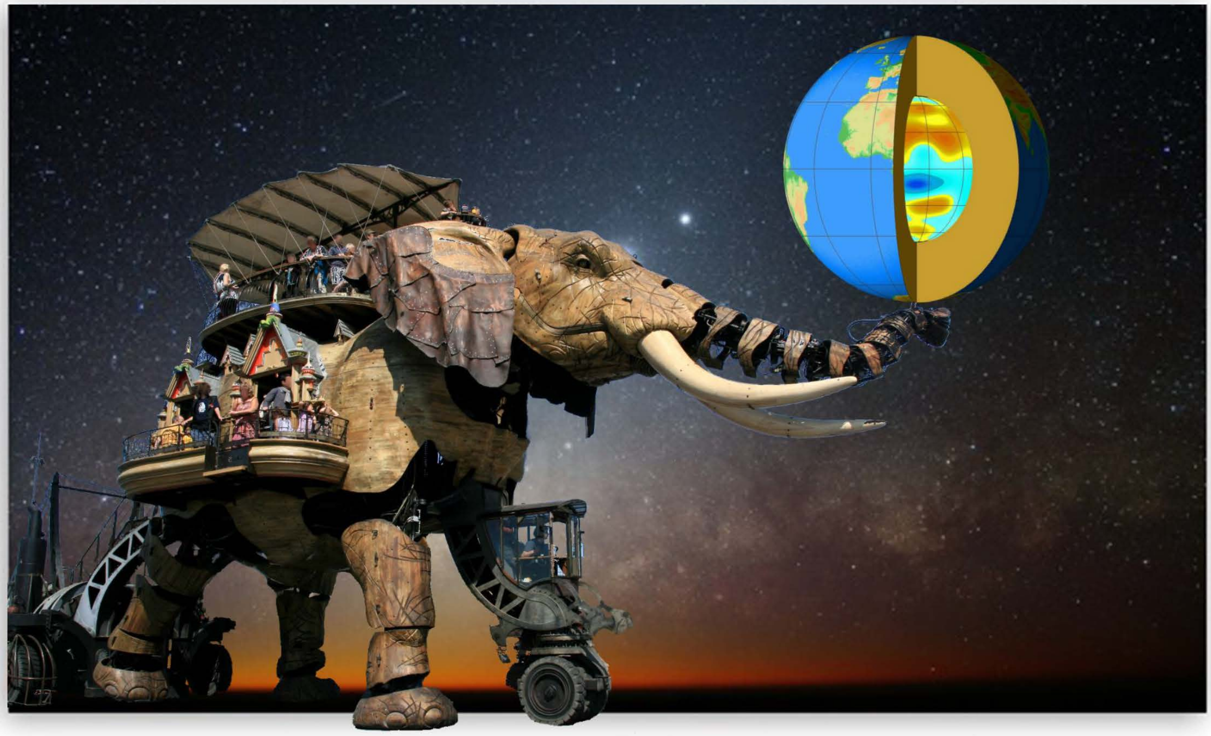
15th Symposium of Study of the Earth's Deep Interior



SEDI 2016
24-29th July
Nantes, France

Abstracts

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Mantle Structure and Composition

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Abstract

Recent observations regarding our understanding of the mantle:
- 142Nd controversy no longer exists – Earth is chondritic

- Collisional erosion models, invoked to address 142Nd story, are not consistent with Ba-La isotopic systematics nor chemical systematics of early Earth mafic to ultramafic magmas.

- Mg/Si of Earth: solely a function of planetary accretion of olivine to pyroxene. Accretion disks have horizontal variations in olivine/pyroxene proportions (temperature-time-space).

- Slab penetration to and apparent stagnation at 1000 km depth coupled with changing shape of ascending plumes at 1000 km depth are consistent with viscosity, not compositional, changes.

- 182W isotopic systematics record early (30-50 Ma post-time-zero) core-mantle separation, however, documented 182W anomalies in sources of modern to ancient magmas remain.

- Measurements of the planet's geoneutrino flux limit the amount of Th & U in the Earth, defining the building blocks of the planets, and describing mantle convective state

Challenges we face in understanding the mantle:

- Compositional attributes of the Transition Zone remain unresolved. Is this region enriched in water (Houser 2016 says no)? Is this region enriched in basalt (Ringwood & Anderson say yes)?

- Defining precisely and accurately (±few %) modal proportion of olivine in top 650 km of the mantle remains a challenge, doing so will constrain compositional evolution of mantle.

- Defining modal content (and uncertainties) of ferropericlase in the lower mantle is required to move beyond speculative models that have transient traction in the literature.

- LLSVP origins is either primordial or subduction related; sources of plume basalts (OIBs) carry a genetic signature of ocean crust recycling and can be traced to LLSVP margins. Xenon isotopes of OIB require 4.4 Ga source evolution difference from Depleted MORB-source Mantle. How?

- Stirring efficiency of the mantle remains to be evaluated. Combined chemical, isotopic

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and geodynamic studies need to model preservations of source heterogeneities.

- Core-mantle mass exchange might occur, but need to document it. Existing claims are not supported with full spectrum of chemical consequences and thus remain baseless.

- Domains of primordial magma ocean differentiates are interpretations of deep Earth seismological features. No geochemical evidence exists to support these interpretations.
- ULVZ domains, parasitically(?) sited on toes of LLSVPs, present an enigmatic feature of CMB that perhaps reflects mass and energy exchange between core, LLSVP and plunging slabs.

Keywords: 142Nd, Mg/Si, LLSVP, 182W, collisonal erosion, geoneutrino, Transition Zone

The mantle transition beneath Europe; from slab to plume and beyond.

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Abstract

The mantle transition zone discontinuities at 410 and 660 km are generally related to mineral phase transitions, and thus the depths at which they occur are indicators of temperature, composition and water content. Here we map the topography of the '410' and '660' beneath Europe, which tectonically is a natural laboratory to look at the effects of ponding slabs beneath Southern Europe and of a plume beneath Iceland. Seismic studies of the conversions of pressure to shear waves (Pds phases) are an important tool to observe lateral variations in these discontinuities. Here we collect a Pds data set across all European seismic stations since 2000 that are available through ORFEUS or IRIS; resulting in > 500,000 event-station pairs. We construct receiver functions through iterative deconvolution and after quality control keep _˜40,000 high quality receiver functions. We combine all receiver functions in common conversion point and slowness stacks at different frequencies to map discontinuities down to 1400 km. We correct for velocity structures using recent tomographic models. We draw three main conclusions from our observations:
In the topography of the discontinuity around 660 km, we find broadscale depressions of 30 km beneath central Europe and around the Mediterranean. These depressions do not correlate with any topography on the discontinuity around 410 km. Temperature or the pressure of water cannot solely explain the strong depressions. Our preferred hypothesis is the dissociation of ringwoodite into akimotoite and periclase in cold downwelling slabs at the bottom of the transition zone. The strongly negative Clapeyron slope predicted for the subsequent transition of akimotoite to bridgmanite explains the depression with a temperature reduction of 200–300 K and provides a mechanism to pond slabs in the first place.

Beneath the Icelandic plume, we see depressions in the 660 which is opposite from what is expected for an excess temperature. No realistic plume structure (increasing the corrections for mantle velocity) can change the sign in the topography. Our hypothesis is that this is a signature of a majorite dominated mantle transition zone at high temperatures. Both cases show a sign of complexity when interpreting the '660'.
When looking at deeper structures, we see local conversion from 950-1050 km. Frequency dependence analysis of these observations suggest they come from a sharp discontinuity, which can only be

Keywords: mantle transition zone, 1000 km, receiver functions

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The geodynamics of melting in the Asthenosphere

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Abstract

At geological time-scales, the mantle behaves as a high Rayleigh number fluid, i.e., thermal convection takes place and produces cells circulating at variable sizes and speeds. A lot of effort has been made to understand the upwelling part of these cells occurring underneath ridges and hotspots where they give birth to volcanoes. Nevertheless, local passive (adiabatic) sub-lithospheric mantle upwellings are likely to be more widespread and even common below oceanic plates. Just like under volcanoes, mantle is expected to undergo decompression melting in these concealed upwelling regions but the magma produced may be trapped and not have any volcanic expression. Here, we intend to discuss the fate of these deep melts and try to present a broad view of their geophysical and geochemical expressions. We suggest that these melts are broadly ponding in the upper part of the asthenosphere defining the Low Velocity Zone, which can also be featured by high electrical conductivities. In our analyses, we model mantle melting that is favored by two critical parameters: high temperatures and/or elevated concentrations of H2O and CO2. It is frequently modeled as a chemical process in a static system, where thermodynamics is used to define the quantity of melts produced as a function of temperature and volatile contents. On the other hand, fluid mechanics tell us that the melt produced having low viscosity and low density tends to migrate away from its solid source at a rate depending on a variety of physical parameters; permeability and density/viscosity contrasts being the most influent. Combining thermodynamics and fluid mechanics, we show that CO2-H2O melts tend to focus at the lithosphere-asthenosphere boundary, where melt contents can reach 1-2%. This can easily explain many geophysical observations on the LVZ. The magnitude of the geophysical signal at the LVZ is related to convection (upwelling) in the asthenosphere; upwelling produces decompression-melting and the melt tends to accumulate below the impermeable lithosphere. The lithosphere-asthenosphere boundary must be featured by a strong and focused weakening where strain localizations enable decoupling between the plates and the asthenosphere. This geodynamic configurations is probably not always conceivable, particularly during the Archean, since temperatures was much hotter and melting much deeper.

Keywords: mantle, melting, volatiles, geophysics, geodynamics

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Mantle history and dynamics

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Abstract

The present day structure of the mantle is mapped by seismic tomography with a rapidly increasing precision. We will discuss these seismic observations and the implications for the nature of the thermal and compositional anomalies that are observed in the mantle. The presence of internal anomalies can it turn be used to infer the large scale rheological properties on the mantle. The present day mantle structure is inherited from billion years of plate tectonics and probably from the Hadean time of Earth's accretion and of the solidification of silicates. We will show that various structures of the abyssal mantle could indeed be related to the delayed crystallization of a magma ocean, whereas the bulk of the mantle bear the imprint of subductions since Mesozoic. Although our knowledge of the structure and dynamics of the mantle has improved, the origin of plate tectonics remains an unsolved problem. Plastic rheologies can be used in numerical simulations to mimic very realistically the formation of plate boundaries. However the links between laboratory observations of deforming rocks and what is used in numerical codes have not been made. The rheology of the mantle and lithosphere are likely non Newtonian and time dependent. Their viscosities are a function of both deviatoric stresses and grainsize and in a way that may be much more complex that what can be observed in laboratory on short time scales. The grain size is indeed a function of stresses (that favor recrystallization and thus a reduction of grain size) and time (as grains naturally coarsen on geological time scale). The complex mineralogy of the mantle, where grains of different compositions interact, also imply that the mantle rheology cannot be simply derived from that of its major component. I will advocate that a better understanding of the evolution of microscopical properties are necessary to understand our planet geodynamics and why other telluric planets do not seem to be in a plate tectonics regime.

Keywords: mantle structure, mantle dynamics, plate tectonics

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The rheology of the partially molten mantle

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Abstract

Many of the important questions in mantle dynamics are ultimately questions about the mantle's rheology: how do mantle rocks respond when stressed at different conditions of temperature, pressure, grain size, and volatile content? Such questions are particularly pertinent in the uppermost 100 km where the mantle melts, as the presence of melt can lead to a dramatic change in rheological properties.
Laboratory experiments and theory have suggested that at the onset of melting there is a significant (a factor of 5 or more) drop in the effective shear viscosity of mantle materials. One theoretical explanation for the drop, put forward by Takei and Holtzman (2009), is that the presence of melt along grain edges enables a fast path for diffusion, and thus a significant weakening for a material deforming by diffusion creep.

In this presentation I will give overview of grain-scale models of diffusion creep in the presence of melt. I will present some new calculations of the effective shear and bulk (compaction) viscosities of partially molten rocks as function of porosity. Bulk viscosity is typically singular as porosity approaches zero (i.e. no melt), but the character of the singularity depends very much on assumptions about the microscale physics. For example, diffusion-based models can lead to logarithmic singularities in the porosity, whereas microscale models based of Stokes flow (e.g. Simpson et al. (2010)) lead to singularities inversely proportional to porosity. The new models I will present suggest that the effect of melt on the shear viscosity may be less dramatic than the theory of Takei and Holtzman (2009) predicts.

Simpson, G., Spiegelman, M., and M.I. Weinstein (2010), A Multiscale Model of Partial Melts 1: Effective Equations. J. Geophys. Res. 115, B04410.
Takei, Y., and B. K. Holtzman (2009), Viscous constitutive relations of solid-liquid composites in terms of grain boundary contiguity: 1. Grain boundary diffusion control model, J. Geophys. Res., 114, B06205.

Keywords: mantle, rheology, partial melting

*Speaker

Constraints on mantle viscosity structure from the evolution of continental motion and configuration

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Abstract

Continental drift on Earth occurs as a response to the forces exerted on the continents by mantle flow and plate tectonics; yet, continents also change such forces and thus impact on mantle dynamics, structure and evolution. This work elaborates on the question if continental drift and the evolution of continental configuration can be used to constrain mantle and lithospheric characteristics, such as viscosity.
Global spherical models of mantle convection featuring self-consistently generated plate tectonics are used to compute time-evolving continental configurations featuring six continents for different mantle and lithosphere rheologies. The analysis focuses on the partitioning of continental and oceanic plate velocities and on the ability of continents to aggregate and disperse on Earth-like timescales.

The model results suggest that Earth-like continental drift with episodes of collision and dispersal, including the (irregular) formation of supercontinents, requires a viscosity structure that favors mantle flow with intermediately long wavelength. Too short wavelength inhibits efficient aggregation of large continental clusters, while very long wavelength flow does not feature reasonable dispersal frequencies. The wavelength of flow depends on various rheological parameters such as yield stress, activation energy and viscosity layering; however, no unique combination for generating an appropriate wavelength has been identified.
In order to match the oceanic-continental plate-speed partitioning inferred from plate reconstructions since 200 Ma, an upper-lower mantle viscosity jump of _˜30 and a large contrast between lithospheric viscosity and upper mantle are necessary, but no low-viscosity asthenosphere underneath thick continental roots. However, the model results further suggest that this partitioning has experienced strong fluctuations on timescales longer than those captured by recent tectonic reconstructions.

Keywords: Mantle convection models, Continental drift, Viscosity structure

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On the use of satellite magnetic data to explore core dynamics

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Abstract

Magnetic field measurements taken on ground (e.g. by the network of geomagnetic observatories) or in near-Earth space (by Low-Earth Orbiting satellites) provide a unique opportunity to study the Earth's interior. However, what is measured by a magnetometer in space or on ground is the superposition of contributions from various magnetic sources. In addition to the core field part there are fields caused by magnetized rocks in the Earth's crust, by electric currents flowing in the ionosphere, magnetosphere and oceans, and by currents induced in the Earth by the time-varying external fields. The separation of these various contributions based on observations of the magnetic field requires advanced modelling techniques.
The availability of more than 15 years of near-continuous high-precision magnetic observations from the satellites Ørsted (1999 – 2014), SAC-C (2000 – 2006), CHAMP (2000 – 2010) and Swarm (since November 2013) allow for monitoring recent core field changes on a global scale with unprecedented quality. However, satellite magnetic observations require a different treatment than data from ground geomagnetic observatories, since the movement of the satellite (with about 8 km/s) may lead to space-time aliasing. It is therefore not possible to work with time-averaged satellite observations (as typically done when treating ground observatory data to remove, or at least minimize, contributions from ionospheric and magnetospheric sources). As a consequence of this, proper accounting for these external field contributions is essential in order to extract a "clean" core field signal. In particular the much larger external field signatures in the Polar Regions may lead to biased global models of the core field.
This review concerns the use of satellite data for core field studies and the separation of internal and external field contributions, with focus on the three-satellite constellation mission *Swarm* that was launched in November 2013. Magnetic gradient data from the two fly side-by-side (at a distance $<$ 150 km) flying Swarm spacecraft *Alpha* and *Charlie* allow for improved separation of core and external signatures, and thus in a better determination of rapid core field changes.

Keywords: magnetic field modeling

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Transport properties of Earth's core

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Abstract

Heat is transferred through the core by convection and conduction, and only the convective component provides energy to drive the geodynamo. Sha and Cohen (2011) found that the electrical conductivity of solid hcp-iron was much higher than had been assumed by geophysicists, based on electronic structure computations for electron-phonon scattering (e-p) within density functional theory [1]. Thermal conductivity is related to electrical conductivity through the empirical Wiedmann-Franz law of 1853 [2]. Pozzo et al. [3] found that the high electrical conductivity of liquid iron alloys was too high for conventional dynamo models to work-there simply is not enough energy, so O'Rourke and Stevenson proposed a model driven by participation of Mg from the core [4]. Recent measurements by Ohta et al. show even lower resistivities than predicted by DFT e-p, and invoked a saturation model to account for this, [5] whereas, Konopkova et al. found thermal conductivities consistent with earlier geophysical estimates. [6] We are using first-principles methods, including dynamical mean field theory for electron-electron scattering, and highly converged e-p computations, and find evidence for strong anisotropy in solid hcp-Fe that may help explain some experimental results. The current status of the field will be discussed along with our recent results. This work is supported by the ERC Advanced grant ToMCaT, the NSF, and the Carnegie Institution for Science.

X. Sha and R. E. Cohen, J.Phys.: Condens.Matter 23, 075401 (2011); [2] R. Franz and G. Wiedemann, Ann. Physik 165, 497 (1853); [3] M. Pozzo, C. Davies, D. Gubbins, and D. Alfe, Nature 485, 355 (2012); [4] J. G. O'Rourke and D. J. Stevenson, Nature 529, 387 (2016); [5] K. Ohta, Y. Kuwayama, K. Hirose, K. Shimizu, and Y. Ohishi, Nature 534, 95 (2016); [6] Z. Konopkova, R. S. McWilliams, N. Gomez-Perez, and A. F. Goncharov, Nature 534, 99 (2016).

