Title: New core messages: dynamical interpretations of geomagnetic variations across timescales

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The variations of Earth's internally-generated magnetic field occur over a wide range of time scales, from years to billions of years. This signal is a rich source of information on the structure and history of our planet, and on the dynamics of the fluid outer core where it is generated. Our understanding of this system within the paradigm of a convective geodynamo is continually challenged by the inflow of observations. Over the past two decades, satellite geomagnetism has in particular opened a window on previously unsuspected rapid dynamical phenomena taking place in the core.

Numerical simulations of the geodynamo have developed at a rapid pace since almost thirty years, and represent a tool of choice for refining our understanding of core dynamics. In this (non-exhaustive) review, I will present a few recent advances that helped interpreting the geomagnetic signal at various time scales in terms of dynamical structures within the core and their associated underlying force balance.

In a first part, I will review some steps that led to an emerging consensus on a dominant balance between pressure, Coriolis, buoyancy and Lorentz forces, and its realisation in simulations. I will then discuss how this force balance connects to the morphology of the geomagnetic field, and the general circulation in the core as inferred from historical geomagnetic variations. A third part will be dedicated to the review of rapid geomagnetic variations observed by satellites, and their interpretations in terms of hydromagnetic wave propagation. Finally, I will review some recent results on the reproduction of geomagnetic polarity reversals in simulations. For each of these aspects, I will try to outline the current limitations in our understanding and draw possible lines towards the goal of a unified description of geomagnetic variations across time scales.

Fingering convection in the stable layers of planetary cores

Céline Guervilly (Newcastle University)

Stably stratified layers may be present at the top of the electrically conducting fluid layers of many planets either because the temperature gradient is locally subadiabatic or because a stable composition gradient is maintained by the segregation of chemical elements. Here we study the double-diffusive processes taking place in such a stable layer, focusing on the case where the temperature gradient is stable but the composition gradient is unstable. The large difference in the molecular diffusivities leads to the development of buoyancy-driven instabilities that drive radial flows known as fingering convection. We model fingering convection using hydrodynamical simulations in a rotating spherical shell and varying the rotation rate and the stratification strength. We will discuss how this impacts the size and velocity of the flow structures and the formation of zonal flows.

Stratified layers in the Earth's outer core: a window into key processes of the formation, dynamics and evolution of the Earth

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The current or past presence of stratified layers has been proposed in numerous planetary liquid cores (including the Earth's outer core) and in the buried oceans of several icy moons, based on various recent models and observations. Such layers, when they exist, may profoundly affect the thermochemical evolution of planetary bodies as well as the generation and structure of planetary magnetic fields. It is therefore crucial to understand how such layers form and evolve over time.

In this presentation, I will summarise my research on the formation, dynamics and evolution of stratified layers, including recent results on the growth of chemically stratified layers in the cores of the Earth and Mars owing to transfer of light elements across the core-mantle-boundary. I will assess the relevance of diverse mechanisms of layer formation and will show that each of these mechanisms - which are intimately connected to key processes of planetary formation and evolution - leads to stratified layers with specific characteristics and dynamics, that hence produce specific signatures in geophysical observations. The detection (or absence) of stratified layers in the Earth's outer core may thus offer a window into the formation of the core, the structure and growth of the inner core and into the composition and dynamics of the deep mantle.

Magnetic eigenmodes in the plesio-geostrophic model

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Andrew Jackson, ETH Zurich, Switzerland
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Temporal variations of the geomagnetic field at and above the Earth's surface contain contributions from multiple electrical current systems, the most dominant of which is the electric current generated by the fluid flow in the electrically conductive outer core. Conversely, the magnetic field observations can be used to place constraints on the outer core dynamics, which is crucial not only in understanding the complete dynamics of the Earth interior, but also the future evolution of the geomagnetic field. While 3-D simulations have been used in geomagnetic data assimilation (GDA), they suffer from low efficiency, high computational cost, and operate in parameter space that is far away from the realistic Earth. In light of this, a reduced-dimensional description of the system is desired. In the Earth's outer core, rapid rotation of the Earth places the fluid near the geostrophic force balance, organising the flow into columnar structures. Making use of the columnar flow ansatz, the recent plesio-geostrophic (PG) model shows that by taking axial integrals that are symmetric or antisymmetric with respect to the equatorial plane, the ideal magnetohydrodynamic equations in 3-D space can be described by a set of quantities on 2-D manifolds, allowing more efficient computation, with parameters in the parameter space that are closer to the real Earth. We present here the magnetic eigenmodes using the PG equations, linearized around certain background fields. This demonstrates the capability and tests the validity of the PG model. The eigenmode calculation is a first of several steps towards a GDA framework that utilises the PG model as the dynamical core, which would hopefully provide better estimates of the physical parameters and dynamics of the deep interior.

The dynamical connection between axisymmetric azimuthal and meridional flows at the top of Earth's core

MATHIEU DUMBERRY
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Axisymmetric azimuthal (zonal) and meridional flows at the top of Earth's fluid core are connected dynamically. However, how they are connected depends on whether the top of core is strongly stably stratified. If it is, a meridional circulation cause a latitudinal gradient in density, and the latter drives a zonal flow which has a radial gradient (a thermal wind). If stratification is absent or weak, zonal flows extend rigidly deep into the core along the direction of the rotation axis. Shearing of the meridional magnetic field by this rigid flow induces an azimuthal magnetic field, which features a radial gradient in a boundary layer at the core-mantle boundary, and an associated meridional electrical current; the Lorentz force caused by this current is balanced by the Coriolis force from a meridional flow. For either of these scenarios, a prediction of the meridional flow can be made on the basis of the zonal flow. Here, we used core flow models constructed from the observed secular variations of the magnetic field to explore this dynamical connection. The objective is to exploit the relatively simple dynamical relationships that connects the meridional to zonal flows in order to constrain the dynamics at the top of Earth's core.

