamos of the Sun and other stars. Even if they are still far from the real parameter regimes, global magnetoconvection simulations are nowadays able to reproduce the main characteristics of the solar cycle. The rotation profiles in these models, however, are very often unrealistic, exhibiting unobserved shear regions in the mid-latitudes [1], and lacking shear layers, that are actually observed. Nevertheless, even these partially failed models represent the best laboratories to gain better understanding of the dynamo process. Recently, the solar-like models have been explained as Parker dynamo waves [2], which gives support to the idea of turbulent dynamos being at work in the models, and hence most likely also in the Sun. Recently, we carried out an extensive study of the properties of dynamo solutions in solar-like stars with partial convection zones as function of the rotation rate [3]. We showed that the stars undergo a transition from anti-solar to solar-like differential rotation, that also corresponds in the dynamo shifting from an axisymmetric to a non-axisymmetric configuration. Again, these transition points are somewhat offset from those indicated by observational data. The dynamo solutions obtained near the limit of the solar/anti-solar transition are intriguing. Previously, no cyclic behaviour has been reported, but our "transition region" models do show quite well defined ones. Also, the migration of the magnetic field is poleward. In this talk we present our results on

an attempt to explain this dynamo wave using the Parker dynamo wave concept, and measuring the turbulent transport coefficients with the test-field method.

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Understanding rotational dependence of stellar activity using MHD simulations of stellar dynamos and stellar coronae

Jörn Warnecke

The magnetic field in the Sun undergoes a cyclic modulation with a reversal typically every 11 years due to a dynamo operating under the surface. Also, other solar-like stars exhibit magnetic activity, most of them with a much higher level compared to the Sun. Some of these stars show cyclic modulation of their activity similar to the Sun. The rotational dependence of activity and cycle length suggests a common underlying dynamo mechanism. Here we present results of 3D MHD convective dynamo simulations of slowly and rapidly rotating solar-type stars, where the interplay between convection and rotation self-consistently drives a large-scale magnetic field. With the help of the test-field method, we are able to measure the turbulent transport coefficients in these simulations and therefore get insights about the dynamo mechanism operating in these simulations. It allows us to explain the weak dependency of the cycle period found by a Parker dynamo wave operating in our simulations. Furthermore, we find the alpha effect becomes highly anisotropic for large rotation rates, which can explain the high degree of non-axisymmetric of magnetic field in observations and models of rapid rotating stars. Stars spinning faster than the Sun are expected to also produce larger amount of magnetic helicity at their surfaces. On the Sun, magnetic helicity is essential for the release of energy leading to the eruption of plasma via coronal mass ejection and it is thought to play an important role in the heating process of the coronal plasma. Using MHD simulations of solar coronae we find a power law relation between the surface magnetic helicity and the temperature and activity of these coronae, suggesting an important role of magnetic helicity production in understanding rotational dependence of stellar activity.

Dynamo action of Jupiter's zonal winds

Johannes Wicht, Thomas Gastine, and Lucia Duarte

The Juno mission is delivering spectacular data of Jupiter's magnetic field but it remains unclear from which depth the field originates. The new gravity data provide constraints on the depth of the zonal winds observed at cloud level. These winds could possibly contribute to the observed magnetic field signal but their dynamo action remains little understood. In order to clarify these questions, we explore numerical dynamo simulations that yield Jupiter-like magnetic fields and concentrate on the Steeply Decaying Conductivity Region (SDCR), the outer 10% of Jupiter's radius where the conductivity rapidly drops from the metallic value to much lower levels in the molecular hydrogen envelope. Our simulations show that the dynamo action is highly diffusive and therefore quasi stationary. The toroidal field clearly dominates while the locally induced current flows mainly in the latitudinal direction. The simple dynamics yields relations that provide high quality estimates for both the induced field and the electric currents. In a second step, we use these relations to estimate dynamo action in Jupiter's SDCR. At about 0.965% of Jupiter's radius, the toroidal field reaches the level of the observed potential field. The locally induced poloidal field, however, is two orders of magnitude smaller. Radial field induction and Ohmic heating are particularly efficient near the strong surface field patch just south of the equator. The Juno spacecraft can potentially detect the related pattern that clearly reflects the zonal wind structure. A constraint based on the entropy produced by Ohmic heating suggest that the surface wind cannot reach deeper than 0.955% of Jupiter's radius.

Measurement of torsional and sloshing modes in Rayleigh-Benard convection using contactless inductive flow tomography

Thomas Wondrak, Frank Stefani, Vladimir Galindo, and Sven Eckert

Flows driven by temperature differences play an important role in geo- and astrophysics as well as in many metallurgical applications. The dynamics of the large scale circulation (LSC) of Rayleigh-Benard (RB) convection include azimuthal reorientations, cessations, torsional and sloshing modes. In this presentation we will show that the contactless inductive flow tomography (CIFT) is able to visualise these features. This will be shown using numerical simulations as well as measurements at a small model filled with GaInSn.

Reconstruction of large-scale flow dynamics in turbulent Rayleigh-Benard convection

Till Zürner, Felix Schindler, Tobias Vogt, Christian Resagk, Sven Eckert, Jörg Schumacher

We reconstruct the spatio-temporal dynamics of the large-scale flow in an opaque turbulent liquid metal convection flow by joint ultrasound Doppler velocimetry and temperature measurements. The setup consists of a cylindrical convection cell of aspect ratio 1 filled with gallium-indium-tin (Prandtl number 0.029). In a range of Rayleigh numbers from 10^6 to 6×10^7 the flow assumes the form of one large scale circulation (LSC). In accordance to previous experimental and numerical works, signatures of torsional twisting and sloshing modes are found in the measured data. The oscillation frequencies of these modes, as well as momentum and heat transport (i.e. Reynolds and Nusselt Number, respectively) do agree well with the results of numerical simulations, experimental data and theoretical predictions in literature.

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