Keywords: core, electrical conductivity, transport, geodynamo, iron, first, principles

*Speaker

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Melting of iron alloys in Laser-Heated Diamond Anvil Cell

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Abstract

Planetary cores are mainly constituted of iron and nickel, alloyed with lighter elements (Si, O, C, S or H). Understanding how these elements affect the physical and chemical properties of solid and liquid iron provides stringent constraints on the composition of the Earth's core. In particular, melting curves of iron alloys are key parameter to establish the temperature profile in the Earth's core, and to asses the potential occurrence of partial melting at the Core-Mantle Boundary.

As today, throughout the literature, we can observe an overall agreement on the melting temperature of many iron alloys under extreme conditions, with results within mutual uncertainties, irrespectively of the melting diagnostics. However, a controversy has been recently pointed out on the case of pure iron, with XANES measurements (Aquilanti et al, PNAS, 2015) in open disagreement with previous results by x-ray diffraction (Anzellini et al, Science, 2013). Using different melting diagnostics, (X-ray absorption, X-ray diffraction and analysis on recovered samples), we obtained similar results and implying that difference in previous studies are likely related to sample reaction with diamonds or other experimental issues. I will present here melting curves obtained on different iron alloys (Fe-O, Fe-C, Fe-S and Fe-Si alloys), which could provide strong constrain on potential partial melting at the Core-Mantle Boundary.

An O- and Si-rich core seems as well compatible with seismological constraints on density and velocity. However, the consequences of the proposed compositional models on core temperature profile and temperature at the core-mantle boundary (CMB) have not been considered. Thanks to our dataset, we can determine crystallisation temperature for O- and Si-rich core compositions at 135 GPa (3600-3700 K), which is close, if not higher, than melting temperature of silicates. As melting at CMB is at least not ubiquitous, and possibly absent, a significant amount of volatile elements (S, C or H) is needed in the Earth's core to lower enough its crystallisation temperature to preclude the extensive silicates melting.

Keywords: Melting, Iron alloys

*Speaker

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Force balance and wave motion in Earth's core

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Abstract

Fluid flow within Earth's outer core sustains the geodynamo and orchestrates, together with magnetic diffusion, its variability (the secular variation). The variations of this fluid flow reflect the competition between several forces, whose relative importance depends on the length and time scale of interest. The long-term, large-scale force balance is likely to involve the pressure, Coriolis, buoyancy and Lorentz forces. For a given force balance, scaling laws enable predictions of average properties of Earth's core magnetic field and flow to be made. These scaling laws have received considerable attention over the past decade, and their relevance has been mostly assessed on the basis of a database of numerical simulations spanning a moderate portion of parameter space. I will review the various interpretations of the dataset that have been made, and will stress the need for new, more extreme calculations to be included in the database.

The set of equations governing the geodynamo allows for the existence of a vast variety of waves, whose imprint may be observed (direcly or indirectly) in the secular variation and also in the fluctuations of Earth's rotation, on time scales ranging from a few years to several centuries. After discussing observations pointing to the possible existence of a wave-like signal in the secular variation, I will review the developments that have come to the fore recently regarding wave motion in Earth's core, with an emphasis on the dynamics of a stably stratified layer at the top of the core.

Keywords: Outer core dynamics and modeling, geomagnetic secular variation

*Speaker

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Understanding Core Dynamics with Reduced Models

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Abstract

The fluid motions within the Earth's outer core are known to be turbulent and highly constrained by the Coriolis force. Numerical simulations of the governing magnetohydrodynamic equations have provided significant insight into the physics of the geodynamo, but are limited to employing model parameters that remain distant from those that characterize the core due to computational restrictions. A complimentary approach to direct numerical simulation is the development of simplified, or reduced, models that filter dynamically unimportant phenomena from the governing equations. Indeed, this approach has proven invaluable for advancing our knowledge on the dynamics of the Earth's mantle, oceans and atmosphere. I will discuss a particular class of balanced flow models that, in connection with direct numerical simulation and laboratory experiment, can help shed more light on the physics of the core.

Keywords: geodynamo

*Speaker

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Dynamos driven by double diffusive convection with a stably stratified layer and inhomogeneous core-mantle boundary heat flow

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Abstract

Convective motions in the Earth's outer core generating the geomagnetic field is fueled by thermal and compositional buoyancy. Based on molecular values of thermal and compositional diffusivity, we must treat them separately because of at least three-orders-of-magnitude difference of the diffusivity coefficients. Taking the rather unknown effects of core turbulence into account, we have been allowed to combine them together into the codensity. However, even with the turbulent diffusivity, validity of the codensity adopting the same values of thermal and compositional diffusivities may not completely be guaranteed. Hence we have used a dynamo model driven by double diffusive convection instead of using the condensity in order to see whether or not a slight difference between the diffusivity coefficients can affect core flows and resultantly dynamos. As a consequence, it is found that dynamos driven by double diffusive convection often yield morphological difference in the dynamo-generated magnetic field (Takahashi, 2014). With the dynamo model adopting double diffusive convection, we then reconsider the effects on dynamos of a thin layer below the CMB, which is either thermally or compositionally stably stratified. Regardless the origin of the stable layer, of which thickness is 0.1 fold of the core radius (_˜350 km), the resultant magnetic fields at the CMB are rather large-scaled and strongly attenuated compared with those without the layer. In order to be compatible with the observed geomagnetic field strength, it is suggested that the stably stratified layer should be thinner or more weakly stably stratified. Also, we examine effects of inhomogeneous (Y22 pattern) CMB heat flux with the stably stratified layer. Most remarkable is a stabilizing effect on the dipolar components, depending on the ratio of thermal buoyancy to the total buoyancy. In case of a stabilized dipolar dynamo, the ratio of the relative axial helicity in the northern hemisphere to the southern one is almost -1, whereas the relative axial helicity is systematically biased in an either hemisphere in non-dipolar dynamos without the Y22 heat flux at the CMB. In summary, the morphology of the dynamo-generated magnetic field is strongly affected by the ratio of thermal to compositional buoyancy, a stably stratified layer, and CMB heat flux boundary condition. We consider that investigating the integrated effects of the issues examined here should be an important step for understanding dynamics in the Earth's core and also the current state of the geodynamo.

Keywords: dynamo, double diffusive convection, stably stratified layer, inhomogeneous CMB heat flux

*Speaker

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Seismic structures in the core-mantle boundary region

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Abstract

In recent years, seismology has provided increasingly detailed images of the interior of the Earth, especially since the onset of the deployment of temporary seismic arrays: Seismic tomography has revealed that some slabs descend into the lower mantle while others seem to stagnate at the mantle transition zone; Topography of seismic discontinuities can provide information the dynamics of the mantle but also on the mineralogy of the Earth's mantle. Deeper in the Earth, the D" layer has been studied extensively, revealing more and more complex features for which several hypotheses to explain them have been brought forward. Other interesting observations include the topography of the core-mantle boundary, possible detections of hot upwellings in the deep mantle and the presence of large low shear velocity provinces in the lowermost mantle. In this presentation we will review some of these observations from the core-mantle boundary region and their connection to dynamics and mineralogy of the Earth's mantle. The observed structures in the D" region (the lowest 200-400 km of the Earth's mantle) and the lowermost mantle could for example be partly due to the post-perosvkite phase transition that should be visible mostly in cold (fast) regions of the lowermost mantle. The origin of the low velocity regions, however, is still debated. Other possibilities that could cause structures near the core-mantle boundary are deep subducted lithosphere that may be sheared and/or folded, or thermo-chemical layering, subduced mid-ocean ridge basalt, or anisotropy. The different hypotheses will be discussed and their predictions will be compared to seismic observations including as much information of the seismic waves as possible.

Keywords: core, mantle boundary, D", seismic structures

*Speaker

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Observations and models of seismic anisotropy at the base of the mantle: Towards an understanding of flow patterns

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Abstract

What does the pattern of mantle convection look like just above the core-mantle boundary? How does that pattern interact with convective motions in the rest of the mantle and their surface expressions in plate tectonic features? Because of the causative link between deformation and seismic anisotropy, the characterization and interpretation of anisotropy can provide crucial constraints on flow patterns in the mantle. While seismic anisotropy is commonly studied in the upper mantle, it is much more difficult to isolate the signal from lowermost mantle anisotropy; furthermore, major uncertainties remain about the relationships between strain and anisotropy in lowermost mantle minerals. Despite the challenges inherent in studying D" anisotropy, however, it holds exceptional promise as a tool for deciphering patterns of flow at the base of the mantle and understanding the processes that drive those patterns. In this presentation I will discuss several recent studies that have sought to characterize lowermost mantle anisotropy in specific regions, particularly the edges of low shear velocity provinces such as the African and Pacific LLSVPs and the Perm Anomaly beneath Eurasia. I will also present recent and ongoing work to construct data sets of seismic observations that can provide tighter constraints on the geometry of anisotropy than is possible with a single raypath, allowing for the detailed and quantitative testing of different hypotheses for the mechanisms and geometries. We are developing approaches that allow for mineral physics-based forward modeling to identify plausible anisotropic geometries that are consistent with seismic observations; this approach can be used to test the predictions of global and regional models for flow and elasticity at the base of the mantle.

Keywords: Seismic anisotropy, mantle convection, D" region, lowermost mantle

*Speaker

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Boundary control in models of rotating convection

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Abstract

Seismic tomography and mantle convection simulations both strongly suggest that Earth's lowermost mantle supports large-scale lateral temperature anomalies. The manner in which core convection responds to this forcing depends on the pattern and amplitude of the associated lateral variations in heat flow at the core-mantle boundary (CMB). The present-day pattern of CMB heat flow is dominated by a spherical harmonic Y22 component and this forcing has often been invoked to explain prominent non-axisymmetric structure observed in the geomagnetic field and its secular variation. The Y11 pattern has also received much attention given its potential applications to past Earth, early Mars, and the cores of exoplanets that are in synchronous rotation with their parent star. Numerical simulations have found novel effects such as locking and resonance in the boundary-forced system that do not arise in the corresponding homogeneous system. Moreover, simulations often find that the heterogeneous boundary forcing drives large-scale flows that penetrate deep into the interior and sometimes influence conditions at the base of the liquid core. However, it is not clear which effects prevail in the vigorously convecting and rapidly rotating regime that characterises planetary cores. We undertake a systematic investigation of the role of heterogeneous boundary forcing in numerical models of non-magnetic convection in a rotating spherical shell. The dynamics of the homogeneous system are determined by the Rayleigh number Ra, measuring the strength of the basal thermal driving force, the Prandtl number Pr, the ratio of viscous and thermal diffusion, and the Ekman number E, measuring the strength of the Coriolis force. We consider models with Pr=1, E=1e-4 - 1e-6 and Ra up to 500 times the critical value for the onset of homogeneous convection, which is approaching the degree of supercriticality estimated for Earth's core. Boundary forcing is described by either a Y11 or Y22 pattern, and an amplitude q*, with values 2.3 and 5.0 chosen to promote strong boundary effects. Resonance and locking, which have been obtained at Ra just above critical, are not found in our models. The flow pattern directly below the outer boundary differs significantly between homogeneous and heterogeneous cases across the whole spectrum of parameters tested. However, in the interior, the homogeneous and heterogeneous solutions converge as models are moved towards the geophysically relevant limits of high Ra and low E. Applied to Earth's core these results suggest that boundary effects are limited to a relatively thin region below the CMB.

Keywords: Outer core convection, core, mantle interaction

*Speaker

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Other Planets Observations

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Abstract

For terrestrial planets other than Earth, the study of their deep interiors cannot yet be done through seismology as this deployment is still technologically very challenging. Seismic measurements have never been performed except on the Moon, and marginally on Mars (unusable results from Viking). In absence of seismometer and with the objective to determine interior properties, tides, gravity, and rotation studies of the terrestrial planets Mars, Venus, and Mercury (as well as of the icy moons of the solar system) have been the most suitable methods. These methods use spacecraft orbiting around the planet or landed on its surface. The most common way of getting data is to use radioscience Doppler and ranging measurements. Complementary data from radar, altimeter, accelerometer, camera, spectrometers etc. are useful as well.
Mars: Shortly after their formation, the Earth and Mars must have been pretty alike. Nowadays, those neighboring planets show many differences, in particular in their mantle and core. We will present the state-of-the-art knowledge of the interior of Mars, in particular, on the state, dimension, and the composition of the iron core, based on the tidal time variations of the gravity field and on precession and nutations (determination of the moments of inertia of the different layers inside Mars). We will review at what level we are at present and what will be reached with the future NASA InSIGHT (Interior exploration using Seismic Investigations, Geodesy, and Heat Transport) mission and the future ExoMars LaRa (Lander Radioscience) experiment, in 2018 and 2020.

Venus and Mercury: Similarly, the rotation and orientation of Venus and Mercury provide information on their interior. But as these planets are rotating more slowly, only tides and librations (and not precession-nutation) can be used for studying their interiors.
Terrestrial moons: This review paper will marginally touch on the larger planets of our solar system, neither on the smaller ones. However, it is believed that it is also interesting to review what we know about the interiors of the terrestrial moons of our solar system like Europa, Ganymede, Titan etc. as they have similar dimensions to the terrestrial planets. The methods, approaches, and models used in the above-mentioned terrestrial planets are presently also applied to the icy moons of Jupiter and Saturn. This allows to better understand de past and present missions such as Cassini in the Saturnian system and the future missions such as JUICE (JUpiter ICy moons Explorer).

Keywords: terrestrial planets rotation tides interior

*Speaker

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Interior properties of Jupiter's moons from observations of their magnetic field environments

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Abstract

The four large moons of Jupiter, Io, Europa, Ganymede and Callisto are generally referred to as terrestrial-type planetary bodies. They consist of three major layers, i.e., metal rich cores, silicate mantels, and diverse crusts. In the case of Io the crust is mostly made of silicates and sulfur deposits and in the case of the icy moons Europa, Ganymede and Callisto the crusts/outer layers mostly consist of water in solid and liquid phases. Evidence for the liquid phases comes from measurements of induced magnetic field signatures obtained by the Galileo spacecraft near the moons. These measurements provide evidence on different degrees of reliance for electrically conductive layers close to the surface. Within the icy moons, these conductive layers are attributed to saline subsurface layers of liquid water and within Io it could be a magma ocean. In our talk we critically review the evidence for the conductive layers within Jupiter's moons. We also present a new technique to search for a conductive layer, i.e., a saline ocean, within Ganymede using a telescope.

Keywords: Moons of Jupiter, subsurface oceans, magnetic fields

*Speaker

sciencesconf.org:sedi2016:116533

Thickness of Mercury's crust and lithosphere from geoid and topography observations

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Abstract

Measurements of Mercury's topography and gravity fields obtained from laser altimetry and radio-tracking by the MESSENGER spacecraft represent fundamental observations that can be used to infer the thickness of the crust and lithosphere of the planet. The analysis of the geoid-to-topography ratios over the northern hemisphere shows that the observations at intermediate wavelengths - at harmonic degrees between ˜9 and 15 - can be well explained in terms of an Airy model of isostatic compensation of the topography associated with lateral variations of the crustal thickness, whose mean value is estimated to be 35 +/- 18 km. Given the small thickness of Mercury's mantle of only ˜400 km, this crustal thickness implies that Mercury had the highest efficiency of crustal production among the terrestrial planets. The longer wavelength components of Mercury's geoid and topography, however, require a different interpretation. In particular, the degree-2 coefficients of the geoid and shape have long been known for not being consistent with the hydrostatic equilibrium values dictated by the rotational and tidal potentials. Because of the high eccentricity, small obliquity, and 3:2 resonance of the orbit, Mercury's surface experiences an uneven insolation that leads to large latitudinal and longitudinal variations in temperature whose spectrum is dominated by degree 2 and, to a lesser extent, degree 4. Once established, these variations diffuse to depth, imposing a long-wavelength thermal perturbation throughout the mantle. We computed the accompanying density distribution and used it to determine the mechanical and gravitational response of a spherical elastic shell overlying a quasi-hydrostatic mantle. We then compared the predicted geoid and surface deformation at degrees 2 and 4 with the observed geoid and topography. More than 95% of the data can be accounted for if the thickness of the elastic lithosphere was between ˜110 and 180 km when the thermal anomaly was imposed. According to our numerical models of thermal evolution, these values of the elastic thickness can only be achieved about 1 Gyr after planetary formation. This implies that Mercury may have been locked into its 3:2 spin-orbit resonance relatively late in the evolution, possibly as a consequence of a large impact that disrupted a previously synchronous rotational state.

Keywords: Mercury, geoid, topography, thermal evolution

*Speaker
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Dynamics and evolution of Jupiter's and Saturn's icy moons

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Abstract

The exploration of Jupiter's and Saturn's system respectively by Galileo (1996-2003) and Cassini-Huygens (2004-2017), has revealed that several moons around Jupiter (Europa, Ganymede, Callisto) and around Saturn (Titan, Enceladus, Mimas) harbor a subsurface salty ocean underneath their cold icy surface. The composition of these oceans probably results from complex aqueous processes involving interactions between water, rock, organics and volatile compounds from which these bodies were built. Such aqueous processes were presumably vigorous during the early stage of interior differentiation when water and rock separated, but they could be still active in some icy bodies at present, as witnessed by the intense activity observed at Enceladus' south pole by the Cassini spacecraft. The analysis of icy grains emitted from Enceladus indicates the presence of salt and organics mixed with ice, thus providing crucial constraints on the oceanic composition and indirect information on aqueous processes at its origin. The co-existence of water, organics and salts together with a strong heat source associated to tidal friction may potentially lead to the first bricks of life. Even if there is no direct evidence yet, similar ingredients might also be present within Europa, Titan and Pluto. Assessing the astrobiological potential of these oceanic environments require a better understanding of their present-day structure of the satellite interior as well as their possible evolution since their formation. In this seminar, I will give an overview of the current knowledge about the interior of icy moons, with a particular focus on Enceladus, Europa, Ganymede and Titan. I will discuss the possible occurrence of active aqueous processes on these bodies and the implications for the habitability of their subsurface oceans.