A ray-theoretical approach to investigate two-dimensional MHD waves in a stably stratified layer

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Abstract

Stable stratification at the top of the Earth's core may play an important role in the core dynamics. As a starting point for understanding the dynamics of a stably stratified layer in the uppermost core, we focus on horizontally two-dimensional ideal MHD waves that propagate within the stably stratified layer. In particular, linear waves propagating under a toroidal background magnetic field whose magnitude depends only on the latitude are studied. Among such imposed fields, the simplest profile is the Malkus field, the magnitude of which is proportional to the sine of the colatitude. We measure its magnitude using the Lehnert number. For a weak Malkus field (the Lehnert number is much smaller than unity), two distinct types of waves, fast magnetic Rossby (MR) and slow MR waves, exist as discrete eigenmodes. As the Lehnert number increases to order unity, these two types of eigenmodes merge into (retrograde/prograde) Alfvén eigenmodes. However, the profile of the Malkus field is too simple to understand the behavior of waves propagating in the stratified layer. Here we show the numerical results of the eigenvalue problem describing the property of eigenmodes under a non-Malkus field. We report that slow MR eigenmodes disappear under a non-Malkus field because they transform into a (prograde) Alfvén continuous spectrum. Furthermore, we use the ray theory in the case where the Lehnert number is much smaller than unity to explain this mode transformation. Because slow MR waves in the stratified layer may cause decadal and sub-decadal geomagnetic secular variations, more sophisticated investigations, including the influences of the Ohmic dissipation and the poloidal imposed field, should be performed in future work.

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Magnetic field polarity in rapidly rotating hydrodynamic and nonlinear dynamos

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A long-standing question in planetary dynamo theory is whether the preference for the axial dipole field is due to a purely hydrodynamic process influenced by rotation or due to a magnetohydrodynamic process influenced by both rotation and the self-generated magnetic field. In this study, we investigate the axial dipole formation from a small seed magnetic field in rapidly rotating hydrodynamic and nonlinear dynamos. Unlike nonlinear dynamos, hydrodynamic dynamos do not produce an axial dipole from a seed field, which indicates the role of the Lorentz force in forming the dipole.

It has long been thought that the cyclonic motions arising in rapidly rotating convection twist the toroidal magnetic field and produce a large-scale poloidal field. This toroidal-to-poloidal field conversion may occur in hydrodynamic dynamo simulations but surprisingly extracts energy from the dipole field in nonlinear dynamo simulations. Rather, in nonlinear dynamos, the large-scale axial dipole forms through the radial propagation of columnar vortices at the Alfvén wave speed, indicating a poloidal-to-poloidal field conversion. The columns form from the propagation of damped slow magnetic–Archimedean–Coriolis (MAC) waves excited by localized magnetostrophic balances at the peak-field locations. For $\omega_M/\omega_C \gtrsim 0.1$, the kinetic helicity of the slow MAC waves is higher than that of the fast MAC waves, where ω_C and ω_M are the frequencies of the linear inertial and Alfvén waves, respectively. The formation of the dipole through slow MAC wave motions is independent of the nonlinear energy transport in the dynamo. Finally, polarity transitions in low-inertia spherical dynamos occur when slow MAC waves disappear under strong buoyant forcing.

Bounds on quantities in rotating convection heated internally

Ali Arslan

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In geophysical flows within the Earth, turbulence be it the highly viscous overturning motion in the mantle or low viscosity flow in the outer core, is driven by buoyancy and influenced by the Coriolis force due to rotation. While studies of boundary-driven thermal convection subject to rotation (i.e. Rayleigh-Bénard convection) are wide-ranging, our understanding of internally heated convection (IHC) is relatively lacking. Even the simplest models of IHC reveal unique peculiarities such as mean downward convection, decrease in heat transport in 2D and nonlinear Nusselt behaviour, to name a few.

We focus on convection driven by internal heating subject to rotation and prove bounds on the emergent quantities of the flow with the Rayleigh and Ekman numbers. The central emergent quantity in any study of thermal convection is the heat transport by the flow. For IHC, the quantities of interest are the mean temperature $\langle T \rangle$ and heat flux out of the domain $\mathscr{F}_B \mathscr{F}_T$, using angled brackets represent a long time and volume average. Unlike Rayleigh-Bénard in the internally heated case, the two quantities are not related a priori. Given that heat flux in geophysical flows is significant to tectonic activity, mantle dynamics and dynamo action in the liquid outer core, a rigorous understanding of the PDEs used to model convection becomes desirable. The addition of rotation increases the complexity of the PDEs and the resulting chaotic behaviour is unexplored for IHC. By the auxiliary functional method, we present upper and lower bounds on $\mathscr{F}_B$ leaving the bottom boundary and $\langle T \rangle$ for a fluid driven by uniform internal heating subject to rotation. This work builds on ideas first used to prove bounds for Rayleigh-Bénard convection under rotation at large Prandtl numbers. Finally, we indicate routes to proving bounds valid at all Prandtl numbers within the methodology where standard energy methods cannot yield new results.

Title: Inertial Wave Drag Torque at the Earth's Core-Mantle Boundary: Experimental and Analytical Modeling

Authors: Vadim Giraud (1), Jerome Noir (1), David Cebron (2)

(1) ETH Zurich, (2) ISTerre Grenoble

It has been suggested from seismic tomography, normal modes analysis, and mantle dynamics, that the core-mantle boundary of the Earth is not smooth. The proposed topography reaches up to a few kilometers in height. Similar non smooth bounding surfaces are expected in subsurface oceans of icy moons. Interaction between the liquid core/subsurface ocean and the solid surrounding shells will result in a pressure torque that affect the angular momentum balance, the mixing and potentially the generation of a magnetic field. The goal of this study is to develop a model of the interaction of a fluid with the aforementioned topography, in particular we focus here on the torque and energy dissipation.

To identify the fundamental mechanisms at play, we consider the simple problem of a fluid in differential rotation with a regular topography. We perform simulations and experiments using a periodic topography placed at the bottom of a slightly faster rotating cylinder filled with water. We vary three parameters: the height of the topography (h_0), the wavelength of the topography (λ), and the normalized differential rotation (ε). We measure the torque both in the numerical simulations and in the experiment in the limit of small differential rotation and small Ekman number. We observe that the differential motion over the topography generates quasi-geostrophic inertial waves leading to a wave drag. Based on this observation, we developed an analytical model for the torque that compares quantitatively to the numerical and experimental results. We show that for slender topography ($h_0 < \lambda$) the torque scale with ${h_0}^2$, while for non-slender topography ($h_0 > \lambda$) it scales with $h_0\lambda$.

Although simple in principle, this model captures the fundamental physics of the flow/topography interaction. It will pave the route to address the question of planetary fluid envelopes dynamics driven by time dependent libration, tides and nutations with random topography.

Suppression of wall modes in Rapidly Rotating Rayleigh-Bénard convection

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Studying heat transport in rapidly rotating Rayleigh-Bénard convection is of major importance for geophysical flows. For instance, to measure the heat flux of convection in the core of planets such as the iron core of the Earth is the focus of many works. In fact, the efficiency with which heat is transported across the core has direct implications about its past and future dynamics. The canonical model remains the rotating Rayleigh-Bénard convection: a fluid between two horizontal plates at fixed temperature, heated from the bottom and cooled from the top, is put in rotation. In this idealized model, two non-dimensional numbers appears: the Rayleigh number Ra that characterizes the importance of buoyancy compared to dissipative effects and the Ekman number Ek that is the ratio of rotation effects compared to viscous effects. Geophysical flows are typically characterized by very large Rayleigh numbers and very low Ekman numbers, the Rayleigh number Ra is close to 10^{30} and the Ekman number Ek is close to 10^{-15}. In order to reach this asymptotic regime, experiments have been built using tall thin fluid containers [1]. Maximising the height of the containers simultaneously increases the Rayleigh number and decreases the Ekman number. The horizontal size is however reduced to avoid undesirable centrifugal effects. Unfortunately, such configurations are prone to vigorous flows localised along the vertical boundaries... These flows originate from wall modes localised in a thin layer near the walls that appear before the bulk convection and persist even in the presence of the bulk convection [2]. Due to the narrow aspect ratio of experimental devices, heat flux measurements are significantly perturbed by the presence of these boundary flows, whose contributions are expected to be negligible in extended domains of geophysical interest.

With the help of direct numerical simulations, we found a way to suppress these wall modes adding horizontals fins on the vertical walls of the cylinder ([3]) which sizes scale as the wall modes size. The more we increase the Rayleigh number, the more fins we need to suppress or decrease enough the contribution of the wall modes. Indeed, with a sufficient number of fins, it is possible to reach a negligible heat flux of the wall modes compared to the heat flux of the bulk convection, allowing us to recover the right heat flux.

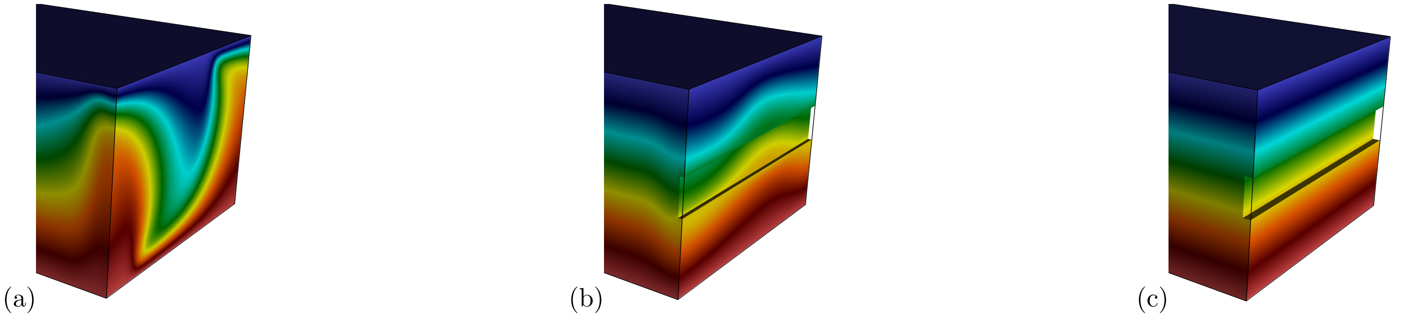

Figure 1: Side visualizations of the temperature field for (a) the case without barrier, (b) $h = 0.2$ and $\epsilon = 0.02$ and (c) $h = 0.2$ and $\epsilon = 0.04$. Wall modes are suppressed for the last barrier.

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Assessment of stable layer formation and its implications for thermal history and magnetic field generation in the Earth's core

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We propose dynamically consistent criteria for the formation and destruction of stable stratification in a radial one-dimensional evolution model of the Earth's core parameterised by thermo-chemical convection. We assume that positive kinetic energy production is required to maintain thermo-chemical convection, while convective motion is inhibited in the region of negative kinetic energy production, resulting in the formation of a stable stratified layer. The radial distribution of the kinetic energy production is calculated from the entropy and compositional convective fluxes under the assumption of adiabatic temperature and homogeneous compositional radial profiles for given thermal and compositional boundary conditions.

We apply this model and scheme for assessing stable layer formation to a realistic reference state of the Earth's core, incorporating the core-mantle chemical coupling modelled by a downward chemical flux through the core-mantle boundary (CMB).

For a given present-day thermal and compositional structure of the Earth's core, a stable region can be found where the present-day CMB heat flow is less than the isentropic heat flow of 12 TW without core-mantle chemical coupling, while this threshold rises to 14 TW when chemical coupling operates at the CMB.

We also perform a backward time integration of the thermal and magnetic evolution model from the present to $t = 4.6$ Ga. With current constraints on the present-day CMB heat flux of between 15 TW and 17.5 TW, a stable region at the top of the Earth's core would not be consistent with the continuous generation of the magnetic field. In contrast, when the CMB heat flow allows lower values between 11 TW and 13.75 TW, and the CMB chemical coupling does not operate, a stable region between 50 km and 75 km thick can develop, assuming continuous magnetic field generation. Therefore, a stable region at the top of the Earth's core cannot be confirmed at this time due to uncertainties in the CMB heat flow and the thermal conductivity of the Earth's core.