Keywords: Icy moons

*Speaker

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The turbulent and magnetic response of planetary fluid interiors to tidal and librational forcing

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Abstract

The turbulence generated in the electrically conductive liquid metal cores and subsurface oceans of planetary bodies may be due, in part, to the role of boundary forcing through such geophysically relevant mechanisms of precession/nutation, libration, tidal forcing, and collisions. Here, we combine laboratory equatorial velocity measurements with selected high-resolution numerical simulations to show, for the first time, the generation of bulk filling turbulence driven by tidal forcing. The transition to saturated turbulence is characterized by an elliptical instability that first excites primary inertial modes of the system, then secondary inertial modes forced by the primary inertial modes, and finally small-scale turbulence. The results of the current work are compared with recent studies of the libration-driven turbulent flows. These separate analog models correspond, in geophysical terms, to two end-member types of mechanical forcing. In tidal forcing, non-synchronous satellites possess elastically deformable boundaries such that shape of the distortion has a non-zero mean motion. For librational forcing, the core-mantle boundary possesses an inherently rigid or tidally frozen-in ellipsoidal shape in a synchronous orbit such that the mean motion of the elliptically deformed boundary is zero. We find striking similarities in both the transition to bulk turbulence and the enhanced zonal flow hinting at a generic fluid response independent of the forcing mechanism. Implications for the generation of a large-scale magnetic field through dynamo action will be discussed.

Keywords: Turbulence, Dynamo, Tides, Libration

*Speaker

Magnetostrophy in spherical dynamo simulations and its implications for planetary magnetism

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Abstract

Theory predicts that the dynamics and dynamos within the rapidly-rotating, electrically-conducting fluid cores of some planets, including the Earth, will be in the magnetostrophic regime, in which the Lorentz force balances the Coriolis force. Although substantial progress has been made in direct numerical simulations of convection-driven spherical dynamos, it remains controversial whether current simulations are truly representative of planetary interiors and can identify the magnetostrophic state as expected in theory. Here we present the signatures of magnetostrophic dynamos in spherical shells, as evidenced by the convective pattern selection, wave motion, and subcritical and strong-field dynamo scenarios. In order to define these characteristics, studies of rotating magnetoconvection are crucial. The dynamics of magnetostrophic dynamos may partly explain key features of observed planetary fields, such as the generation of the large-scale (dipole-dominated) magnetic fields of the Earth and the termination of the early Martian dynamo. Notably, its wave motions can account for observed temporal variations of planetary magnetic fields and have the potential for inferring physical properties, such as the internal field strength, within the dynamo regions. The proven importance of magnetostrophy will enable us to adopt asymptotic approaches, as well as direct numerical simulations, for understanding the dynamics and dynamo action within planets.

Keywords: Planetary magnetic fields, Rotating magnetoconvection, Waves, Length scales, Subcritical dynamos

*Speaker

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Direct models of seismic anisotropy of the inner core

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Abstract

Seismic observations using body waves differential travel times, long period normal modes, and the analysis of autocorrelation of earthquake coda provide strong evidences that the Earth's inner-core is anisotropic, with P-waves traveling faster by up to 3% in the polar than in the equatorial direction. Further analyses refined this observation, providing evidences for both hemispherical and radial variations of the amplitude of anisotropy. However, this apparent complexity should not obscure the first-order observation that the fast propagation direction for inner-core seismic waves is aligned with the Earth's rotation axis. And the observed axial anisotropy still lacks a conclusive explanation. This work focuses on reproducing this first-order observation from a multiscale model. The seismic anisotropy results from a coherent alignment of anisotropic Fe-alloy crystals through the inner-core history that can be sampled by present-day seismic observations. By combining self-consistent polycrystal plasticity, inner-core formation models, Monte-Carlo search for elastic moduli, and simulations of seismic measurements, we build a multiscale model that can reproduce a global seismic anisotropy of several percents aligned with the Earth's rotation axis. We first explore the cubic phases of iron. The abundance of symmetries for elasticity and plasticity of body-centered-cubic (bcc) and face-centered-cubic (fcc) phases combined with the integrated nature of inner-core anisotropy measurements is such that plastic deformation of such crystal structures cannot explain the global inner-core anisotropy. Then, we investigate the effect of an hexagonal-close-packed (hcp) structure for the inner-core Fe alloy. Under the assumption that the inner-core anisotropy results from plastic deformation along a dominant slip system, we find that necessary conditions for a successful anisotropic model are 5 to 20% single crystal elastic anisotropy, plastic deformation by pyramidal slip, and a large-scale flow induced by a low-degree inner-core formation model.

Keywords: inner core

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Core mineralogy: Phase diagram of Fe-light element alloy under multi-megabar pressure

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Abstract

Since the inner core formation is a consequence of crystallization from liquid outer core, the phase diagram of relevant core material at the inner/outer core boundary (ICB) pressure is a key piece of information required to decipher light element fractionation at the ICB and resultant structure in the inner core.
Although extensive efforts in the community have long been made to determine the phase relations of Fe/Fe-alloys, the experiments at the real condition of the ICB condition is still needed because pressure-induced formation of an intermediate compound and/or a structural phase transition dramatically change phase relations including eutectic temperature and composition (Stewart et al., 2007), prohibiting us from extrapolation from lower pressure data. Indeed, a prominent example of iron-sulfur system shows that a simple binary eutectic system Fe-FeS at 1 atm changes to Fe-Fe3S2 at 14 GPa, and then Fe-Fe3S at 21 GPa (Fei et al., 1997; 2000). Note that the formation of Fe-rich compound as an end-member leads the eutectic composition to be more Fe rich. Our earlier study revealed that Fe3S decomposes into S-poor hcp-Fe and S-rich B2 (CsCl-structure) phase above 250 GPa (Ozawa et al., 2013), suggesting new end-member in this system. We then investigated more detailed phase relations in iron-sulfur system at multi-megabar regime.

Fe-6wt.%S and Fe2S were used as a starting composition. The foil with former composition was prepared by an ultra-rapid quench method, providing homogenous mixture of Fe and FeS below 1 micron scale (Morard et al., 2011). The latter was synthesized by a multi-anvil press at 30 GPa. Synchrotron X-ray diffraction measurements were carried out in-situ at high pressure and temperature in a laser-heated diamond-anvil cell at BL10XU, SPring-8. The result shows that hcp-Fe and B2 phases are formed from Fe-6wt.%S from 250-278 GPa at 2000-3000 K. Fe2S formed single phase with B2 structure. Subsequently, unit-cell volumes for B2-Fe2S were measured on decompression to 150 GPa. Then, the resultant compression curve was consistent with the volumes B2 phase formed Fe-6wt.%S. These observations clearly indicate that B2-Fe2S should be considered as a new end-member compound above 250 GPa. Pressure dependence both of eutectic temperature and composition should differ from that below 250 GPa, which call for more direct experiment independent from extrapolation by lower pressure one.

Keywords: DAC, high pressure, inner core, phase diagram

*Speaker

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Seismic signature of melting and freezing near the inner core boundary

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Abstract

Two competing hypotheses have been put forth to explain seismic hemispheric structure in the uppermost inner core and the F-layer in the bottommost outer core, in which simultaneous melting and freezing near the Inner Core Boundary (ICB) are predicted. The inner core solidification process driven by outer core flow coupled to lateral thermal variations near the Core-Mantle Boundary (CMB) suggests higher than average homologous temperature (T/Tm) and/or melting beneath the Pacific Ocean (Western Hemisphere, [WH]) along with freezing beneath Southeast Asia (Eastern Hemisphere, [EH]), whereas that driven by eastward translation of the inner core suggests freezing in the WH and melting in the EH. Results from mineral physics experiments show that iron phases (HCP, FCC, BCC) preferred for the inner core exhibit significant deviation from ideal elastic behaviour characterized by a sharp drop in velocity along with an exponential increase in attenuation near their respective melting temperatures. Within the hemispherical structure of the inner core, however, such a feature is not observed. In fact, only a positive correlation between isotropic velocity and attenuation is observed. To investigate this seeming discrepancy, we constrained the meso-scale (intra-hemispherical) structure of the inner core by inverting PKIKP and PKiKP waveforms in the 130○-140○ distance range for precise velocity and attenuation structure using a novel deconvolution technique, whereby we minimized the effects of source and crustal and mantle structure. Our meso-scale structural model for the region beneath the Pacific shows a clear inverse correlation between isotropic velocity (lower) and attenuation (higher) consistent with mineral physics predictions. This observation implies that the region beneath the Pacific has higher than average homologous temperature and is possibly melting. The rest of the inner core exhibits a positive correlation between velocity and attenuation. This new observation emphasizes the fact that hemispheric structural model often constrained only from velocity is an overly simplified and spatially-aliased representation of reality. Our meso-scale model favours an inner core solidification process driven by outer core convection coupled to lateral thermal variations near the CMB. We continue to probe meso-scale features in the inner core using newer datasets containing PKIKP, PKiKP, and antipodal PKIIKP waveforms, and our preliminary results are reflective of the complex nature of uppermost inner core at meso-scale, which seems to correlate with melting and freezing processes.

Keywords: inner core, mesoscale structure, melting, freezing, outer core convection, solidification

*Speaker

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Posters

Please use double-sided adhesive tape to hang posters, no pin.

Lowermost mantle thermal conductivity and core-mantle boundary heat flux modelled from high-pressure experimental measurements

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Abstract

We use new bridgmanite ((Mg,Fe)SiO3) lattice thermal conductivity measurements obtained from high pressure mineral physics experiments in combination with thermo-chemical models derived from normal mode seismology (probabilistic tomography) to map lateral variations in lowermost mantle (2000-2891 km) thermal conductivity, and in core-mantle boundary (CMB) heat flux. Experimental data were obtained by combining ultrafast time-domain thermoreflectance with high pressure diamond anvil cell technology. At lower mantle pressure (120 GPa), this new dataset indicates that the conductivity of iron-bearing bridgmanite, (Mg0.93,Fe0.07)SiO3, decreases by about a factor 2 compared to that of pure Mg-bridgmanite. Combined with maps of temperature and composition (iron content and fraction of bridgmanite) derived from probabilistic tomography, which predict an enrichment in iron within the large low shear-wave velocity provinces (LLSVPs), and assuming that thermal conductivity varies with temperature as (1/T)ˆn with $n = 0.5$, our experimental data show that lowermost mantle thermal conductivity decreases by up to 50% within LLSVPs, mainly as a result of the excess in iron and bridgmanite in these regions. CMB heat flux varies accordingly, with heat flux lows in LLSVPs. At global scale, however, heat flux anomalies are dominated by temperature anomalies, with heat flux highs located beneath the southern tip of South America, and beneath Japan. These results may have important implications on the dynamics of both LLSVPs and outer core.

Keywords: Thermal conductivity, lower mantle, CMB heat flux

*Speaker

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Seismological constraint of velocity and density contrast across the upper mantle discontinuities beneath East Asia

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Abstract

Subduction process operating over much of the Earth's history induces long-term mantle mixing, chemical heterogeneity and recycles volatiles into the mantle. Transition zone seismic discontinuities, among all, hold the key to understand the consequences of mantle mixing, the distribution of chemical heterogeneities, hydration or/and compositional layering in the deep upper mantle and the transition zone.

To help answer these questions, we adapt a simple, effective and high resolution probing of mantle discontinuity through examination of forward and backward scattering waves in the context of teleseismic receiver function method, which enable us to characterize the essence of discontinuity properties such a velocity contrast, density contrast, transition sharpness and gradient. The direct P-to-s conversion (Pds) is mainly sensitive to the shear wave velocity contrast, while the topside reflections (PpPds) are sensitive to the impedance contrast and density. Frequency-dependent property of the discontinuities and its depth gradient can be estimated through broadband analysis of receiver functions at the central period of _˜1-15 seconds.

We compute 'high-quality' receiver functions in L-Q-T coordinate system to examine the Pds and the PpPds caused by the 410 and the 660 using Chinese (_˜1000 stations), Korean (52 stations) and F-net Japanese (73 stations) seismic network data. Our massive dataset have superb coverage beneath East Asian continents, and ensure the stable extracting of the weak multiple signals from 410 and 660. We can expect the spatial resolution greatly enhanced. Here we present a first glimpse of discontinuity property in the vicinity of stagnant slab beneath northeast China, Korea and Japan, offering an excellent opportunity to quantify the role of mantle mixing in the presence of current and past subduction.

Keywords: mantle discontinuity, velocity contrast, density contrast, east Asian, receiver function multiples

*Speaker

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Structure-preserving modeling of damped seismic waves

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Abstract

Most of the information on the Earth's deep interior can be obtained from seismic waves. High-precision modeling of seismic waves at the global scale involves long-time and high-precision calculation of seismic wave propagation, it is indispensable to studies of the Earth's deep interior. This is one of difficult problems in the seismological research fields. For developing methods of seismic inversion and high-resolution seismic wave imaging, the above-mentioned problem has to be solved as perfect as possible. Also, for long-term simulations of seismic wave (e.g., global-scale seismic wave propagation modelling and Earth's free oscillations modelling), the high precision of long-time calculations is very crucial.
Modeling seismic waves in the time domain using direct methods involves discretization of partial differential equations. Because the traditional methods (nonsymplectic schemes) for temporal discretizations are not structure-preserving schemes, it is extremely difficult to avoid accumulated errors in long-time numerical simulations for partial differential equations using these methods. Although some structure-preserving methods for modeling seismic waves have developed for the past few years, these methods are only suitable for undamped waves. However, realistic seismic waves, more or less, are damped waves.

In this paper, a symplectic method for structure-preserving modeling of damped seismic wave is presented. In the method presented, an explicit second-order symplectic scheme is used for the time discretization. The performance of the proposed scheme has been tested and verified using numerical simulations of attenuating seismic-wave equation. Seismic wavefield modeling experiments on a heterogeneous medium with both damping and high parameter contrasts demonstrate the superior performance of the approach presented for suppression of numerical dispersion. Long-term computational experiments display the remarkable capability of the approach presented for long-time simulations of damped wave equations. Promising numerical results suggest the approach is suitable for high-precision and long-time numerical simulations of wave equations with damping terms, as it has structure-preserving property for the damping term.
Acknowledgments This work is supported by the National Natural Science Foundation of China (Grant No. 41574053)

Keywords: Structure, preserving modeling, damped seismic waves, long, term simulations, Earth's free oscillations modelling

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Shear-wave velocity and attenuation of the lowermost mantle beneath the western Pacific using waveform inversion

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Abstract

We investigate the elastic and anelastic structure of the lowermost mantle at the western edge of the Pacific large low shear-wave velocity province (LLSVP) by inverting S and ScS waveforms. The transverse component data were obtained from F-net for 54 deep sources beneath Tonga and Fiji, and filtered between 12.5 and 200 s. We observe a regional variation of S and ScS arrival times and amplitude ratio, according to which we divide our region of interest into five sub-regions. For each sub-region, we then perform 1D waveform inversion simultaneously for shear-wave velocity (Vs) and quality factor (Q). We find that, compared to the four other models, which are very similar with one another, the model obtained for the central region sampled by the Fiji events (sub-region 2) has lower Vs and Q. This difference is observed throughout the depth range 2000-2890 km, but is more pronounced around 2800 km and deeper. Interestingly, the sub-region 2 encompasses the Caroline plume, which appears as slower than average in Vs on recent tomographic models. Because all sub-regions are located within the Pacific LLSVP, the differences in Vs and Q in the layer 2500-2980 km may be related to temperature variations within this LLSVP. At shallower depths (2000-2500 km), we suggest that the differences between sub-region 2 and the surrounding sub-regions denote temperature differences between the ambient mantle and the Caroline plume. At these depths, a careful comparison between the temperature difference calculated from the Vs and Q anomalies indicate that part of the low Vs anomaly observed in sub-region 2 may be related to small amount of iron-rich material entrained by the Caroline plume.

Keywords: Shear, wave velocity, Seismic attenuation, Waveform inversion, Lowermost mantle, Pacific LLSVP

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sciencesconf.org:sedi2016:105902

Out-of-plane signals – what can they tell us about the Earth's mid- and lower mantle?

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Abstract

The Earth's mid- and lower mantle is thought to be dynamically well mixed and more homogeneous than the upper or lowermost mantle. Tomographic inversions for P- and S-wave seismic velocities show images of long wavelength structures like fast velocity regions descending into the deep Earth or the two antipodal large slow shear-wave velocity provinces at the base of the mantle extending upwards to around 1000 km depth. However, direct observations of mantle heterogeneities are scarce but necessary to make statements concerning their structural differences. To investigate the mid- and lower mantle we search for seismic signals that reach a seismic array with a backazimuth deviating from the theoretical backazimuth of the earthquake and therefore call them out-of-plane signals. Information on slowness, backazimuth and travel time of the observed out-of-plane arrivals is used to backtrace the wave through a 1D velocity model to its scattering or reflection location and to map seismic heterogeneities in the mid- and lower mantle. Assuming only single scattering in the backtracing algorithm, most detected out-of-plane signals have to travel as P-to-P and only a few as S-to-P phases, due to their timing. The located reflection points present a view of the 3D structures within the mantle. To validate our approach, we calculate and process synthetic seismograms for 3D wave field propagation through a model containing a slab like heterogeneity and compare them with the earthquake data. Taking into account the radiation pattern of each event in direction of the great circle path and towards the calculated reflection point, it is possible to compare the polarities and waveforms of the out-of-plane signals with the direct P arrivals. The data set consists of earthquakes from Japan, the Philippines and the Hindukush recorded at North American networks (e.g. USArray, Alaska and Canada). The data cover a period from 2000-2012 with a minimum magnitude of 5.6 Mw and depths below 100 km. We focus on two different regions: slabs around the North Pacific and the mid Pacific low velocity anomaly. The location of the reflection points found generally agree with fast or slow velocities mapped by seismic tomography models suggesting, that we map slabs enter the lower mantle and heterogeneities with rather low velocities in the mid Pacific.

Keywords: array seismology, mantle processes, North Pacific, computational seismology

*Speaker

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Crustal and upper mantle structure beneath the Middle-Lower Yangtze Metallogenic Belt revealed by broadband seismic observations

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Abstract

From May 2012, China University of Geosciences (Beijing) began to deploy a temporary broadband seismic network that was designed to explore the crustal and upper mantle structure of the Middle-Lower Yangtze Metallogenic Belt (MLYMB) and its adjacent regions with an average station spacing of about 50 km. The first phase of this experiment, which consists of 20 CMG-3ESPC broadband seismometers, operated from May 2012 to June 2014. Since June 2014 the second phase began to operate, which consists of 15 CMG-3ESPCD and 10 NANO broadband seismometers. By using the data collected from this experiment and from Chinese provincial networks, we first conducted ambient noise and two-plane-wave tomography and obtained the upper mantle structure of the study region. The results showed that in the uppermost mantle a low-velocity zone at about 100-200 km depth is observed beneath MLYMB, at the same time, NingWu and NingZhen ore districts are clearly characterized by strong low velocity anomaly at the depth of about 70-200 km. The depth extent of the low-velocity zone becomes shallower from the southwest JiuRui ore district to northeast NingWu ore district. The observed low-velocity zone may represent the cooling hot upper mantle that was partially molten in the past resulting from partial melting of the paleo-Pacific plate or of an enriched mantle source induced by the westward subduction of the paleo-Pacific plate. Meanwhile, we conducted receiver function analysis to investigate the crustal structure of the MLYMB. The results showed that the Moho depth varies greatly along the MLYMB. The shallower Moho was observed beneath NingZhen ore district and Hehuai basin, this may be caused by the upwelling of the hot materials from the mantle.