Prediction of fluctuations in inner core rotation and variations in length-of-day based on modelled core flow

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Abstract:

Convective flows facilitate the exchange of angular momentum between the solid Earth and liquid core, and this results in length-of-day (LOD) changes. Possible coupling mechanisms to explain these LOD observations include gravitational and electromagnetic coupling, yet their relative contributions remain unclear. The gravitational torques depends on the longitudinal misalignment of the inner core topography. However, the latter is not directly observable.

In this work, we use modelled core flow at the top of the core to predict the time-dependent electromagnetic torque on the mantle. We use the same core flow, inside the tangent cylinder, to infer the flow at the inner core boundary. The latter causes fluctuations in inner core rotation and in its longitudinal misalignment, and this permits to make a prediction of the gravitational torque. We survey the parameters space and model assumptions in an effort to match both the LOD changes and the recent seismic observations of the fluctuating differential rotation of the inner core.

On the thermochemical convection and thermochemically-driven hydromagnetic dynamos at the high Prandtl number

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We investigate the thermochemical convection and hydromagnetic dynamos in a spherical shell using the so-called codensity formulation. Attention is focused on cases where the chemical part dominates the thermal part (the thermal part is almost negligible). We study first the hydrodynamic case (non-magnetic convection) and then the hydromagnetic dynamo, all for high values of the Prandtl number and various values of the Ekman number. The generated flows are large-scale and columnar. For high Prandtl numbers, convection is less supercritical comparing the cases when the Prandtl number equals one), while the hydromagnetic dynamo fails. If the dynamo works, the generated magnetic fields are dipolar, and the dynamos are strong-field. For both non-magnetic convection and hydromagnetic dynamo, we observe the self-consistent formation of a stably stratified layer at the top of the shell.

Inviscid torsional oscillations in a spherical shell

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We study the properties of cylindrical oscillations of electrically-conducting fluid in the presence of an axisymmetric magnetic field, a phenomenon known in geomagnetism as torsional oscillations since their discovery by J. B. Taylor and S. I. Braginsky. The chosen geometry is a spherical shell, consistent with Earth's present-day geometry. Fluid viscosity is generally absent in our calculations, but magnetic diffusivity is retained, consistent with geophysical reality. Two different background magnetic fields that provide the restoring torques to the motions are considered, one of dipole parity (SH1) and the other of quadrupole parity (SH2). Quality factors of the modes are as high as $O(60)$ for the fundamental mode in SH1, and $O(50)$ for the same mode in SH2. We find that the quality factors for both SH1 and SH2 exhibit the same scaling, proportional to $Lu^{1/2}$, where Lu is the Lundquist number that compares Alfven wave timescale to Ohmic diffusion time. This behaviour is related to the fact that ohmic dissipation mainly occurs near the rotational axis in the case of an axisymmetric background field, as well as at the inner and outer boundaries.

A parameter study on full sphere dynamos

May 31, 2024

Author(s): Fabian Burmann (ETH Zurich) Jiawen Luo (ETH Zürich), Philippe Marti (ETH Zurich), and Andrew Jackson (ETH Zurich)

Abstract:

Although the geomagnetic field exists since about 4 Gyr, recent estimates for the formation of the Earth's inner core go back no further than 500 Myr to 1 Gyr. Consequently, the Earth's dynamo has been operating in a full sphere geometry since most of its existence. Nevertheless, numerical simulation of dynamos in a full sphere remain rare in literature, partly due to the difficulty of an adequate treatment of the singularity at the centre of the sphere.

Using a fully spectral simulation framework (QuICC), where the choice of radial basis functions guarantees smoothness in the entire domain allows us to compute dynamos in a whole sphere. Since we cannot rely on the buoyancy release of the inner core, our dynamos are driven by internal heat sources and fixed flux boundary conditions take account of the secular cooling of the planet.

Here we present the results of a systematic parameter study covering a wide range of Ekman numbers E (ratio of viscous to Coriolis forces), magnetic Prandtl number Pm (ratio of viscous diffusivity and magnetic diffusivity) and the Rayleigh number Ra (strength of the convective forcing). Our dataset allows us to systematically analyse the behaviour of the velocity and magnetic field as a function of the input parameters and we present scaling laws for several output parameters. In comparison to spherical shell dynamos, we find a smaller regime for dipolar magnetic fields (in Ra and Pm) and a larger Pm is needed to establish dynamos.

REGIMES OF ROTATING CONVECTION IN A TANGENT CYLINDER

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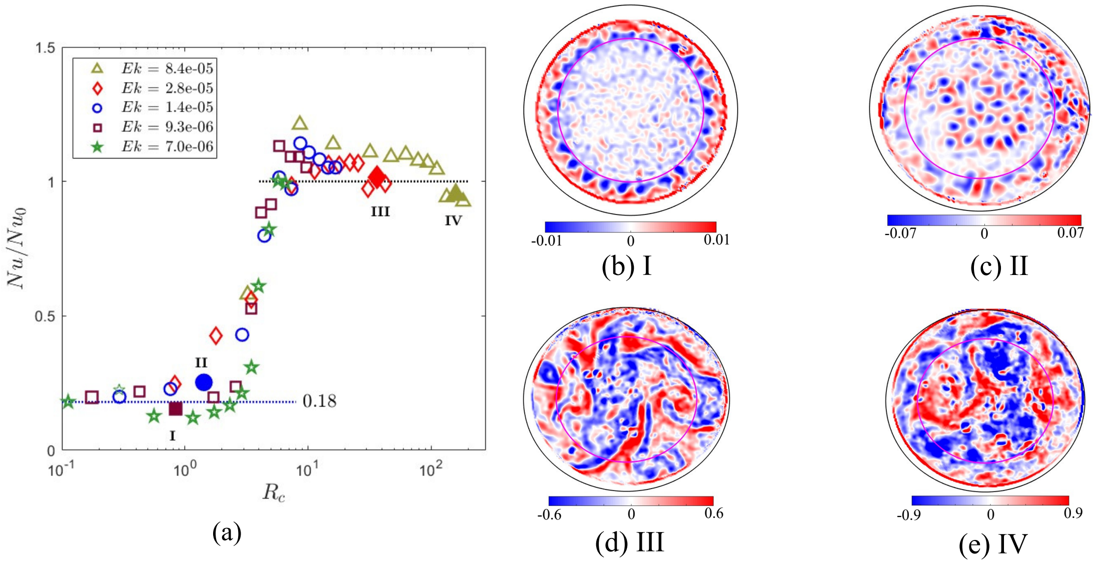
Keywords— Geophyscial flow, Tangent cylinder, Baroclinicity, Rotating convection

The dynamics of liquid planetary cores is controlled by the complex interplay between buoyancy, the Coriolis force due to planetary rotation and the Lorentz force due to planetary magnetic fields. Yet the combination of these three forces and the extreme regimes in which they operate make the resulting flow particularly arduous to elucidate. The main effect of rotation is to oppose fluid motion across an imaginary cylindrical surface called *the Tangent Cylinder* (TC) obtained by extruding the equatorial perimeter of the solid inner core along the rotation direction, and up to the boundary between the liquid core and the mantle [1]. Because this boundary is imaginary, mass and heat transfer into the TC, and in turn, on the convection within the TC region is expected to differ from that inside a solid cylinder with well-defined boundary conditions. To clarify this question, we reproduce this geometry experimentally in the Little Earth Experiment (LEE) [2, 3] using water and optical velocity mapping.

We find that convection is highly modified compared to a solid cylinder [4] due to the presence of baroclinicity near the top of the TC. There is an additional inertia to the system due to baroclinicity which causes an early breakup of the Taylor-Proudman constraint. The flow remains dominated by the Coriolis force even at very high criticality and the regimes shows signs of rapidly-rotating geostrophy. The convection spans the subcritical, cellular, columnar, plumes, and large-scale vortices /geostrophic turbulence regimes (figure 1). The LEE experiment provides an unique pathway to reach the commonly inaccessible geostrophic regime by creating an baroclinically driven flow using a TC-like geometry.



(a) (b) I (c) II (d) III (e) IV

Figure 1. (a) Variation of Nusselt number (Nu) normalized by its value for no rotation (Nu_0) *vs.* level of supercriticality $(R_c = Ra/Ra_c)$ with respect to the onset for and infinite plane layer. (b-e) Snapshot of z-vorticity, $\omega(x, y, t)$ for cases I, II, III and IV highlighted in (a) at $h = 0.66H$, where H is the height above the heater. The purple cirlce represents the TC.

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On precession driven flows in ellipsoids

May 31, 2024

Author(s): Fabian Burmann (ETH Zurich), Lennart Kira (ETH Zurich) and Jerome Noir (ETH Zürich)

Abstract:

In a geo- and astrophysical context, precession driven flows have been suggested as a steering mechanism to sustain planetary dynamos and/or associated with dissipation in planetary cores and subsurface oceans. While the case of precessing cylinders, spheres and spheroids has received much attention in the literature, the case of a precessing ellipsoid has received far less attention.

Using a complementary experimental and numerical approach, we focus on two aspects of precession driven flows inside an ellipsoidal cavity: the behaviour of the base flow of uniform vorticity and the development of fluid instabilities leading to turbulent flow structures.

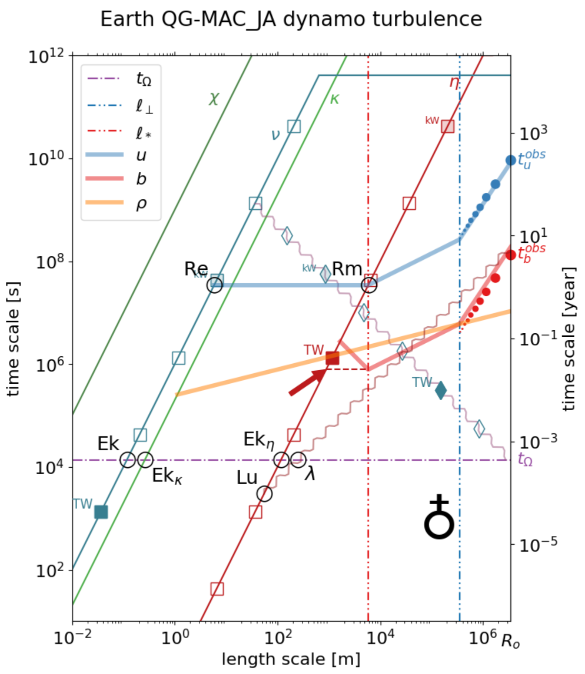
With regard to the former, we show that depending on the ellipsoid deformation, the base flow shows either a single solution as a function of the forcing amplitude (characterised by the Poincaré number, Po) or exhibits two branches , possibly leading to a hysteresis cycle in Po. At large enough forcing amplitude the flow in the ellipsoid becomes unstable and we observe an equi-partition of kinetic energy in the base flow and the instablities. Finally, we discuss the underlying instability mechanism (boundary layer and/or parametric instabilities) based on three independent criteria observed in our experiments.

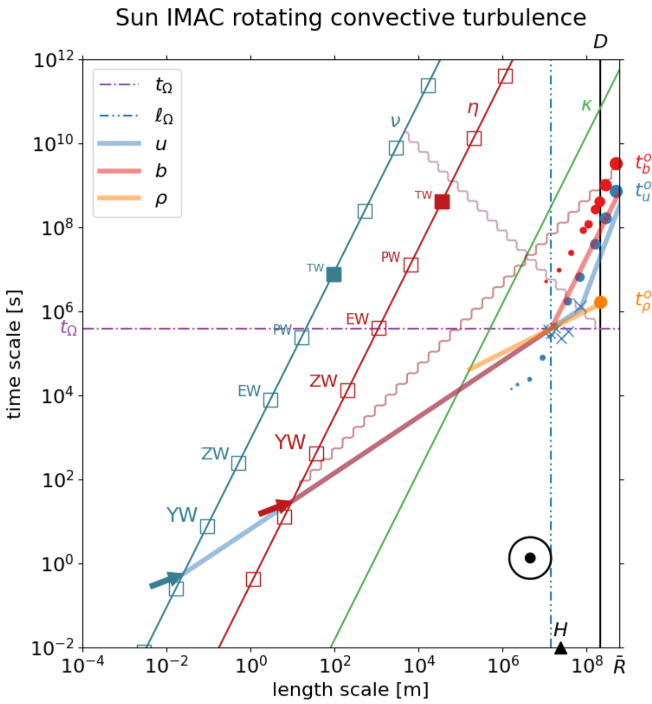
τ-ℓ diagram BYO

Henri-Claude Nataf[1], Nathanaël Schaeffer[1] and Quentin Noraz[2]
[1]Univ Grenoble Alpes, CNRS, ISTerre, Grenoble, France.
[2]RoCS, Institute of Theoretical Astrophysics, University of Oslo, Oslo, Norway.