Keywords: Middle, Lower Yangtze Metallogenic Belt, seismic observation, crust and upper mantle, geodynamics, seismology

*Speaker

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Waveform modeling of the subducted Hess Conjugate beneath Gulf of Mexico

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Abstract

Morphology of subducted slab remnants is essential to our understanding of the subduction and tectonic history. Here, we image a block of subducted Farallon plate beneath the Gulf of Mexico in the transition zone and lower mantle, using waveforms from a series of deep-focus earthquakes in South America recorded by the USArray. In addition to travel time anomalies, the edges of the slab cause strong multipathing of S and ScS at different distances. We jointly invert the ScS and S travel time, amplitude and waveform complexities for the best fitting rectangular shaped slab model. Our inversion results indicate a about 1000-km long slab dipping toward the S40E direction, with the shallow end above the transition zone. The slab core is 100 km thick with extended tapered sides with about 50 km at both the top and bottom edges. In conjunction with plate reconstruction implications, the acient subducted oceanic plateau, Hess conjugate, is likely responsible for the origin of the submerged slab remnant.

Keywords: waveform modeling, Hess conjugate, Farallon plate, sharp edges

*Speaker

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New constraints on the shear velocity structure of the Earth's mantle from the joint inversion of normal mode, surface wave and body wave data

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Abstract

We present SEISGLOB2 our new degree 40 shear velocity tomographic model of Earth's mantle. SEISGLOB2 results from the joint inversion of published normal mode data with our surface wave (22,000,000 Rayleigh wave phase velocities measured by Durand et al., 2015) and body wave (400,000 travel times measured by Zaroli et al., 2010) datasets. We made a major effort to include cross-coupling structure coefficients which provide new and valuable constraints on odd spherical harmonic degrees in the lower mantle. SEISGLOB2 enables us to better image the slabs and the structure of the LLSVPs. In particular, we clearly observe some behaviour changes of slabs, hotspots and LLSVPS at around 1,000 km depth where these structures generally stop and then extend laterally. The presence of such a transition can have great impacts on our understanding of the mantle dynamics and should thus be taken into account in future modeling.

Keywords: tomography, 1000km depth transition, body waves, normal modes, surface waves

*Speaker

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Constraining heterogeneity properties throughout the mantle from scattered seismic waves

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Abstract

Current global tomography models generally agree on the location and amplitude of large-scale three-dimensional structure, but these models do not reliably map heterogeneity smaller than about 1000 km in size. To constrain the strength and size-distribution of smaller scale structure, we characterize and model scattered energy in the global seismic wavefield. We present results from global analyses of P coda, PKP precursors, and PKKP precursors which give constraints on upper mantle heterogeneity, lowermost mantle heterogeneity, and core–mantle boundary topography, respectively. Our focus is on constraining the spectrum of heterogeneity throughout the mantle by analyzing the frequency dependence of scattered energy. In the upper mantle, we find significant heterogeneity at intermediate scales (5–500 km), modeling the character of long-period P coda with a heterogeneity power spectrum that decays as 1/wavenumber (1/k). This spectrum ties together constraints from large-scale structure from tomography studies and smaller-scale structure inferred from high-frequency scattering results. In the lowermost mantle, the short time-duration of PKP precursors limits our analysis to scales smaller than about 30 km, where we find that heterogeneity in seismic wavespeed is an order of magnitude weaker than it is in the upper mantle. The frequency dependence of PKP precursors, however, suggests that the shape of the lower-mantle heterogeneity spectrum is similar to—and possibly slightly whiter than—the 1/k upper mantle spectrum.

Keywords: small scale heterogeneity, compositional heterogeneity, seismic wave scattering

*Speaker

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Anomalous ScS2/ScS ratios, estimates of Q, and the influence of shear-velocity heterogeneity in the lower mantle

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Abstract

The seismic phases ScS and ScS2 (i.e., ScSScS) are shear wave reflections off the outer core. ScS and ScS2 are among the cleanest signals in seismograms: they have high amplitudes and do not interfere with other major phases. The ratio R = ScS2/ScS of the ScS2 and ScS amplitudes has been widely used to constrain the quality factor Q of attenuation in the mantle.

Among all Global Seismic Network stations, *Kanamori and Rivera* (2015) observed the highest values of R for station AFI (Afiamalu, Western Samoa). They also observed that the ScS2-ScS difference time recorded at AFI is about +10 s longer than predicted by PREM. These two seismic observations indicates that the shear wave speed in the mantle beneath Samoa is 1% lower than in PREM and that Q > 1400. It implies that 25-s period shear waves are delayed but not attenuated by the Large Low Shear Velocity Anomaly (LLSVP) beneath the Pacific.

Using specfem3D (*Komatitsch and Tromp*, 2002) wave propagation simulations for simple lower mantle structures based on tomographic model S40RTS, we demonstrate that a "plume-like" low-velocity structure in the lower mantle can explain the anomalous traveltime delays and high wave amplitudes. An explanation for slow shear wave propagation without intrinsic attenuation does not require a creative solution from mineral physics.

Keywords: LLSVP, plume, wave attenuation (Q), 3D wave propagation

*Speaker

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Effect of phase transformations on microstructures in deep mantle materials

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Abstract

Phase transformations induce microstructural changes in deep Earth materials, including changes in grain size and orientation distribution. The effect of phase transformations on mineral microstructures is usually studied using electron microscopy on quench products from high P/T experiments. The method allows for a precise evaluation of the microscopic mechanisms involved. It is limited, however, to samples that can be quenched to ambient conditions and allows for investigations at a single P/T point for each experiment. In recent years, we extended the use of multigrain crystallography to samples inside diamond anvil cells under mantle P/T conditions (Nisr et al 2014). The method allows for monitoring the orientations of hundreds of grains and grain size variations during various physical processes, such as plastic deformation and successions of phase transformations (Rosa et al, 2015). Here, we will show results concerning hydrous Mg2SiO4 during the series of α-β-γ phase transformations up to 40 GPa and 850 ◦C. Such results are important to understand the descending behaviour of subducted slabs, observations of seismic anisotropy, and polarity changes for seismic waves reflected of deep Earth interfaces. The data is used to asses the effect of the transformation on grain orientation and grain sizes. In particular, we do not observe orientation relationships between the parent α-phase and the daughter β-phase phase, suggesting an incoherent growth. We also observe significant grain size reductions and only little grain growth within the newly formed phases. These new results are important for understanding the mechanical behavior of subducting slabs, seismic anisotropy in the Earth's mantle, and phase transformation mechanisms in olivine. Now that it is validated, the method can also be applied to other phases that can not be studied using electron microscopy, such as perovskite and post-perovskite.

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*Speaker

sciencesconf.org:sedi2016:111302

Keywords: High pressure, mineral physics, phase transformations, microstructures, anisotropy, grain size, Earth's mantle

Imaging the subducting Pacific slab beneath Northeast China with the dense NECsaids array

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Abstract

Tomography studies show similar morphology of the subducting Pacific slab beneath northeast China, which was stagnant in the mantle transition zone. Resolving the accurate velocity perturbation and geometry of the slab is essential for better understanding of the thermal, chemical structure of the mantle earth, as well as geodynamics. Here we used P receiver function technique to study the fine structure of subducting Pacific slab beneath Northeast China. Teleseismic waveform data from regional permanent broadband seismic stations and our temporary NECsaids array (NorthEast China Seismic Array to Investigate Deep Subduction) in Northeast China were combined to image the upper mantle structure. The receiver functions were computed using time-domain deconvolution method with Gaussian low pass filter. Careful visual inspection was then conducted to remove bad traces with low signal-to-noise (SNR) and low coherence. The large high-quality receiver functions beneath Northeast China allow us to study the upper mantle structure and the slab structure in great detail. We use Common-conversion-point (CCP) stacking technique to image the lateral variations in the upper mantle. The bin size is chosen to be comparable with the first Fresnel zone of the receiver functions at 410 km and 660 km depths. The bins only for receiver functions more than 100 are used to image. We observed clear interfaces (one corresponds to velocity increase, the other one corresponds to velocity decrease) on the upper and lower side of the deep earthquakes, which are expected to indicate the subducting Pacific slab. To test the impact of interfaces in receiver functions, we add a high velocity layer between the 410 km and 660 km depth to model the effect of slab. We found that only a velocity perturbation larger than 3% between slab and surrounding mantle can provide sufficient seismic energy to image the slab, matching with our observations.

Keywords: the subducting Pacific slab, Northeast China, NECsaids array

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Behaviour of mantle transition zone discontinuities beneath the Indian Ocean from PP and SS precursors

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Abstract

As part of the RHUM-RUM project (Réunion Hotspot and Upper Mantle – Réunions Unterer Mantel), we investigate the upwelling plume beneath the volcano Piton de la Fournaise on La Réunion. A long-lived mantle plume is suspected to be responsible for the formation of the island. Understanding the depth origin and dimensions of such a plume helps to better understand mantle processes and the heat flux of the Earth. In this study, we use underside reflections of PP and SS waves off the upper mantle seismic discontinuities at 410 and 660 km depth, which bound the mantle transition zone (MTZ). In order to investigate the topography of these discontinuities, differential travel times between the main phase and the precursor signals are measured. The 410 km discontinuity, which exists due to the exothermic phase change of olivine to wadsleyite, should be depressed significantly in the presence of hot material. Because of the opposite Clapeyron slope of the phase change of ringwoodite to magnesiowuestite and bridgemanite at 660 km depth, the topography of this discontinuity should be elevated. All in all, a thinned MTZ is expected were hot material is present. We analysed over 8500 events with Mw $\geq$ 5.8 and bounce points distributed over the entire Indian Ocean. Using different source-receiver combinations yield a dense coverage of PP and SS bounce points in the study area, also with crossing ray paths. Array seismology methods, such as vespagrams and slowness-backazimuth analysis, are used to enhance the signal-to-noise ratio and to detect and identify the weak precursor signals. The differential travel times of PP and SS arrivals and their precursors of robust stacks are corrected for crustal features and converted into depth values. In our data, we can detect clear underside reflections of the MTZ discontinuities as well as other discontinuities like the Lehmann or X-discontinuity in the upper and also lower mantle. The results so far indicate a deep 410 km discontinuity close to Réunion and Mauritius and under the tip of India. The 660 km discontinuity seems to be elevated in those regions as well as over the entire Indian Ocean.

Keywords: Body waves, PP/SS Precursors, Upper mantle seismic discontinuities, Plume, Indian Ocean

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Insights into the presence of post-perovskite in Earth's lowermost mantle from tomographic-geodynamic model comparisons

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Abstract

Lower mantle tomography models consistently observe an increase in the ratio of shear-wave velocity (Vs) to compressional-wave velocity (Vp) variations in the lowermost mantle, accompanied by a significant negative correlation between Vs and bulk-sound velocity (Vc) variations. These seismic characteristics, also observed in the recent SP12RTS model, have traditionally been interpreted as indicative of large-scale chemical variations, though more recently the lower mantle post-perovskite (pPv) phase has also been invoked as a possible explanation. As geodynamical calculations of isochemical and thermochemical flow predict a fundamentally different style of mantle convection, interface topographies and core heat flow, we seek to answer the following questions: Are a high Vs/Vp ratio and a negative Vs-Vc correlation indicative of chemical variations? How much of the signal can be attributed to pPv? Can we distinguish between isochemical and thermochemical models using global tomographic models? To answer these questions, we compare first-order features of SP12RTS to synthetic tomographic images derived from whole mantle convection models. These models are converted to seismic velocities using constraints from mineral physics, reparametrised and convolved with the tomographic resolution operator. In contrast to previous studies, where only the Vs structures have been compared, we use both the Vs and Vp resolution operator of SP12RTS to allow direct comparisons of the resulting velocity ratios and correlations. We include geodynamic models with and without pPv and/or chemical variations to investigate the origin of the high Vs/Vp ratio and Vs-Vc anti-correlation. Although the tomographic filtering significantly affects the synthetic tomography images, we demonstrate that the patterns observed in the ratios and correlations of seismic velocities are robust features. Our study suggests that the seismic characteristics of SP12RTS require the presence of post-perovskite, both outside and inside the LLSVPs. However, these characteristics cannot be used to discriminate between isochemical and thermochemical models of mantle convection.

*Speaker

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Keywords: Tomography, lower mantle, Convection, LLSVPs, pPv

3D Earth - A Dynamic Living Planet

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Abstract

In our contribution we present the "3D Earth" project where we aim to establish (i) a global 3D model of the crust and upper mantle based on the analysis of satellite gravity and magnetic missions in combination with seismological models and (ii) analyse the feedback between Earth's deep mantle and the lithosphere. This project is in the framework of the ESA Support To Science Element.
To analyse the deep mantle, we will try to combine mantle conductivity and mineral physics with the observations from satellite gravity and magnetic data. We exploit the characteristic sensitivity of the geophysical data to different parts of the crust and mantle. The general concept is that estimates of magnetic and density sources for the lithosphere will be used to model the temperature and composition in the crust and upper mantle for comparison with P- and S-wave velocity models. The seismological methods will be analysed in order to estimate the role of temperature and composition on seismic velocity variations and to evaluate the uncertainties in tomography models.

We address the vertical stratification of the lithosphere and especially cratonic mantle, or the compositional vs. temperature signatures in seismic tomography models. The challenge is to integrate the different sensitivity of the various geophysical methods and relate the diverse data accurately to variations in parameters describing the lithosphere at different depths. The unique globally homogenous coverage of the Earth provided by satellite data allows such a consistent analysis on a global scale.

Consequently, our analysis will also address the link between the lithospheric and sub-lithospheric gravity field, which is a key element to understand processes in the mantle dynamics. Models of mantle dynamics, which will also take into account the architecture of the core-mantle boundary, will be used to estimate the dynamic topography variations through time.
Our global crust and upper mantle models will be a valuable input to explore some long-standing problems regarding the nature and evolution of the lithosphere in 4D. This knowledge will enhance our understanding of the interaction between the deep lithosphere and surface tectonics towards an end-to-end 3D simulator. In addition we will use nested modelling to consistently include regional models within our global models.

Keywords: 3D Earth, upper and lower mantle, satellite gravity and magnetics, seismic tomography

*Speaker

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Seismic observations of mid-mantle discontinuities on a global scale

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Abstract

Recent tomographical studies have found that some slabs stagnate at the 660 km discontinuity, whereas others stagnate at 1000 km depth. Very few slabs continue subducting into the mid mantle (Fukao & Obayashi, 2013). Conversely, upwelling material also shows deflection at various depths. These depths show some relationship to observed mantle discontinuities. The apparent transition at 1000 km depth is particularly enigmatic, as both subducting slabs and upwelling material are observed to be displaced here (French & Romanowicz, 2015). Although some recent publications suggest that the transition is a viscosity jump (Rudolph et al., 2015) or a compositional difference (Ballmer et al., 2015), the relationship to observed seismic discontinuities is unclear.
Here, we present the first global-scale interrogations of mid-mantle discontinuities. We have compiled a large high quality global dataset of over 45,000 hand-picked SS phases. We use SS precursors to search for the presence (of lack thereof) of discontinuities in the mid-mantle, from 700 km to 1200 km depth. The data are partitioned into spherical caps to generate regional maps, using different cap sizes to investigate the lateral extent of the discontinuities. Differential precursor-SS travel time measurements with respect to AK135 are used to estimate the depth of the discontinuities. Amplitude ratios of precursors/SS help to constrain velocity and density contrasts across the boundaries. Our observations find evidence for multiple discontinuities at various depths in the mid-mantle; discontinuities at 900 and 1100 km depth are the most prevalent, followed by 1000 and 1350 km.

We analyse the locations of mid-mantle discontinuities for any relationship to SS tomographical models, and the locations of hotspots and large igneous provinces. Constraining the link between seismic observations and geodynamical features is essential to provide insight into the continued evolution of Earth's mantle and its convection processes.

Keywords: mantle, transition zone, discontinuities, seismology, body waves, megameter discontinuity

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Correlation of seismic heterogeneity across scales throughout the mantle

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Abstract

Small-scale mantle heterogeneity has previously been seismically observed through analysis of scattered seismic waves. Studies using a variety of methods have mapped the distribution of small-scale structure within the lowermost and uppermost mantle, as well as throughout the mantle. Some past work has observed scattering heterogeneity in regions associated with convective and dynamic processes: subduction zones in the upper mantle, and mantle plumes and piles in the lower mantle. Here we analyse scattering related to PKPPKP (PKP.PKP), a P-wave wave that travels through the mantle, outer core, and back into the mantle where it is back scattered at some depth and travels to the station through the mantle and core. PKP.PKP can scatter from and thus resolve small, sharp contrasts in seismic structure throughout the entire depth range of the mantle. Previous studies demonstrate the use of this probe for observing heterogeneity within a large volume of the mantle, but studied only limited datasets. Using a collection of over 1000 earthquakes recorded at 13 small-to-medium aperture seismic arrays, we are able to investigate about 60% of the volume of the mantle for scattering heterogeneities and precisely resolve the scattering location within the Earth in latitude, longitude, and depth. We analyse the frequency range from 0.5 to 2.0 Hz permitting detection of heterogeneity from 3-28 km in size. While we are unable to distinguish whether scattering heterogeneity is thermal or chemical in origin, our study reveals scattering heterogeneity spanning all depths in the mantle. Scattering abundance versus depth mimics the depth variation of the RMS of tomographically derived large-scale shear wave velocity heterogeneity: more scattering heterogeneities are observed at the boundary layers with fewer in the mid-mantle. Scattering heterogeneity displays relationships with the lateral locations of strong large-scale seismic structure. In the lower mantle, abundance of scattering heterogeneity strongly correlates with moderately low seismic shear-wave velocities, strongest lateral velocity gradients, and the locations of hotspots that are seen to rise from the CMB to the shallow Earth. In the upper mantle, scattering heterogeneity shows no statistically significant correlation with either high or low seismic velocities. The three-dimensional distribution of small-scale seismic heterogeneity may inform us of the mantle's flow and dynamic processes.