Want to guess the dynamic regime of your favorite planet/star/DNS/experiment/spherical cow? Bring its required properties following the examples below, and we'll build its τ-ℓ regime diagram together, testing various force balance scenarios (following Nataf & Schaeffer, *CR Geosciences*, *in press*, 2024). We'll then compare predictions with observations, if available, and add the result on our poster!

property	symbol	unit	Earth's core	Sun convective zone
outer radius	R_o	m	$3.48\ 10^6$	$6.96\ 10^8$
inner radius	R_i	m	$1.22\ 10^6$	$4.87\ 10^8$
available convective power	P_{diss}	W	$3\ 10^{12}$	$3.85\ 10^{26}$
mass	M_o	kg	$1.835\ 10^{24}$	$5.37\ 10^{28}$
rotation rate	Ω	s^{-1}	$7.27\ 10^{-5}$	$2.6\ 10^{-6}$
magnetic diffusivity	η	m^2s^{-1}	1	3.12
kinematic viscosity	ν	m^2s^{-1}	10^{-6}	$1.1\ 10^{-3}$
thermal diffusivity	κ	m^2s^{-1}	$5\ 10^{-6}$	$6.51\ 10^5$
thermal expansion coef	α	K^{-1}	$1.2\ 10^{-5}$	$4.5\ 10^{-6}$
density	ρ	$kg\ m^{-3}$	10.9	58.14
gravity	γ	$m\ s^{-2}$	8	372.2
heat capacity	C_P	$J\ kg^{-1}\ K^{-1}$	850	$3.94\ 10^4$





Get the τ-ℓ package from https://gricad-gitlab.univ-grenoble-alpes.fr/natafh/shell_tau-ell_programs and join the initiative!

A Scaling law for core-heating by giant impacts and implications for dynamo onset

Authors: Peter E. Driscoll (1), You Zhou (2,1), Mingming Zhang (1,3), Christian Reinhardt (4)
(1) Earth and Planets Laboratory, Carnegie Institution for Science, (2) Planetary Science Research Center, Chengdu University of Technology, (3) Institute for Geophysics, University of Texas, Austin, (4) Institute for Computational Science, University of Zurich

Abstract

The Moon forming giant impact was a singular event in the history of the Earth. It is responsible for setting the mass, angular momentum, and “initial” thermal state of the Earth and Moon at the end of accretion. This event likely had a long-lasting impact on the thermal and magnetic evolution of Earth’s core.

In particular, the impact heating of Earth's core is expected but unknown, and crucial to the onset of the geodynamo. The uncertainty is due to the difficulty of preserving a record of such a high energy environment, and the common assertion that any deep super-heating during formation would be rapidly lost through magma ocean cooling.

Here we systematically investigate core heating due to giant impacts using the Smoothed Particle Hydrodynamics (SPH) code Gasoline with simulations spanning a range of impact angles, impact velocities, and impactor masses. From these models we derive a scaling law for core heating that predicts the radial core temperature profile following an arbitrary impact parameters (impact angle, mass, and velocity).

Our findings show that some realistic impacts scenarios can deposit significant heat into Earth's core, raising the average core temperature by about 3000 K, and about 500 K hotter than the overlying mantle. Most of the core heating comes from accretion of the super-heated impactor (e.g. Theia) core, that merges quickly with Earth’s proto-core. This accreted impactor core is hotter than the proto-Earth core, so it is thermally buoyant and stays at the top of the core. This creates an

enormous thermal stratification.

This impact-induced thermal stratification will prevent thermal convection and dynamo action in the core until this super-heat is removed by the mantle. Using a parameterized cooling model, we estimate the time it would take for the core to cool to an adiabat state for a range of plausible impact scenarios. We find that for a canonical Moon forming impact, the Earth could have removed this impact heat in about 250 Myr, setting the stage for a hadean onset of the geodynamo at around 4.2 Ga, consistent with the oldest claims for geodynamo activity.

Thermochemical convection in the outer core with heterogeneous core-mantle boundary heat flux

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Thermochemical convection in Earth's outer core is known to drive the geomagnetic field. The latent heat and light elements released due to the crystallization of the solid inner core provide both thermal and chemical buoyancy sources. However, most outer core convection models use the codensity approach, ignoring the vastly different diffusivities and different boundary conditions for the thermal and chemical fields, and therefore cannot account for double-diffusive effects. We consider a top-heavy double-diffusive rotating convection model with a Boussinesq mixture of light elements in a heavy fluid confined within a spherical shell. At a fixed rotation rate (represented by the Ekman number, $E = 10^{-5}$) and fixed diffusivity ratios (represented by thermal and chemical Prandtl numbers $Pr_T = 1$ and $Pr_\xi = 10$), we vary the thermal and chemical driving represented flux Rayleigh numbers ($Ra_T = 9 \times 10^6 - 1.2 \times 10^8$ and $Ra_\xi = 3 \times 10^6 - 10^{10}$), to locate the geophysically relevant "rapidly rotating" regime of convection. A detailed analysis of the force balance demonstrates a transition from a thermal wind to a chemical wind balance with increasing chemical forcing in the azimuthally averaged "mean" forces. The transition is found to occur at buoyancy ratio, $\Lambda = (Ra_T/Pr_T)/(Ra_\xi/Pr_\xi) \simeq 1$. However, the corresponding "fluctuating" balance is quasi-geostrophic in all directions.