*Speaker

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Keywords: Mantle, deep Earth, seismology, arrays, scattering

Mantle composition: using convection history to improve inferences

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Abstract

Mantle composition was determined early on in the history of the solar system as Earth accreted. The compositional dependence of density then meant that this composition had a strong influence on the evolution of the convecting mantle. However, mantle composition is very poorly constrained, limiting the study of both planetary formation and mantle evolution. Here we present a new method for inferring mantle composition, based on pattern recognition, which uses large scale in situ observations of the mantle to make fully probabilistic inferences for bulk major element composition. Our approach has two major advantages over previous methods. Firstly, we take large scale in situ observations which average over large regions, removing potenitally misleading effects of small scale heterogeneities. We also therefore do not need to extrapolate from any set of petrological samples. This large-scale, in situ approach therefore has advantages over inferences made from terrestrial basalts, which only sample the upper mantle, or meteorites which potentially sample unrepresentative parts of the solar nebula. Secondly, by using a large set of convection simulations we consider the impact of composition on the evolution of the mantle, allowing us to constrain composition more precisely by taking into account the compositional signal present in convection patterns. We can therefore find composition with more certainty than when inverting a single observation of density structure, as we would if we started with seismic tomography of Earth. We use a sampling based inversion method, our samples being hundreds of convection simulations run using StagYY with self consistent mineral physics properties calculated using the Perple_X package. The observations from these simulations are used to train a neural network to make a probabilistic inference for major element oxide composition of mantle convection simulatons. We find we can constrain bulk mantle FeO weight percent, FeO/(FeO+MgO) and FeO/SiO2 using observations of the temperature and density structure of the Earth.

Keywords: Major element mantle composition, neural networks, geodynamics, nonlinear inversion

*Speaker

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Modelling the basalt fraction in the transition zone using P-to-S conversions

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Abstract

Dynamic simulations of Earth's thermo-chemical evolution predict an uneven distribution of basalt throughout the mantle [e.g., Nakagawa et al. (2010)]. In particular, the transition zone may be enriched in basalt due to the 'basalt filter effect'. Thermodynamic models based on free energy minimization allow us to predict mineral assemblages and radial seismic profiles for variable mantle composition. Here we regard the composition of the mantle as a mechanical mixture of basalt and harzburgite, and simulate receiver-side P-to-S conversions for 1D seismic profiles of these mixtures, and compare synthetic receiver functions to waveform data from the USArray.

Keywords: transition zone, receiver functions, mineral physics, eclogite, seismology, mantle composition

*Speaker

Large low shear velocity provinces: inferences, uncertainties, and interpretations

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Abstract

Decades ago, seismic tomography brought into focus two nearly antipodal large low shear velocity provinces (LLSVPs) at the base of the mantle. These extend up over 1000 km off the CMB in places. High-resolution forward modeling waveform studies document sharp transitions into the LLSVPs from the surrounding mantle, coinciding with the strongest lateral Vs gradients in tomography. Vp tomography also identifies low velocity provinces, but Vs reductions are significantly stronger. These findings have been used to argue for a compositionally distinct origin to LLSVPs. Past numerical convection experiments with a dense basal thermochemical layer and plate motion histories imposed at the surface demonstrate the dense material collects into piles with a similar planform layout as seismic LLSVPs, with plumes that rise off pile peaks and cusps, which can be near pile margins. This is compatible with correlations between LLSVP edges and hotspot locations, as well as computed origination locations of large igneous province eruptions. Several tomographic studies privide evidence for plumes connecting some hotspots to LLSVPs. ULVZs have been found near and within LLSVPs, and mapped with properties consistent with partial melt of some deep mantle component. Flow predictions indicate the hottest mantle occurs within piles away from edges. Thus ULVZs seen at LLSVP edges (and away from LLSVPs) argues ULVZs have a composition different from piles and surrounding lower mantle. Trace element analyses of hotspot lavas identify the need for isolated reservoirs somewhere in the mantle, with some isotopic systems being preserved from very early Earth. Thus LLSVPs may be long-lived thermochemical piles that act as geochemical reservoirs. The stability and survival of

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thermochemical piles at the base of Earth's mantle depends upon several factors, which are not well constrained observationally, including the viscosity and density differences between piles and surrounding mantle. End member possibilities for creating a thermochemical layer (and/or piles) include an early earth origin (e.g., a crystallized remnant of a basal magma ocean) or alternatively grow-as-you-go possibilities (e.g., convective accumulation of CMB chemical reaction products, or deeply subducted basaltic oceanic crust). While today's seismological snapshot doesn't help in constraining either end-member, the geochemical data support long-lived thermochemical structures. Our current seismic work involves measurement of diffracted P and S waves and multi-bounce Sn and ScSn shear waves to improve seismic sampling of the lowest mantle.

Keywords: LLSVP, thermochemical piles, plumes, BMO

Subslab anisotropy beneath the middle American subduction zone

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Abstract

To understand how the asthenosphere is entrained by subduction of oceanic lithosphere we measured source-side anisotropy for events in the middle American subduction zone (MASZ) received by seismic stations on the Pacific islands. Properly correcting the receiver-side anisotropy is crucial to the interpretation of source-side anisotropy and thus subslab structure. The receiver-side anisotropy beneath a station can be parameterized by a combination of azimuthal anisotropy, usually provided by SKS shear wave splitting, and radial anisotropy, provided by a global model. We employed an inverse-propagator matrix method to remove the full receiver-side anisotropy, rather than only removing its azimuthal component. We found that the fast direction is predominantly trench-oblique in the northern segment of the MASZ and trench-normal in the southern segment. Because of the young age of the Cocos plate in northern MASZ, the trench-oblique fast directions may be induced by the combination of current seafloor spreading and the absolute plate motion. The variation of trench-retreat to trench-advance southeastward along the MASZ may also be partially responsible for the trench-oblique pattern. We are now applying the inverse-propagator method to source-side anisotropy measurements in other subduction zones to gain more insights of the asthenosphere subduction.

Keywords: subduction zone, subslab, anisotropy

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Assessing the macroscopic olivine grain growth through the microscopic physical properties of the intergranular medium

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Abstract

Grain size in the Earth's mantle is a fundamental parameter that has crucial implications on large-scale processes, such as seismic wave propagation, the permeability and the rheology of rocks. However, grain size is constantly evolving with time, where static grain growth implies an increase of the average grain size whereas dynamic recrystallization contributes to its decrease. Static grain growth is most dominant in grain size-sensitive deformation regimes (i.e. diffusion creep and grain boundary sliding) and is classically defined by an Arrhenius equation of the form: *r_fˆn - r_iˆn = k_0 t exp(-Ea / RT)*, with *r_f* and r_i, the final and initial grain radii, n the grain size exponent, t the experimental duration, k_0 a material-dependent factor and Ea the empirical activation energy. These growth parameters are highly dependent on the value of *n*, which has considerable implications when extrapolating from laboratory to geological time scales. Here, we will show that there is no clear *n* value that can be extracted from grain growth experiments and that this value must be fixed based on the appropriate theoretical background. We have therefore investigated static grain growth of olivine-rich mantle aggregates in an intergranular medium being dry, melt-bearing and water-oversaturated. Grain growth experiments were performed and modeled by considering different growth mechanisms (i.e. diffusion-limited and interface reaction-limited). We have established the dry olivine grain growth law from previously published experimental grain growth data at 1-atm and high-T conditions. Grain growth rates for these samples are limited by silicon diffusion at grain boundaries through an effective width of 30 nm, which is a factor 30 larger than the structural grain boundary width. Grain growth experiments performed on melt- and water-bearing aggregates show, however, that they are significantly faster than for dry samples. They also indicate that they are comparable regardless of the liquid fraction (i.e. $> 0\%$). This result implies that liquid-bearing olivine grain growth is limited by precipitation reactions at the crystal/liquid interface rather by diffusion through the liquid phase. We propose a general grain growth law, which takes into account dry grain boundaries as well as wetted grain-grain interfaces, through the wetness parameter. We show that our unified grain growth law considerably deviates from classical empirically-derived Arrhenius laws, with critical differences at geological time scales. We expect that

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our law will help unravel physical properties that are dependent on processes happening at the grain boundary scale, such as rheology, diffusion or permeability.

Keywords: olivine grain growth, wetness, HP, HT experiments

Seismic analysis of the lower mantle beneath the Pacific using shear-wave travel-times and 3D synthetics

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Abstract

The structure, origin, and convective nature of the large low velocity anomaly beneath the Pacific are still highly debated. In our study we analyze 19 earthquakes within the Tonga-Fiji region recorded at broadband stations in the Western United States at an epicentral distance range of approximately 75-81○. Array seismological methods were used to enhance the signal to noise ratio. We measure relative travel times of S, SKS, PS and ScS waves with respect to P waves on both horizontal components to obtain diverse sampling of the Pacific low velocity anomaly. The highly variable traveltime delays indicate that the large low velocity anomaly has a complicated structure. We will model these travel time delays using the AxiSEM method and tomographic models as starting models.

Keywords: large low shear velocity province, ultra low velocity zone, array seismology, numerical modelling

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Investigation of the polarity variations of the 410 km discontinuity reflections beneath the North Atlantic

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Abstract

We investigate the amplitude and polarity behavior of precursor arrivals to the PP seismic waves that reflect off the 410 km discontinuity beneath the North Atlantic. Numerous source-receiver combinations provided us with a dataset of reflection points beneath our investigation area. Array seismological methods were used to enhance the signal to noise ratio. For each event the polarity of the PP phase is compared to the polarity of the precursor signal. Our observations indicate of polarity reversals for some of the events in the dataset. We looked at two possible sources of generating polarity reversals in this region. We test epicentral distance dependence of polarity behavior. Comparison between the observed polarities and epicentral distances of the events reveal a specific pattern of polarity behavior depending on the epicentral distances of the earthquakes. The events with epicentral distances greater than 118 degrees mostly show opposite polarities, while for those with smaller epicentral distances the same polarity of the main phase and precursor signal is dominated. Modelling of PP and P410P reflection coefficients leads us to a model with smaller contrasts in Vp, Vs and density, compared to those for the pyrolite or ak135 velocity model. This reduction in elastic properties and seismic velocity of the minerals can be explained by the effect of hydrous wadsleyite in this region, however, the joint effect of water and iron cannot be completely ruled out.

A second possibility to explain the polarity reversal of the reflected signals could be the olivine deformation dependence of polarity observations. The effect of various types of deformation geometries on reflection coefficients of the P and S waves at the 410 km discontinuity were tested, as well as the influence of percentage of alignment of olivine and wadsleyite crystals on the polarity variations of the reflected waves. The results indicate the visible

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polarity reversal of the S waves reflected off the 410 km discontinuity as a function of applied deformation geometry and the level of deformation, while for the P wave this effect seems to be smaller. Including more complicated cases in the reflection coefficients calculations, such as two anisotropic layers above and below the 410 km discontinuity, may provide a better fit to our observations of polarity reversals in this region.

Keywords: 410 km discontinuity, Polarity reversals, PP precursors

A comparison of the P- and S- wave boundaries of the African Large Low Shear Velocity Province

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Abstract

The lowermost mantle is dominated by two large regions of reduced seismic velocities, located beneath Africa and the Pacific which are typically referred to as the Large Low Shear Velocity Provinces (LLSVPs). Many tomographic S-wave models agree on the position of the two major LLSVPs, while P-wave models generally show more variability. Nonetheless the precise location and structure of the African LLSVP is ill resolved in tomographic models. This study focusses on the African LLSVP and aims to map its boundaries using high resolution P and S-waves as well as core diffracted phases. The data-set is assembled from large magnitude, deep sources in South America, Asia and Indonesia (magnitude $>$ 5.5 and deeper than 100 km) recorded at broadband receivers across Africa, Europe, North and South America. This dataset covers the region beneath the Atlantic and western Europe that is characterised by a transition from fast to slow seismic velocities generally assumed to form the edge of the LLSVP. This extensive and geographically wide-spread data-set provides the largest lateral coverage across the northern and western boundaries of the African LLSVP to date. With the source and receiver combinations available P(Pdiff) and S(Sdiff) sample the vast majority of the northern boundaries on both the western and eastern flanks. Using Pdiff and Sdiff travel-time residuals a new model of the boundary of the African LLSVP beneath the Atlantic along the CMB is produced. Using travel-time information of P- and S-waves turning higher in the mantle we are able to locate the LLSVP boundary away from the CMB. The use of P- and S- waves allows a comparison of boundary locations and structure likely providing insight into the origin of the LLSVP and we detect small-scale variations in P- and S-wave structure in the sampled locales. At both the Pacific and African LLSVP boundaries several studies have shown that shear-wave splitting changes close to the boundaries and within the LLSVP interiors shear-wave splitting appears to be very weak to non-existent. Using the existing data-set Sdiff anisotropy measurements are made across the sampled boundaries and the results show weakened, but complex splitting as the LLSVP is entered. These results serve to confirm and complement the boundaries imaged by the travel-time study and will allow insight into the existence of post-perovskite in the LLSVP.

Keywords: LLSVP, seismology, lower mantle

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Evidence for deep melting in the European upper mantle from seismology

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Abstract

The recent development of full waveform seismic tomography on continental scales has provided new insights into the seismic structure of the lithosphere and asthenosphere. In particular, we can map shorter wavelength, high-amplitude velocity anomalies which would traditionally be damped and spatially smeared using classical methods. Quantitative interpretation of these anomalies – expressed as absolute rather than relative velocities – may open up the possibility of identifying important dynamic processes such as melting, that would otherwise go undetected or unconstrained.
In this study we focus on the S-wave speed (Vs) structure beneath Europe, as obtained from full waveform inversion. The European upper mantle is characterised by seismic wave speeds that are slower than the global average. However, especially low velocities ($<$ 4.0 km/s) are seen beneath Iceland and other parts of the mid-Atlantic ridge, as well as beneath Iberia, reaching a minimum between 120-130 km.

Using Vs alone, in the absence of any other observable (e.g. Vp, density), it is difficult to constrain the chemical composition beneath Europe. This is because chemistry (C) and temperature (T) have sensitivities to Vs which trade off with each other. However, even considering the full range of possible chemical compositions, taking into account mineral intrinsic anelasticity, and allowing for the presence of fluids, it is very difficult to create sufficiently low velocities to fit the slowest regions of the tomography model, using simple variations in T or C. Doing so requires either extremely high temperatures or unrealistically high attenuation. However, the slowest velocities can readily be modelled by including c. 1-2% melt. We discuss whether melt provides the most likely explanation for the slow regions, considering also the effect of more advanced anelasticity models such as "elastically accommodated grain boundary sliding", recently suggested by Karato et al. (2015).

The possibility of deep melting beneath Europe, and its quantitative identification via seismic tomography, offers exciting new constraints on geodynamic and geochemical processes.

Keywords: seismic tomography, seismic attenuation, mineral physics, upper mantle, melt

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Models of deformation and texture inheritance at the base of the mantle

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Abstract

The profound changes in physical properties across the Earth's core-mantle boundary makes this region key for the understanding of global-scale dynamics. As well as moderating any interaction between the metallic core and rocky mantle, the lowermost mantle also hosts the basal limb of mantle convection acting as a kind of inaccessible inverse lithosphere. In principle, knowledge of seismic anisotropy permits us to probe mantle flow in this region. However, in order to understand anisotropy in terms of flow, we need to know how the minerals present in the lowermost mantle deform and generate the textures that lead to bulk anisotropy. Previously, by combining predictions of mantle flow with the simulation of texture development in deforming post-perovskite aggregates, we have explored how different slip system activities give different predictions for the long-wavelength anisotropy in the lowermost mantle. By converting these results into models compatible with global scale radially anisotropic seismic tomography we have shown how different predictions correlate with tomographic inversions. We found that the most recent experimental indication of the active slip systems in post-perovksite, where dislocations gliding on (001) are most mobile, give predictions that were anticorrelated with results from tomography at long wavelengths. This means that it is difficult to explain the observed patterns of seismic anisotropy in the lowermost mantle as being due to the generation of lattice-preferred orientation in post-perovskite. A possible resolution to this difficulty is offered by experiments on analogues, which show that texture can be inherited during the perovskite to post-perovskite phase transition. Here we modify our previous approach to include this effect. This results in distributions of predicted seismic anisotropy that are in better agreement with tomography. In particular, we find that models where texture is generated by deformation of post-perovskite dominated by dislocations gliding on (001) followed by texture inheritance during the phase transition to perovskite driven by increasing temperature results in models that correlate with tomography at spherical harmonic degrees 1-5. In particular, texture inheritance in our models results in a better match to tomography in regions where the vertically polarised shear waves propagate more quickly than horizontally polarised shear waves.

Keywords: post, perovskite, anisotropy, mantle convection

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GLAD-M15: First-generation global adjoint tomography model

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Abstract

We present the first global tomographic model (GLAD-M15) constructed based on 3D spectral-element simulations and adjoint methods. Synthetic seismograms and Fréchet derivatives were calculated using the GPU-accelerated version of the SPECFEM3D_GLOBE package (Komatitsch & Tromp 2002) accommodating effects due to 3D anelastic crust & mantle structure, topography & bathymetry, ellipticity, rotation, and self-gravitation. GLAD-M15 is the result of 15 conjugate-gradient iterations with transverse isotropy confined to the upper-mantle. Our starting model is the 3D mantle model S362ANI (Kustowski et al. 2008) with 3D crustal model Crust2.0 (Bassin et al. 2000) on top. We simultaneously inverted crust and mantle eliminating the need for widely used "crustal corrections" thus it is also the first global model that naturally unifies crustal and mantle structure. We used data from 253 earthquakes in the magnitude range $5.8 \leq \mathrm{Mw} \leq 7.0$. In our first-generation model, we first focused on the elastic structure thus to linearise the problem we made frequency-dependent traveltime measurements of waveforms at three components where we assimilated more than 3.8M measurements during the last three iterations. We started iterations by combining body-waves down to 30 s with surface- & body-waves down to 60 s. The shortest period of the surface waves was gradually decreased, and in the last three iterations the minimum period was 45 s. We also started using 180 min-long seismograms after the 9th iteration and assimilated minor- and major-arc body & surface waves and included 17 s body waves after the 12th iteration. The 15th iteration model features enhancements of well-known slabs such as the Hellenic and Japan Arcs, as well as subduction along the East of Scotia Plate, which does not exist in the starting model; a tantalizingly enhanced image of the Samoa/Tahiti plume, as well as various other plumes and hotspots, such as Caroline, Galapagos, Yellowstone, and Erebus. Using a multi-scale smoothing strategy, our results suggest that we are getting closer to the resolution of continental-scale studies in areas with good data coverage,

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such as underneath North America.

We continue our iterations while demonstrating to invert for global azimuthal anisotropy in the next generation model. Meanwhile, we are optimising the adjoint tomography workflow by developing tools for pre- and post-processing steps to ultimately assimilate data from all available seismic networks and earthquakes in the global CMT catalogue. We perform our simulations on Oak Ridge National Laboratory's Cray XK7 "Titan", a computer with 18,688 GPU accelerators.

Keywords: computational seismology, full waveform inversion, global seismic tomography, mantle, crust, plume, hotspot, slab

Anelasticity across tidal timescales: a self-consistent approach

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Abstract

Wahr & Bergen (1986) developed the widely-adopted, pseudo-normal mode framework for predicting the impact of anelasticity on Earth's body tides. Lau *et al.* (2015) recently derived an extended normal mode treatment of the problem (including a minor variant of the theory known as the direct solution method) that makes full use of theoretical developments in free oscillation seismology spanning the last quarter century, avoiding a series of assumptions and approximations adopted in the traditional theory for predicting anelastic effects. There are two noteworthy differences between these two theories: (1) the traditional theory only considers perturbations to the eigenmodes of an elastic Earth, whereas the new theory augments this set of modes to include the relaxation modes that arise in anelastic behavior; and (2) the traditional theory approximates the complex perturbation to the tidal Love number as a scaled version of the complex perturbation to the elastic moduli, whereas the new theory computes the full complex perturbation to each eigenmode. We highlight these differences using a series of synthetic calculations, demonstrating that the traditional theory can introduce significant error in predictions of the complex perturbation to the Love numbers due to anelasticity and the related predictions of tidal lag angles. The simplifying assumptions in the traditional theory have important implications for previous studies that use model predictions to correct observables for body tide signals or that analyze observations of body tide deformation to infer mantle anelastic structure. Finally, we also highlight the fundamental difference between apparent attenuation (i.e., attenuation inferred from observations or predicted using the above theories) and intrinsic attenuation (i.e, the material property investigated through experiments), where both are often expressed in terms of lag angles or Q. In particular, we demonstrate the potentially significant bias introduced in estimates of Q and its frequency dependence in studies that have treated Q determined from tidal phase lags or measured experimentally as being equal. The observed or theoretically

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predicted lag angle (or apparent Q) differs from the intrinsic material property due to inertia, self-gravity and effects associated with the energy budget. By accounting for these differences we show an example of how apparent attenuation predicted using the extended normal mode formalism of Lau *et al.* (2015) is mapped to intrinsic attenuation. The theory allows for more generalized mappings which may be used to robustly connect observations and predictions of tidal lag angles to results from laboratory experiments of mantle materials.

Keywords: Anelasticity, Tides, Attenuation, Dissipation

Radiogenic isotope asymmetry of the Crozet hotspot

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Abstract

The Crozet Archipelago (Indian Ocean) includes five islands showing contemporaneous volcanism and which are distributed into an Eastern group (Possession and Est Islands) and a Western group (Pingouins, Cochons and Apôtres Islands). In order to portray the source of the Crozet Archipelago, we discuss new Sr-Nd-Pb-Hf isotope compositions of 20 lava samples from Possession Island. The data is combined with previously published results from the Crozet Archipelago to show that the isotope variation of the Eastern group of lavas is limited and restricted to values close to the common component "C" recognized in oceanic basalts. In contrast to the Eastern group of lavas, the Pingouins Island lavas of the Western group have substantially lower 87Sr/86Sr and higher 206Pb/204Pb ratios. The existence of two trends in the 208Pb/204Pb vs. 206Pb/204Pb diagram is the most striking result displayed by the Crozet Archipelago data. For a given 208Pb/204Pb ratio, the lavas from the Eastern group display lower 206Pb/204Pb ratios compared to the lavas from the Western group (i.e. Pingouins Island). These linear isotope arrays indicate significant heterogeneity within each of the two trends, both with distinct lead radiogenic and least radiogenic end-members.

We demonstrate that the isotope dichotomy between the lavas from the Eastern and Western groups do not result from variations in the melting processes across the archipelago, but instead reflects the chemical structure of the Crozet mantle plume. A pseudo-binary mixing model best explains the isotope systematics of lavas from the Crozet Archipelago. In this model, the least radiogenic end-members, which reside in the upper mantle, are explained by mixing 2.5% and 1.5% of the lower continental crust with the depleted upper mantle, for the Eastern and the Western group of lavas respectively. These end-members have similar isotope compositions as the nearby DUPAL basalts from the Southwest Indian Ridge. The lead radiogenic end-members are intrinsic to the Crozet mantle plume and can be reproduced by recycling 1 Gy oceanic basaltic crust with about 2% "terrigeneous" sediments for the Eastern group of lavas and by recycling 1 Gy gabbroic crust with 1.5% "terrigeneous" sediments for the Western group of Pingouins Island lavas.

The presence and preservation of two distinct isotope domains within the Crozet mantle plume is similar to the bilateral geochemical asymmetry observed for some Pacific and Atlantic hotspots. Based on these results, we infer that the Crozet hotspot may be related to a deep-seated mantle plume.

Keywords: Crozet, hotspot, mantle heterogeneity

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Geochemistry of intraplate magmas generated by melting in mantle plumes: the primary role of the lithospheric thickness.

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Abstract

Intraplate magmatism occurs at the Earth's surface regardless of plate age or tectonic setting, as a consequence of dynamics rooted in the convective asthenospheric mantle. A large compositional range of intraplate melts is produced related to a diversity of eruptive styles, in particular, with volatile-rich melts in explosive eruptions. Such a diversity highlights several key processes in the melt source regions that have not yet been captured by a global model linking apparently tectonically unrelated and chemically disparate intraplate melts: Volatile-rich kimberlites, exclusively found on cratons, and OIBs, which have higher silica contents apparently correlating with the thickness of oceanic lithospheres.
The presence of CO2-rich melts inside the upper mantle has so far been revealed by experimental petrology and by textural and chemical evidence in oceanic and cratonic xenoliths undergoing metasomatism. However, the equilibrium chemical composition of these melts in the upper mantle ranging from a carbonate-rich to a silicate-rich melt need to be properly defined in a P-T space. Using Margules' formalisms, we established a multi-component model defining the chemical potential of silica in the melt produced by mantle melting in presence of CO2-H2O. This parameterization is calibrated on crystal-liquid and liquid-liquid equilibria obtained by experimental studies in the P-T range 1-14 GPa and 1000-2000◦C.
This thermodynamic modeling is the most appropriate tool for defining the melt composition in a large pressure-temperature-chemistry window in presence of volatiles. We simulate the mantle melting within an ascending plume and emphasize the primary role of the lithospheric thickness on the geochemistry of melts, from oceanic lithospheres to old cratons. OIB are predicted beneath the young oceanic lithosphere of hotspots, with a lithospheric thickness from 60 to 100 km. More the lithospheric thickness increases, more the final pressure of melting or melt equilibration increases, and more the extent of melting decreases. Consequently, the melt composition varies: SiO2 and Al2O3 decrease whereas MgO and FeO increases. Beneath cratons, with a lithospheric thickness up to 200-250 km depth, kimberlitic melts can be stabilized in the asthenospheric mantle for the hottest conditions, by considering an

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adiabatic regime with Tp > 1350∘C. Thereby, the compositional continuum of intraplate melts, from kimberlitic melts to OIB, doesn't require chemical heterogeneities in the source. Moreover, variations in the bulk volatile content (degree of mantle enrichment) and the potential temperature have secondary effects, even if the latter can cause important changes in the melt composition in the plume head beneath cratons.

Keywords: thermodynamics, chemical potential, intraplate melt, volatiles, SiO2, lithospheric thickness, mantle plumes

Wavelet-based group and phase velocity measurements: application to ambient noise cross correlation observations from OBS survey offshore eastern Taiwan

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Abstract

Robust seismic tomography of the earth's interior relies largely on high-accuracy measurements of frequency-dependent group and phase velocities of seismic waves. Traditionally, the measurements are carried out by applying a series of Gaussian or narrow bandpass filters centered at specific frequencies to wave packets and estimating the arrival times at the peak envelopes and phases of the Fourier spectra of the narrowly filtered waveforms. However, seismic signals are inherently nonstationary and their spectral characteristics varying with time are not well represented by a sum of sinusoids. Particularly in recent years, empirical Green's functions (EGFs) extracted by cross correlating ambient seismic noise between two stations, provide the unprecedented interstation path coverage within highly instrumented regions for high-resolution tomographic studies. Dispersion analysis of the retrieved signals including fundamental and higher mode surface waves and even body waves commonly excited by highly nonstationary noise sources becomes a routine but essential task. Here we present a wavelet-based dispersion measurement algorithm for ambient noise data. A continuous wavelet transform is first applied to a given time series which gives the scalogram containing modulus (amplitude) and phase as a function of both time and frequency in wavelet domain. We then calculate instantaneous frequencies by taking the phase derivative with respect to time. The instantaneous frequencies located at the maximum modulus in wavelet domain are selected as a function of arrival time and further interpolated to obtain a smooth branch of ridge points, namely representative instantaneous frequencies, at which the corresponding arrival times and phases are also determined immediately for group and phase velocity measurements. We apply this newly-developed method to cross correlation functions of ambient noise records on broadband ocean bottom seismometers and differential pressure gauges deployed offshore eastern Taiwan. We investigate the spectral characteristics and dispersion properties of the prominent arrivals including fundamental and higher

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mode Rayleigh waves predominant in the frequency range of about 3-8 s and about 1-3 s, respectively, and very long-period infragravity waves up to 300 s, which will be further used for studying the structures of the oceanic crust and upper mantle and the source origin contributing to the generation of these waves.

Keywords: group and phase velocity measurement, wavelet transform, ambient noise cross correlation, ocean bottom seismometer

Toward a comprehensive understanding of transition zone discontinuities: A new constraint near the stagnant slab region beneath China

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Abstract

Plate tectonics and subduction operating over much of the Earth's history can induce mantle mixing, chemical heterogeneities and recycle volatiles into the mantle. Some slabs are penetrating into the deep lower mantle, but others are stagnated near the transition zone (TZ). Presumably, the thermochemical state of the TZ is a consequence of delicate balance and feedback between the short-term and long-term mixing. Near the stagnant slab, what's the thermochemical state of the TZ? what's the degree of hydration in the TZ?
TZ seismic discontinuities hold the key to resolve the mystery of mass and heat transport in the Earth's mantle as well as the composition of the Earth's interior. But deciphering discontinuity properties are not trivial. Data were typically limited to either mantle triplications, converted waves (P-to-S or S-to-P) or mantle reflections (e.g. SS precursors, ScS reverberations). These observations place constraints on the velocity gradient near the discontinuity as well as discontinuity reflectivity, but hardly offer independent information on the density jump or/and density gradient. In few cases where multiple datasets are jointly analysed to resolve the density jump, the region of sensitivity (or the fresnel zone) of different dataset does not necessarily coincide. Finally, the use of short period (about1 Hz) data (e.g., P'P' precursors) or long period (> about 0.1 Hz) data (e.g., SS precursors) does not allow us to simultaneously address the transition width and the gradient near the discontinuity.
We advocate a simple and effective strategy. Specifically, we involve broadband direct converted waves (e.g., P410s, P660s) and the topside reflections (the multiples, e.g., PpP410s, PpP660s) in the context of P wave receiver function technique. Such a tactic not only minimizes tradeoffs between velocity and density jumps, but allows self-consistent estimates of the shear velocity jump, the density jump, the transition width and the velocity/density gradient near the boundary. We will detail our first attempt near the region of stagnant slab beneath China. These new observations, along with the thermodynamic framework, HeFESTo, allow us to test and validate hypotheses including the state of mantle mixing and equilibrium, compositional heterogeneities and the degree of hydration in the TZ.

Keywords: mantle transition zone, 410 and 660 seismic discontinuities, mantle mixing, basalt, hartzburgite

*Speaker

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Electrical conductivity of the mantle using 2 years of Swarm magnetic measurements

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Abstract

The Swarm mission was launched in November 2013. With now more than 2 years of measurements we can update and improve the 1-D electrical conductivity profile of the Earth's mantle down to 2000 km that we derived from L1b magnetic field measurements (Civet et al., Geophys. Res. Lett., 2015). The methodology is the following, we first derive a model for the main magnetic field, correct the data for a lithospheric field model, and additionally select the data to reduce the contributions of the ionospheric field. We then model the primary and induced magnetospheric fields for periods ranging between 2 and 256 days and perform a Bayesian inversion to obtain the probability density function for the electrical conductivity as function of depth. In the first version, we observed a conductivity increase of three orders of magnitude between 400 and 900 km depth. Assuming a pyrolitic mantle composition, this profile has been interpreted in terms of temperature variations leading to a temperature gradient in the lower mantle close to adiabatic. The interpretation in terms of temperature may however be ambiguous in this depth range because the mineralogical phase transitions are associated with strong electrical conductivity variations. In addition models of electrical conductivity of individual minerals based on laboratory measurements do not agree and some discrepancies may exist among them, which need to be considered. Using almost two years of data will lead to a better spectral resolution of the external (inducing) and internal (induced) Gauss coefficients. Hence, we expect to obtain at least 2 estimates for each investigated frequencies. This will help to increase the signal-to-noise ratio and should provide a better picture of the mantle's response submitted to the inducing source. We finally expect the probability density function of the electrical conductivity to be narrower, in particular in the transition zone (400-700 km) where the electrical conductivity increases dramatically because of the different phase transitions.

Keywords: Induction, electromagnetic, Swarm, mantle, conductivity

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Assessment and applications of long-period high-rate GPS waveforms

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Abstract

We present 1 Hz GPS waveforms recorded during and after the 2003 Tokachi-Oki earthquake for various period bands (T > 30 s) and distances from the epicentre. With this study we aim at providing valuable data between periods of 30s and 500s, corresponding to long-period surface waves and the first normal mode of the free oscillation of the Earth, respectively. We assess the performance of the waveforms at the light of comparisons with synthetic seismic displacement waveforms. We find that GPS is well capable of recovering millimetre ground motion oscillations in a wide range of periods, potentially providing valuable information on the lithosphere and upper-mantle heterogeneities on a scale of 300 - 3000 km. We use these GPS waveforms to estimate the source characteristic of the Tokachi-Oki earthquake, assuming a point source at the periods and distances investigated. We compare moment tensor solutions based on seismic data only, GPS data only and a combined seismic-GPS dataset. We further explore using GPS data to estimate the mechanisms of other large magnitude (Mw > 6) earthquakes in Japan. Using a combined dataset of GPS and seismic waveforms we invert for structure in the Japanese area, and present our first tomography results.

Keywords: GPS waveforms, moment tensor, tomography, mantle structure

*Speaker

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Gravity signal of density anomalies near the crust-mantle boundary

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Abstract

Large-scale processes in the lithosphere are linked to the core-mantle boundary. Density anomalies above the core-mantle boundary are also large enough to be seen in the gravity field. The geometry of these anomalies amount to hundreds of km's with density contrast up to 100 kg/m3. In sensitivity tests using blocks of such dimensions and realistic density contrasts result in a change in gravity of tens of mGal. Though it is hard to separate the gravity signal from other long-wavelength signals resulting from shallower part of the Earth, we argue that the gravity signal from structures at the deepest part of the lower mantle should be part of any analysis of the long-wavelength gravity field. Further work will use seismic models to simulate more realistic density anomalies. This presentation is part of the ESA Support To Science Element - 3D Earth project which commences this year and is presented in the poster of Szwillus et al.

Keywords: gravity, D", LLSVP, core mantle boundary

*Speaker

Temporary patches of post-perovskite within lowermost mantle reservoirs of primordial material

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Abstract

We perform numerical experiments of thermochemical mantle convection in 2-D spherical annulus geometry to investigate the distribution of post-perovskite (pPv) with respect to the location of basal primordial reservoirs of dense material, which model the large low shear-wave velocity provinces (LLSVPs) observed in the lowermost mantle. High core-mantle boundary (CMB) temperatures (3750 K and more) lead to strong anti-correlation between the locations of pPv and large primordial reservoirs, while low values lead to a pPv layer fully covering the outer core. Combined with large values of the Clapeyron slope (> 13 MPa/K), intermediate values of the CMB temperature (around 3400 K) avoid a full pPv layer and allow pPv phase change to occur within the primordial reservoirs. Through interactions between cold downwellings and primordial reservoirs, low viscosity pPv leads to the formation of long-lived, thin tails of primordial materials extending laterally at the edge of these reservoirs. In addition, for CMB temperatures and pPv Clapeyron slopes around 3400 K and 15 MPa/K, respectively, small patches of pPv also form within the primordial reservoir. These patches are short-lived, typically a few hundreds of Myr, and they are a few hundreds of kilometers long and a few tens of kilometers high. If primordial reservoirs are enriched in iron, as might be the case for LLSVPs, the presence of temporary pPv patches within their interior may provide an explanation for the ultra-low velocity zones (ULVZs) observed at the bottom of the Earth's mantle.

Keywords: Thermo, chemical convection, post, perovskite, LLSVP

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Periodicities in the Geomagnetic Polarity Timescale

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Abstract

The sequence of the reversals of the geomagnetic dipole is far from a strictly periodic process. At the same time, it is quite reasonable to expect the structure of this timescale should reflect, in some way, the features of nonrandom dynamic processes which are certainly generated in the geodynamo mechanism. An object of the present work is finding the periodicities and characteristic times in the geomagnetic polarity timescale. The wavelet analysis of the geomagnetic polarity timescale is conducted for the past 250 Ma. The signs of cyclicity with a period of about 50 Ma are revealed.