We proceed by imposing a laterally heterogeneous thermal flux at the core-mantle boundary (CMB) in our double-diffusive simulations. Recent thermally-driven simulations with lateral variations in CMB heat flux produce local regions with a subadiabatic thermal gradient near the CMB (Mound *et al.* 2019), termed as regional inversion lenses (RILs). This may reconcile the conflicting inferences about the possibility of a globally stratified layer at the top of the core (Gastine *et al.* 2020), by accommodating the possibility of both stable and unstable regions. Our goal is to assess the effect of chemical buoyancy on the RILs. In these models, the parameter space also includes the pattern and amplitude of lateral variation in the CMB heat flux. These RILs are characterised by their strength, measured by a characteristic Brunt-Väisälä frequency (N), and their thickness (L), defined as the distance of the point of neutral stability from CMB. The dependence of these quantities on the chemical forcing has been explored.

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Title: The influence of boundary topography on outer core dynamics

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Abstract

The presence of Large Low Shear Velocity Provinces below southern Africa and the southern Pacific suggests that there are multiple regions where the core mantle boundary deviates significantly from spherical geometry. The coupling of the fluid motions of the outer core to these boundary intrusions may exert large torques on the mantle and may also play a role in geodynamo control.

In this study we investigate the effect of boundary topography on rotating, thermal convection in a fluid sphere with no-slip boundary conditions. We use a spectral element code to perform three-dimensional hydrodynamic simulations in a spherical shell with an irregular outer boundary.

The rotation rate, buoyancy forcing and topographic amplitude are varied to interrogate the behavior of the system as the control parameters are made more Earth-like.

We report global transport quantities as well as the torques exerted by the fluid on the outer shell, and compare to cases in which topography is absent. Furthermore, we investigate the turbulent length scales of the flow and discuss in the context of irregular boundaries.

An overview of the possible axial and equatorial torques acting on the mantle from MAC waves in the Earth's core

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Magneto-Archimedes-Coriolis waves are a type of oscillatory motion, supported by any density-stratified medium under rotation, that is permeated by a magnetic field. In the Earth's core the propagation of these waves depends on the presence of a stably stratified region, and while there is some seismological evidence pointing towards the existence of such a layer near the core-mantle boundary, an unequivocal detection of the layer has yet to arrive.

Nevertheless some recent studies on the wave dynamics in the Earth's outer show that MAC waves, propagating in the outermost stably stratified layer, can be used to explain some magnetic field observations as well as the length-of-day signal coming from the core. In supposed constrast, different studies achieve the same thing without the need to evoke a stably stratified outer layer.

In this study we consider these two assumptions, and provide a description of the wave motions in a full 3D spherical model of the Earth's outer core, both with and without a stratified layer. By computing the viscous- and electromagnetic torques from the core on the mantle, resulting from the different waves, we discuss the plausibility of MAC wave signatures to be observed in data sets of the magnetic field, length-of-day variations and polar motions and provide some constraints on the strength and character of the stratified layer.

Can galactic dynamos be explained by anisotropic conductivity ?

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June 3, 2024

Abstract

The galactic magnetic field has been studied for several decades. The turbulence of plasma gases within galaxies results in a magnetic diffusion time that is very short compared to the galactic lifetime. Consequently, the galactic magnetic field must be regenerated by the dynamo effect. A dynamo model based on the anisotropy of electrical conductivity has recently been developed. Assuming better electrical conductivity along galactic spiral arms, the anisotropic dynamo can be applied. However, this dynamo requires a necessary condition: $\sin(p) \cdot \Omega' > 0$, where $\Omega' = \partial_r \Omega$ and $p \in [-\frac{\pi}{2}, \frac{\pi}{2}]$ is the pitch angle of the spiral arms. Nearly all observed galaxies have trailing arms and a decreasing Ω, except for NGC 4622, which has leading arms and an increasing Ω. To date, no known galaxy satisfies this relationship, and consequently, the anisotropy of the spiral arms cannot explain the existence of galactic magnetic fields until further notice.

Magnetic Taylor-Proudman Constraint explains flows into Tangent Cylinders

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Convection is the beating heart of planets such as the Earth: the rate at which the planet cools, spins-down and the dynamics of its magnetic field are all controlled by the complex interplay between buoyancy, the Coriolis force due to planetary rotation and the Lorentz force due to its magnetic field in the liquid inner core of the planet. Yet the combination of these three forces in extreme regimes makes the resulting rotating turbulent magneto-convection particularly arduous to elucidate. The main effect of rotation is to oppose fluid motion across an imaginary surface in the shape of a so-called *Tangent Cylinder* (TC) extruded from the equatorial perimeter of the solid inner core along the rotation direction, and up to the boundary between the liquid core and the mantle [3]. Magnetic fields on their own have a similar effect [1] and recent work suggests that intense flow within this region may participate in the planetary dynamo that sustains the Earth's magnetic field [2].

We show that when the magnetic field is close to aligned with background rotation, the classical *Taylor-Proudman* Constraint, which underpins the existence of the TC, extends into a new constraint on the combined current density of mass and charge [8]. In magneto-rotating convection, the new *Magnetic Taylor-Proudman Constraint* (MTPC) kinematically binds the radial and the azimuthal components of the flow at the TC boundaries. This constraint explains and quantifies the flow into the TC due to the departure from the classical Taylor-Proudman contraint incurred by the Lorentz force. Its main is consequence that when a magnetic field is present, the flow does not follow the Tangent Cylinder but can meander in and out of it. This is consistent with recent observations and numerical simulations showing that the TP constraint is violated by flows through the Earth's TC [4, 2, 5].