Keywords: Geomagnetic polarity timescale, wavelet analysis, periodicities and characteristic times, cyclicity

*Speaker

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On the Cooling of a Deep Terrestrial Magma Ocean

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Abstract

Several episodes of complete melting have probably occurred during the first stages of the Earth's evolution. We have developed a numerical model to monitor the thermal and melt fraction evolutions of a cooling and crystallizing magma ocean from an initially fully molten mantle. For this purpose, we numerically solve the heat equation in 1D spherical geometry, accounting for turbulent heat transfer, and integrating recent and strong experimental constraints from mineral physics. We have explored different initial magma ocean viscosities, compositions, thermal boundary layer thicknesses and initial core temperatures. We show that the cooling of a thick terrestrial magma ocean is a fast process, with the entire mantle becoming significantly more viscous within 20 kyr. Because of the slope difference between the adiabats and the melting curves, the solidification of the molten mantle occurs from the bottom up. In the meantime, a crust forms due to the high surface radiative heat

Keywords: Early Earth, thermal evolution, magma ocean, numerical modeling

*Speaker

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Dynamic topography and lithospheric stresses since 400 Ma

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Abstract

We present a model of dynamic topography and lithospheric stresses in a reference linked to the fixed Africa since 400 Ma. We start with a simple geodynamical model in which we combine contributions due to subducted lithosphere and to long wavelength upwellings during the last 400 million years. Once built this model of temporal variation of the large-scale mantle heterogeneities, we calculate the associated geoid, surface topography and lithospheric stresses and compare them with geological observations. We rediscover that slabs create broad topographic depressions (about -2000 m) which may explain the appearance of some basins since the Carboniferous, related to the drift of the continent over a slab.
We find that the Peri-Pacific girdle of subduction creates a large-wavelength positive topography (about 600m) at the center of the ring, that is to say over Africa. This extension creates faults with an NW/SE azimuth, parallel to the direction of the subduction zone along the West coast of South America which is the most active part of the ring of subduction during this period. We correlate this Triassic extension over Africa with the observed mesozoic and cenozoic direction of the rifts.

Keywords: Mantle dynamics—topography—shear stresses

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Plate tectonics and global-scale mantle water cycle insight from numerical modeling

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Abstract

The water cycle across the Earth's mantle is crucial for understanding the co-evolution system of deep Earth's interior and surface climate [Tajika and Matsui, 1992; Sandu et al., 2011]. The key issue for such an Earth-system modeling would be a stable plate tecotnics over the geologic time-scale with stable surface water ocean. Using thermo-chemical mantle convection simulations with three water migration processes (regassing, degassing and dehydration) [Nakagawa and Speigeman, submitted], three typical convective regimes (mobile, episodic and stagnant lid) with vayring the friction coefficient of brittle lithosphere are found but the parameter range for boundaries of the mobile lid/episodic lid regime would be shifted for higher friction coefficient compared to the dry mantle model [Nakagawa and Tackley, 2015]. This would be caused by the effects of viscosity reduction caused by the hydrous lithsophere [Nakagawa et al., 2015; Crameri and Tackley, 2015]. On the mantle water circulation in the mobile lid-like regime, two-types of water cycle are found corresponding to mantle temperature variations: 1. Water flux balanced dynamics and 2. Regassing-dominated dynamics. When the mantle temperature would be sufficient high such that the mantle transition zone minerals could not store the water supplied from cold subducting slabs, both regassing and dehydation would be balanced and the mantle water content could not be changed with time. Once the mantle temperature would be cooled down to store the water in mantle transition zone, the mantle water content starts increasing rapidly because the regassing would be dominated dynamics in the mantle water cycle system. The time-scale on occurrence of rapid increasing of mantle water content would be related with the friction coefficient of pseudo-plastic yielding that would be needed for occurring the plate-like bahavior. In order to be a consistent mantle water content with high pressure experiments (1 to 2 OMs in the mantle; OM=Ocean Mass), the balaced water flux dynamics should be found over the geologic time-scale corresponding to about 0.2 of friction coefficient. This value of friction coefficient would be lower-bound value for acceptable range suggested from petrological constraints.

Keywords: Plate tectonics, Mantle convection, Water cycle, Mantle transition zone

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3D spherical geodynamic modeling through time

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Abstract

Calculations of mantle convection generally use constant rates of internal heating and time-invariant core-mantle boundary temperature. When considering calculations that span the age of the solar system, both of these assumptions must be relaxed. In this work I consider 3D spherical convection calculations that span the age of the Earth with concentrations of heat producing elements that decrease with time, a cooling core boundary condition, and a mobile lid. I begin from a hot initial temperature, consistent with a relatively short accretion time for the formation of the planet. I find that the choice of a mobile or stagnant lid has the most significant effect on the average temperature as a function of time. However the choice of mobile versus stagnant lid has less of an effect on the distribution of hot and cold anomalies within the mantle. I find the same pattern of broad upwelling temperature structures in these new mobile lid calculations that has previously been described in stagnant-lid calculations relevant to Mars [1,2]. The viscosity of the asthenosphere has a profound effect on the pattern of temperature anomalies, even in the deep mantle [3]. If the asthenosphere is weaker than the upper mantle by more than an order of magnitude, then the a pattern of temperature anomalies with one or two large plumes results. If the asthenosphere is less than an order of magnitude weaker than the upper mantle, then the pattern of temperature anomalies takes the form of narrow cylindrical upwellings and cold down going sheets. [1] Zhong & Zuber (2001) *EPSL* 189, 75–84. [2] Roberts & Zhong (2006) *JGR* 111, E06013. [3] Anderson & King (2014) *Science*, 346, 1184-1185.

Keywords: mantle convection, thermal history, core, mantle boundary

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Constraining mantle convection models with paleomagnetic reversals record and numerical dynamos

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Abstract

We present numerical models of mantle dynamics forced by plate velocities history in the last 450 Ma. The lower mantle rheology and the thickness of a dense basal layer are systematically varied and several initial procedures are considered for each case. For some cases, the dependence on the mantle convection vigor is also examined. The resulting evolution of the CMB heat flux is analyzed in terms of criteria known to promote or inhibit reversals inferred from numerical dynamos. Most models present a rather dynamic lower mantle with the emergence of two thermochemical piles towards present-day. Only a small minority of models present two stationary piles over the last 450 Myr. At present-day, the composition field obtained in our models is found to correlate better with tomography than the temperature field. In addition, the CMB heat flux pattern slightly differs from the average temperature field in the 100-km thick mantle layer above it. The evolution of the mean CMB heat flux or of the amplitude of heterogeneities seldom presents the expected correlation with the evolution of the paleomagnetic reversal frequency suggesting these effects cannot explain the observations. In contrast, our analysis favors either 'inertial control' on the geodynamo associated to polar cooling and in some cases break of Taylor columns in the outer core as sources of increased reversal frequency. Overall, the most likely candidates among our mantle dynamics models involve a viscosity increase in the mantle equal or smaller than 30: models with a discontinuous viscosity increase at the transition zone tend to agree better at present-day with observations of seismic tomography, but models with a gradual viscosity increase agree better with some of the criteria proposed to affect reversal frequency.

Keywords: Mantle processes, Dynamics of lithosphere and mantle, Plate motions, Dynamo: theories and simulations, Reversals: process, time scale, magnetostratigraphy.

*Speaker

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An alternative scenario for the thermal and geomagnetic evolution of the Earth

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Abstract

Large amounts of heat are permanently lost at the surface yielding the classic view of the Earth continuously cooling down. Contrary to this conventional depiction, we propose that the temperature profile in the deep Earth has remained almost constant for the last 3 billion years (Ga) or more. The core-mantle boundary (CMB) temperature reached the mantle solidus of 4100 (+/-300) K after complete crystallization of the magma ocean not more than 1 Ga after the Moon-forming impact. The CMB remains at a similar temperature today; seismological evidences of ultra-low velocity zones suggest partial melting in the D"-layer and, therefore, a current temperature at, or just below, the mantle solidus. Such a steady thermal state of the CMB temperature excludes thermal buoyancy and compositional convection from being the predominant mechanisms to power the geodynamo over geological time. An alternative mechanism to produce motion in the outer core is mechanical forcing by tidal distortion and planetary precession. The conversion of gravitational and rotational energies of the Earth-Moon-Sun system to core motions could have supplied the lowermost mantle with a variable intensity heat source through geological time, due to the regime of core instabilities and/or changes in the astronomical forces. This variable heat source could explain the dramatic volcanic events that occurred in the Earth's history.

Keywords: Magma ocean cooling, thermal evolution, core temperature, maintaining geodynamo

*Speaker

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Bridgmanite Enriched Ancient Mantle Structures (BEAMS): A model to unify lower mantle geophysics, geochemistry, and geodynamics

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Abstract

The Bridgmanite Enriched Ancient Mantle Structures (BEAMS) hypothesis explores a scenario in which the lower mantle could retain relative Si enrichment through time. Due to the higher relative viscosity of Si rich materials BEAMS would resist erosion into the convecting mantle. Harzburgite is the olivine rich rock that makes up most of the cold subducting oceanic lithosphere or slabs that enter the mantle in subduction zones and travel through the mantle eventually reaching the core-mantle boundary, CMB. Harzburgite contains around 25% ferropericlase, (Mg,Fe)O, which is two orders of magnitude less viscous than bridgmanite. Thus, as more slab material descends into the lower mantle, it eventually transitions from a load bearing to an interconnected weak layer rheology and forms channels that allow subducted material to flow more freely. This material is then heated by the core and its positive buoyancy leads to the formation of upwelling channels away from subduction zones. Once this plan form is in place, it remains stable over geologic time. The BEAMS model explains: 1) The observed change in the dominant tectonics from the surface to the CMB. 2) The discrepancy between geochemical data that indicate the mantle is not fully mixed with seismology and dynamics models which indicate vigorous, full mantle convection. 3) The decreased seismic signal from slab material in the mid mantle. The harzburgite is more sensitive to the iron spin transition and cold slabs have less of a velocity contrast with the higher velocity bridgmanite. 4) The long-term stability of Large Low Shear Velocity Provinces (LLSVP) over geologic time. It has been difficult to explain how this seismically slow, hence soft material could control lower mantle dynamics. We suggest the LLSVP are stable because the BEAMS ambient mantle is strong.

Keywords: lower mantle, seismology, geodynamics

*Speaker

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Thermal convection in the solid mantle interacting with magma oceans at either or both of its boundaries

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Abstract

It has been proposed that the crystallization of the Earth mantle started in the middle of the primitive magma ocean, leading to a situation with a solid shell surrounded by two magma oceans. With such a configuration, the internal and external boundaries of the solid mantle are melting/freezing interfaces. Plumes or plates reaching these interfaces are then able to pass through the boundaries by melting, the flow being balanced by freezing of a magma where plumes move away from the boundaries. The phase change interfaces are then semi-permable boundaries. The effects of such interfaces has already been studied in the context of the inner core dynamics, with a melting/freezing condition at the inner core boundary. We propose here to use a similar condition to study the effects of the presence of magma oceans on the convection in the solid mantle. We performed the linear stability analysis of the problem, as well as fully non-linear numerical simulations using the convection code StagYY. Two main effects are observed: the horizontal wavelength of convection and the radial heat transfer are increased, potentially leading to a translation regime of the solid shell similar to the already suspected translation of the inner core.

Keywords: magma ocean, linear stability analysis, mantle dynamics

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Convection in the solid mantle with possibility of melting/freezing at either or both of its horizontal boundaries

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Abstract

Different modes of mantle crystallization from the magma ocean are possible, upwardly from the bottom or from the mid-mantle both up- and downwardly. After the surficial magma ocean has fully crystallized, a basal magma ocean may have survived for several Gyrs. The existence of a magma ocean above and/or below the solid mantle greatly affects the convective dynamics of the solid mantle by allowing phase change across its horizontal boundaries. This problem is investigated by a combination of linear and weakly non-linear stability analysis and full finite amplitude dynamical calculations. In this presentation we restrict ourselves to cartesian calculations, the spherical shell case being presented in a companion presentation by Morison et al. The phase change possibility across each boundary is controlled by a dimensionless parameter Phi, the ratio of the phase change timescale to the viscous relaxation timescale in the solid. When Phi is small at both boundaries, a translation mode is possible where the whole layer is moving vertically, melting at one boundary and freezing at the other. This convection mode is found unstable with respect to a deforming mode whose wavelength increases when Phi is decreased, which also makes the heat transfert efficiency increase. In addition, we investigate the effect of the net motion of the crystallizing boundary on the stability of solid mantle.

Keywords: mantle convection, magma ocean, early Earth, thermal evolution

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2D boundary-element modelling of free subduction: Influence of the overriding plate

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Abstract

This work uses the boundary-element method to explore the dynamics of subduction of a dense lithospheric plate (subducting plate, SP) beneath an overriding continental plate (OP). For simplicity, the model is two-dimensional, the plates are purely viscous, and the ambient fluid is infinitely deep. The negative buoyancy of the slab is the only driving force, and subduction is triggered by a finite-amplitude perturbation in the form of a short proto-slab.

For reference, we first determine scaling laws for two characteristic instantaneous velocities of the SP in the absence of an OP : the sinking speed V of the slab, and the plate speed U_SP. By means of a scaling analysis of the forces acting on the plate, we find that V obeys a scaling law of the form V=V_Stokes = fct(St), where V_Stokes is a characteristic Stokes sinking speed and St is the plate's 'flexural stiffness'. The parameter St in turn depends on the viscosity ratio between the plate and the ambient fluid, and on a dynamic length scale, the 'bending length', that is the sum of the lengths of the slab and of the seaward flexural bulge. Turning to U_SP, we find that this velocity exhibits a near-perfect logarithmic dependence on the plate length LSP, and we determine a scaling law of the form U_SP/V_Stokes = A(St) + B(St) log(LSP/ell), where ell is the slab length.

Next, we add a rigid and neutrally buoyant OP to the model in order to determine how its presence influences the reference scaling laws discussed above. The OP adds two new length scales : the length L_OP of the OP itself, and the width d of a low-viscosity lubrication layer separating the SP and the OP. The presence of the OP decreases V by a factor of .0-6.0 depending on both St and d values. Increasing L_OP and/or decreasing d diminishes both V and U_SP. Ongoing work involves the determination of quantitive scaling laws for characteristic subduction velocities in the presence of an OP. We will also show preliminary results for time-dependent subduction with an OP.

Keywords: dynamics of lithosphere and mantle, subduction zone, overriding plate influence, mechanics and modelling

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The relative influence of H2O and CO2 on the primitive surface conditions and evolution of rocky planets

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Abstract

Recent literature reveals how different the telluric planets' water content can be, depending on processes and origins of water. Furthermore, for Earth mass planets, estimates of their atmospheres water content range between 0.3 to 1000 water oceans.
Here we simulate the secular convective cooling and solidification of a 1D magma ocean (hereafter "MO") in interaction with the outgassed atmosphere. Varying the initial CO2 and H2O contents (respectively from 0.1 × 10-2 to 14 × 10-2 wt% and from 0.05 to 2.2 times the Earth Ocean current mass (MEO)), the solar distance - from 0.63 to 1.30 AU -, the atmosphere treatment (grey or non-grey) and the clouds existence, we describe their relative influence on an Earth like planet's (Earth's mass, size, mantle/core ratio, gravity and density) surface conditions at the MO phase term, and especially its ability to form a water ocean. The atmosphere-MO coupling occurs through the heat flux and volatile concentrations balances at the surface. We define the end of the MO as the time when the heat flux from the vigorous convecting mantle becomes negligible compared to the incident solar flux, linked to the dramatic increase of viscosity as the MO solidification reaches the surface, which considerably reduces the convection intensity and the heat transfer. This particular time coincides with the possible apparition of a water ocean and with the development of a thermal boundary layer at the surface, thick enough to limit the interactions between the two reservoirs. As a first step, we assume a bottom-up solidification of the MO.

The planetary surface pressure-temperature conditions resulting from the solidification are conditioned by the sun-planet distance and the initial CO2 and H2O contents in the MO. There is a critical sun-planet distance Rc below which water will never condense, whatever the initial volatile content. For distances larger than Rc, water condensation strongly depends on the relative proportion of CO2 and H2O. The higher the H2O content, the easier it is to reach the equilibrium water vapor pressure and therefore to condense water, for the

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tested range of CO_2 contents. Otherwise, for $[H_2O]_{t0} < 1.8$ MEO, too much CO_2 precludes the formation of a water ocean by greenhouse effect.
In order to study exoplanets surface conditions, and the wide diversity of these gas rich extrasolar worlds, we propose a simple scaling law to explain the relative influence of the tested parameters on the water condensation.

Keywords: magma ocean, water condensation, primitive Earth, rocky planets

Small-scale dynamic topography in whole-mantle convection models

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Abstract

Surface topography is the result of both external (erosion and sedimentation) and internal processes (tectonics and mantle convection) that continuously shape the Earth with different rhythms and scales. Mantle convection is important to surface topography as it contributes to long-term global sea-level trends [1], the geometry of intra-continental sedimentary basins [2], and produces geoid anomalies [3]. Classically, geodynamicists decompose topography in an isostatic component, resulting from density variations within the lithosphere, and a dynamic component, often defined as the topography resulting from mantle flow. Global models of residual topography, an observation-based proxy for the dynamic component of topography [1,4], suggest that the dynamic topography predicted by numerical models of mantle convection overestimate by one order of magnitude the role of deep and large-scale (degree 1 to 4) mantle thermochemical anomalies and underestimate the scales of mantle dynamics smaller than degree 15. Here, we present mantle convection models with large lateral viscosity variations and a yield stress law for lithosphere that self-generate plate-like tectonics, and produce both large-scale and small-scale convection in the upper mantle. Contrary to previous models in which the rheology is simpler, these models predict small scales in the spatial and temporal distribution of isostatic and dynamic topography, as observed on Earth. The effect of rheology parameters on surface topography is explored through 2D spherical annulus models [5] computed with StagYY [6]. Power spectra of dynamic topography are similar in 2D annulus and 3D spherical models. The temporal scales of dynamic topography evolution are also studied, with particular attention to continents.