The theory is tested on the *Little Earth Experiment* (LEE) [6, 7, 8] where rotation, magnetic field and buoyancy can be controlled, and where rotating magnetoconvective patterns are visualised for the first time. LEE models the liquid core with a vessel representing the core-mantle boundary, with a cylindrical heating element placed at its centre representing the solid inner core and the buoyancy it creates. The vessel is filled with a transparent electrolyte, driven in rotation and placed inside a large magnet imitating the feedback of the Earth's magnetic field on the flow. Particle Image Velocimetry and thermistors provide us with velocity maps and local temperature measurements. We operate LEE in regimes where the flow inside the TC is either 3D or quasi-2D, and show that the time- and azimuthally- averaged radial flow near the TC boundary indeed follows the prediction of the Magnetic Taylor-Proudman constraint. When the Lorentz and Coriolis forces are comparable, the time and azimutally averaged flow exhibits a radial component through the Tangent Cylinder, of intensity consistent with the MTPC. Furthermore, LEE operates in the quasi-static MHD regime, where the induced magnetic field is too small to affect the externally imposed one (See for example [9]). We find that in this regime, the flow fluctuations too exhibit a component through the TC that is also controlled by the MTP constraint.

This constraint explains and quantifies how magnetic fields reshape rotating flows in configurations relevant to planetary interiors and in wider class of magneto-rotating flows in general.

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A comparison of scaling behavior between rotating dynamos and convection in spherical shells

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Abstract

Accurately characterizing the dynamics of Earth's outer core is imperative for understanding the evolution of the geomagnetic field. Numerical models of rotating spherical dynamos can exhibit a variety of different force balances, depending on the magnitude of the non-dimensional control parameters. Here we use numerical models to study dynamos that approach the so-called magnetostrophic force balance, defined by a four-way balance between Coriolis, pressure gradient, buoyancy and Lorentz forces. This balance is present on both large (global) and small (convective) length scales. The asymptotic behavior of the system is investigated in detail and compared with non-magnetic convection. One of the main properties of the dynamos is a temperature perturbation that is independent of the Ekman number, Ek, and that also appears to saturate with Rayleigh number, Ra; a consequence of this is that the buoyancy force can balance the Coriolis force at leading order in the dynamos. All computed length scales of the velocity and magnetic fields exhibit a systematic asymptotic dependence on Ek – estimates for these dependencies are obtained from the numerical data. The viscous and ohmic dissipation length scales remain comparable in magnitude across the explored parameter space, though different scalings are observed; the viscous dissipation length scale varies as $Ek^{1/3}$ (similar to rotating convection), whereas the ohmic dissipation length scale shows a slightly weaker scaling, varying approximately as $Ek^{1/6}$. The asymptotic behavior of the flow speeds is the same for both dynamo and convection cases and indicates that $Ek^{1/3}$ length scales remain the dominant energy containing scales over our investigated range of parameters.

Roughness at the CMB: Laboratory exploration of topographical effects on rotating high-conductivity convection

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Topography can develop at the Earth's core-mantle boundary on a variety of scales [1, 2], from global-scale tidal deformations to meso-scale disruptions caused by lower mantle dynamics and structures, to small-scale roughness caused by interactions between the core and mantle material. Different scales of topography lead to significantly different effects on core flow: for example, meso-scale topography could trigger thermal Rossby waves [3] while small-scale topography could affect the lateral motion of convective vortices [4]. Despite the richness of this problem, few laboratory forays have been conducted thus far.

In this upcoming study, we will construct two new laboratory rotating convection setups – one in water, one in liquid gallium – able to accommodate multiple scales of boundary topography. In water, we will be able to reach more Earth-like parameter regimes and obtain detailed reconstructions of the flow. In gallium, we will more closely model the fluid properties of the Earth's outer core. We will use our results to develop predictive models of the flow using scaling laws, flow observations, and literature comparison. Ultimately, we hope to link our results to observed behaviors of the Earth's magnetic field. Topographical effects may even have provided an energy source to the geodynamo prior to formation of the Earth's inner core.

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Upper bound of heat transfer for the anelastic liquid model of Rayleigh-Bénard convection

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In geophysics and astrophysics, the relevant dimensionless parameters such as the Rayleigh number for convection are so large that it is of interest to rely on scaling laws to derive quantities like the heat flux driven by a given temperature difference. In the case of the Rayleigh-Bénard configuration, there has been a series of rigorous upper bounds of the heat flux derived from the governing equations. The first one was obtained by Howard [1], in the Boussinesq approximation, whereby the upper bound is determined under some integral restrictions derived from Navier-Stokes and thermal equations. Later, the so-called background method was introduced by Doering and Constantin [2] and was shown to lead to equivalent results by Kerswell [3]. Recently, a more direct method was derived by Seis [4] which was also itself reconnected to the previous methods by Chernyshenko [5]. All these methods concern the Boussinesq approximation. We have obtained, for the first time, an upper bound in the anelastic liquid approximation [6], with a method inspired from the approach by Seis [4]. Our method, like that of Seis, relies on the maximum principle. This principle is easily applicable in the Boussinesq approximation to bound the temperature field between the cold and hot values imposed at the boundaries. However in compressible convection, it is more difficult to have results: in the anelastic liquid approximation, we have a minimum value for the entropy, as it cannot be lower than the value imposed at the cold boundary. This is enough to derive an upper bound of the heat flux [6] under the form $Nu < 146\, Ra^{\frac{1}{2}}/(2-\mathcal{D})^{\frac{5}{2}}$, where Nu, Ra, and $\mathcal{D}$ are the Nusselt, Rayleigh and dissipation numbers.

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The Inviscid dynamo

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Earth's magnetic field is believed to be generated in the metallic outer core through a process known as geodynamo. Direct numerical simulation (DNS) of geodynamo has successfully reproduced many features of the Earth's field. Still, even the state-of-the-art simulations have a much higher viscosity than the Earth's outer core. Taylor (1963) proposed a reduced model by neglecting inertia and viscous force. A modified model that partially re-introduces the inertia term back is termed the torsional wave (TW) dynamo model, since it admits torsional oscillations, a special type of Alfven wave.

In this study, we present new results of inviscid dynamo simulation at a reasonably high truncation level $L_B = 80$. We observe the geostrophic flow dominates the velocity field, and the dipolar component dominates the magnetic field. The inviscid solution fundamentally differs from the viscous dynamos ($E = 10^{-5}$), which all have non-dipolar magnetic fields.