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Keywords: Dynamic topography, mantle convection, temporal and spatial scales

Mixing in early Earth: influence of self-consistent plate tectonics and melting

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Abstract

It is generally thought that the early Earth's mantle was hotter than today, which using conventional convective scalings should have led to vigorous convection and rapid mixing with a time scale of about 100 Myears (Coltice and Schmalzl, 2006 GRL). Geochemical observations, however, indicate that mixing in the early Earth was much slower than this expectation (1-2 Gyears), leading to the suggestion that early Earth had stagnant lid convection (Debaille et al., 2013 EPSL). Additionally, the mantle's thermal evolution is difficult to explain using conventional scalings because early heat loss would have been too rapid, which has led to the hypothesis that plate tectonics convection does not follow the conventional convective scalings (Korenaga, 2003 GRL).
One physical process that could be important in this context is partial melting leading to crustal production, which has been shown to have the major effects of (i) buffering mantle temperature and carrying a significant fraction of the heat from hot mantle (Nakagawa and Tackley, EPSL 2012), (ii) making plate tectonics easier (Lourenco et al., EPSL 2016), and causing compositional differentiation of the mantle that can buffer core heat loss (Nakagawa and Tackley, GCubed 2010).

Here, the influence of this process on mantle mixing is examined, using secular thermo-chemical models that simulate Earth's evolution over 4.5 billion years. Mixing is quantified both in terms of how rapidly stretching occurs, and in terms of dispersion: how rapidly initially close heterogeneities are dispersed horizontally and vertically through the mantle. These measures are quantified as a function of time through Earth's evolution.
Results indicate that mixing (as measured by either stretching or dispersal) under simulated early Earth conditions was not very rapid, with some heterogeneities surviving for up to 2 billion years. The explanation for this is that convective velocities were not as high as simple scalings require because much of the heat is transported by a magmatic heat pipe mechanism rather than conductive cooling of oceanic lithosphere. Thus, there is no problem reconciling geochemical and geophysical constraints on early Earth mixing times without invoking a different tectonic mode to today.

Keywords: mantle convection, mixing, geochemistry

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Investigation of metal-silicate equilibration after impact by the measurement of the thermal equilibration in a laboratory fluid dynamics model

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Abstract

According to N-body simulations and meteorites analysis, a common feature of the early dynamic of the solar system is the collision of proto-planets. The fact that these objects were already differentiated and for a very large part molten even before they collided makes these impacts a secondary step of mixing for the liquid iron of the core and the silicate magma, putting them in close proximity and allowing diffusion to take place. Hence the initial state of telluric planets in terms of repartition of temperature and radio-elements has probably been drastically affected by these events.

Up to now, the efforts to address the problem of the metal equilibration during its fall through the silicate magma have focused on resolving the fluid mechanics of the problem in order to then apply a diffusion-advection model. Using a balloon filled with liquid gallium alloy as an analog for the iron core of the impactor, and a viscous fluid as an analog for the silicate magma, we were able to produce flows matching the dynamical regime of the geophysical application. In addition to high speed recording of the flow, we performed direct measurements of the diffusive exchanges integrated during the fall of the liquid metal by heating the gallium alloy and measuring its mean temperature immediately before and after its fall.

We find that the classical representation of this flow as an "iron rain" is far from the experiments, both in terms of fluid mechanics and diffusive exchanges during the phase where most of the equilibration is accomplished. Indeed, the equilibration length scale depends on the initial size of the metal diapir and on the viscosity of the magma, whereas the falling speed is only controlled by the initial size. Experimental videos and equilibration coefficients suggest than the model of turbulent thermal, as described by Deguen et al. (2013), explains properly the data, provided it is integrated over the fall.

Keywords: fragmentation, equilibration, fluid dynamics experiment

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Numerical study of the effect of water on mantle convection and its tectonic regime

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Abstract

The lithosphere of the Earth is fragmented into plates moving relatively to each other. The plate motions originate from mantle convection and the lithosphere forms its upper thermal boundary layer. Therefore plate tectonics highly depends on the convection underneath as well as on the physical properties of the lithosphere itself. Furthermore, water, which reaches the Earth's interior through the hydrated downwelling slabs, is known to have a strong impact on the rheology of rocks and solidus temperature, even in small proportions – this is why a deeper understanding of the flow of H2O in the mantle is mandatory to improve our depiction of mantle convection and plate tectonics. Thereby, while several experimental and seismological studies aimed at constraining the localized effect of water in various features, we are here focusing on its global contribution to mantle convection.

In this study we use the code StagYY (P. Tackley, 2008) to model mantle convection in a 2D-spherical geometry, in which we include a water component through numerical tracers to model the cycle of water in the Earth's interior. The viscosity and solidus are temperature and water content dependent and a yield stress is included to allow plate-like behavior. We show that a continuous hydration through subduction combined with dehydration by basaltic eruptions along ridges can lead to a stable, plate-like tectonic regime in a stationary state for the water flow, whereas suppressing the return flow of water at subduction zones leads to the formation of a dry layer beneath the lithosphere, which eventually decelerates or freezes the plate motion within 1 Ga.

Our findings could explain the observable differences between the Earth, with a liquid hydrosphere and active plate tectonics, and Venus, where the surface is dry and mantle convection operates in a stagnant-lid or intermittent plate-tectonics regime.

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Keywords: mantle convection, plate tectonics, mantle hydration, water, modeling

Seismological evidence for a non-monotonic velocity gradient in the topmost outer core

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Abstract

The solid inner core of the Earth consists of heavy minerals Fe and Ni with a fraction of light elements such as O, S and Si. These lighter elements are expelled from the inner core during its formation, rise up through the outer core as the result of buoyancy, and are trapped below the core-mantle boundary (CMB). Seismological evidence has been presented both for and against the existence of light materials at the top of the outer core. In this study, we use waveforms of recorded and modeled SmKS waves to investigate the effect of velocity perturbation under the CMB on the differential traveltimes between SKKS and S3KS waves. Due to the long propagation distance and interference with neighboring phases, the arrival times of SKKS and S3KS waves are difficult to define accurately in the records. Therefore, in our analysis we measure both the observed and model-predicted traveltimes by cross-correlating the waveform of the Hilbert-transformed S3KS with that of SKKS. We obtained 606 high-quality S3KS-SKKS differential traveltimes from 78 deep earthquakes (depth ^{3} 400 km). We use synthetic seismograms calculated by the direct-solution method (DSM) in a suite of one-dimensional models with different structural profiles under the CMB to examine the existence of a zone of lowered velocity at the top of the outer core. Then we conduct a Bayesian inversion of the observed differential traveltimes for the velocity structure at the top of the outer core. The Metropolis-Hastings Monte Carlo algorithm is adopted for an efficient sampling of the model space. Inversion result indicates that the seismic velocity in the 800-km layer under the CMB is on average 0.07% lower than that in PREM. The clear depth-dependent velocity profile strongly favors the existence of light elements and chemical stratification at the top of the Earth's outer core.

Keywords: outer core, stratification, multiple SKS wave, direct solution method (DSM)

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Magnetic jerks induced by field roughness

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Abstract

Geomagnetic jerks are the shortest temporal variations of the core magnetic field registered by observatories and satellites. Neither the physical mechanism producing such abrupt changes nor their spatio-temporal characteristics at the Earth's surface are well understood and remain as outstanding issues in geomagnetism. We used a set of synthetic core flow models to solve the radial magnetic induction equation in order to reproduce geomagnetic jerk characteristics. Our results demonstrate that jerks may be caused by roughness of the field on the core-mantle boundary. We propose a polynomial fit to secular variation time-series and compare magnetic jerk amplitudes to those of geomagnetic data. We demonstrate that even steady flow models may reproduce important characteristics of geomagnetic jerks, such as non-simultaneous behaviour, non-global pattern, spatial variability of amplitudes and stronger jerks in the radial component. However, secular acceleration changes of sign in our synthetic models produce too weak amplitudes compared to geomagnetic jerks.

Keywords: geomagnetic jerks, core flow models

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Using archaeomagnetic field models to constrain the physics of the core: robustness and preferred locations of reversed flux patches

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Abstract

Archaeomagnetic field models cover longer timescales than historical models and may therefore resolve the motion of geomagnetic features on the core-mantle boundary (CMB) in a more meaningful statistical sense. Here we perform a detailed appraisal of archaeomagnetic field models to infer some aspects of the physics of the outer core. We characterize and compare the identification and tracking of reversed flux patches (RFPs) in order to assess the RFPs robustness. We find similar behaviour within a family of models but differences among different families, suggesting that modelling strategy is more influential than data set. Similarities involve recurrent positions of RFPs, but no preferred direction of motion is found. The tracking of normal flux patches (NFPs) shows similar qualitative behaviour confirming that RFPs identification and tracking is not strongly biased by their relative weakness. We also compare the tracking of RFPs with that of the historical field model gufm1 and with seismic anomalies of the lowermost mantle to explore the possibility that RFPs have preferred locations prescribed by lower mantle lateral heterogeneity. The archaeomagnetic field model that most resembles the historical field is interpreted in terms of core dynamics and core-mantle thermal interactions. This model exhibits correlation between RFPs and low seismic shear velocity in co-latitude and a shift in longitude. These results shed light on core processes, in particular we infer toroidal field lines with azimuthal orientation below the CMB and large fluid upwelling structures with a width of about 80○ (Africa) and 110○ (Pacific) at the top of the core. Finally, similar preferred locations of RFPs in the past 9 kyr and 3 kyr of the same archaeomagnetic field model suggests that a 3 kyr period is sufficiently long to reliably detect mantle control on core dynamics. This allows estimating an upper bound of 220-310 km for the magnetic boundary layer thickness below the CMB.

Keywords: Archaeomagnetism, Reversed flux patches, Core processes

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Earth magnetic field temporal spectra from annual to decadal time scales

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Abstract

The spectrum of the observed geomagnetic field has been estimated – e.g. in Constable & Constable (2004), for frequencies ranging from thousands of Hertz to 10ˆ{-14} Hertz. At periods of decades the core field is dominating the spectrum. It decreases with frequencies like 1/k to the 4. For shorter periods, ranging from few months to few years, the spectrum of the core field is unknown, but it is often assumed that it has the same 1/k to the 4 decrease rate. It is an open question to know if that is verified at all spatial scales. In this work we investigate if such hypothesis is acceptable for the largest scales – i.e. for the Gauss coefficients of low spherical harmonic degrees. We used Secular Variation (SV) estimates between 1953 and 2014, derived from observatory data, and a magnetic field modelling technique based on correlations (Holschneider et al., 2016). We show that the spectra of the core field SV at observatory positions behave like 1/k to the power 2 down to periods as short as a year, and that the associated SV Gauss coefficients have generally the same behaviour, with possibly an exception for SH order 0 coefficients – i.e. zonal coefficients. We conclude that the 1/k to the 4 decrease rate hypothesis is generally valid for the core magnetic field at all spatial scales larger than five thousand kilometres (spherical harmonic degrees smaller than 6).

Keywords: geomagnetic field, Core field, temporal spectum

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Array analyses of SmKS waves and the stratification of Earth's outermost core

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Abstract

In this study we investigate the validity of a Vp model of the Earth's outermost core, KHOMC (Kaneshima and Helffrich, 2013; called KH2013), and show supports for the presence at the top of the outer core of a depth range that has a distinct Vp gradient from the bulk of the outer core. With the aim of updating our previous study (Kaneshima and Matsuzawa, 2015; called KM2015), we perform a systematic search for seismic array data to be used in SmKS wave analyses. The events sought in this study were recorded by broadband seismometer networks in the world: Europe, US, Asia, Japanese F-NET, Australia, Alaska, and South America. Compared to KM2015, the SmKS ray paths of the new data set nearly double in number and cover the outermost core more globally. We measure differential travel times between S3KS and S2KS (called dt3-2), dt4-3, and dt5-3 by array techniques.
We confirm that KHOMC gives better fits than other outer core models (KM2015). The expanded data set also allows us to investigate a few regions that were not sampled by the KM2015 data set. Array measurements for SmKS of those ray paths show reasonable agreements with KHOMC, indicating that the model reflects global features of the outer core.

We find, for the events with the highest quality data recorded densely with an aperture about 2000 km, that reliable differential slownesses (dp3-2 and dp4-2) are measurable with small uncertainties less than 0.02 s/o. The measured slownesses for southeastern Asia to the US (distances from 110 to 140 deg) have unique sensitivity to the outer core 200 to 400 km below the CMB, and the Vp structure of KHOMC for this depth range is consistent with the measured dp3-2. As these slowness data were not used to build KHOMC, the agreement gives an independent support for the critical feature of the model, the presence of a high-Vp-gradient layer 300 to 400 km thick.
The new data set of SmKS differential times are inverted by a tau-p method to refine the Vp values of KHOMC, including those at deeper than 400 km below the CMB. The essential features of KHOMC are preserved after the inversion. The Vp anomalies relative to PREM for the depths 400 km to 800 km below the CMB are less than 0.03km/s, consistent with the degree of agreement between different Vp models for the depth range.

Keywords: Outermost core, Vp model, SmKS waves, seismic array analyses, Vp gradient, stratification

*Speaker

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Global view on the Laschamp geomagnetic field excursion

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Abstract

Two new spherical harmonic geomagnetic field models of the time interval 50-30 ka before present including the Laschamp (41ka) and Mono Lake (32-35 ka) excursions provide a global view of these events and facilitate comparisons of excursion characteristics to numerical dynamo simulations.

One model is based on all available paleomagnetic data, comprising 30 directional and 42 relative intensity sediment records and 172 volcanic results. Low sedimentation rates, environmental influences or problematic dating can reduce the reliability of sediment records, which often manifests in regionally incompatible records. For several areas, comparisons revealed clear differences between a small number of compatible and additional incompatible records. We derived a second model, retaining only compatible data and single records from regions where no other data were available. This model includes 12 directional and 18 relative intensity records from sediments, with data from both hemispheres. The modelling method is generally the same as used for millennial scale field models. Important aspects of the data processing are that all data records were kept on their independent age scales, some of them were updated with recent dating information, and all relative intensities were scaled by a 2 Myr axial dipole moment reconstruction (PADM2M). Both models produce similar characteristics and allow identification of robust features.

We investigate intensity and complexity of the field at the Earth's surface, large-scale radial field structures at the core-mantle boundary and geomagnetic power spectra and compare dipole to non-dipole power over the time span of the model. The models indicate the field was clearly dipole-dominated before the excursion, which quickly develops when dipole and higher degree contributions reach the same level at the core-mantle boundary. During the excursion non-dipole power clearly dominates over dipole power. Intensity weakens over the whole Earth's surface and directions are globally non-uniform. Between the Laschamp and the end of the modelling interval the field is less dipole-dominated than preceding the excursion. This includes the globally less well expressed Mono Lake excursion. Similar observations come from a numerical dynamo simulation producing an excursion strikingly similar to our models of the Laschamp excursion.

Keywords: Geomagnetic excursions, geomagnetic field models, radial field at CMB

*Speaker

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Temporal characterisation of reversed-flux patches and their contribution to axial dipole decay

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Abstract

The South Atlantic Anomaly (SAA) is the region at the Earth's surface where the intensity of the magnetic field is at its lowest, typically 30,000 nT and lower. This weak zone is problematic for satellites operating in this region, as they are prone to upsets due to collisions with charged particles entering the SAA.

The SAA is coupled to regions at the core-mantle boundary (CMB) where the sign of the radial magnetic field is opposite to that of the dipole state, also known as reversed flux patches (RFPs). These RFPs can act as a proxy for the SAA: they locally cancel out the magnetic field, reflected as a weak spot at the surface. Additionally, they are thought to be a precursor to a magnetic polarity reversal.

Here, we present our characterisation of RFP evolution over the period 1590-1990 CE and their contribution to axial dipole decay. First, we describe our methods to define RFPs and how their combined area on the CMB has changed through time. Our results indicate that this area has increased approximately sixfold over the past four centuries. Additionally, we show that roughly one-third of the decay of axial dipole moment over that period is due to this RFP growth. This is a large effect relative to their combined area, which has been less than one tenth of the CMB surface throughout this period. Our spectral analysis of RFPs indicates that they are predominantly degree 6 features, and that they are not particularly sensitive to other degrees. We therefore suggest that the results shown here are robust, as the increase in data quality, and with that field roughness, has a relatively small effect on the presence of RFPs.

Keywords: geomagnetism, South, Atlantic Anomaly, reversed, flux patches

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Decadal variability in core surface flows deduced from geomagnetic observatory monthly means

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Abstract

Monthly means of ground observatory magnetic field measurements are a key data source for studying temporal changes of the core magnetic field. However, when calculated in the usual way, external field contributions may remain, which makes them less favourable for studying the field generated by geodynamo action. We calculate revised monthly means using robust methods and after removal of external field predictions, including a new way of characterising the magnetospheric ring current. Geomagnetic secular variation (SV) is calculated as the first annual differences of these monthly means, which also removes the static crustal field. SV time series based on revised monthly means (*rmm*) are much less scattered than those calculated from ordinary monthly means (*omm*), and their variances and correlations between components are smaller. We demonstrate their utility by calculating core surface advective flow models, assumed large-scale, between 1997 and 2013 directly from the data. Sets of models assuming constant flow over three months exhibit large and rapid temporal variations. For models of this type, it is easier to fit the SV derived from *rmm*, although the flow models are able to follow excursions in SV derived from *omm* that are likely to be external field contamination rather than core signals. Having established that we can find flow models adequately fitting the data, we assess how much temporal variability is required. Previous studies have suggested that flow changes may consist purely of torsional oscillations (TO). We invert for flows in which changes inconsistent with TO are heavily penalised; they have an unacceptably large data misfit. However, imposing the penalty less severely so as to fit the data as well as by flows assumed constant over three months demonstrates that very little flow variability is required to reproduce rapid SV changes. Although flow changes are small, flow acceleration can be locally (temporally and spatially) large, in particular when and where core surface secular acceleration peaks. Flow resolution matrices show that their spherical harmonic expansion coefficients are not well resolved, and can be strongly correlated. Averaging functions, a measure of our ability to determine the flow at a given location, are poor approximations to the ideal, even when centred on core surface pointsbelow areas of high observatory density. Resolution and averaging functions are noticeably worse for the toroidal flow component, which dominates the flow, than the poloidal flow component, except around the magnetic equator, where averaging functions for both components are poor.

Keywords: Geomagnetism, Core flow, Torsional Oscillations

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VO-ESD: a modified virtual observatory approach with application to Swarm measurements

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Abstract

A description of the temporal variations of the main geomagnetic field (i.e., the secular variation or SV) is crucial to the understanding of core dynamo generation. It is known with high accuracy at observatory locations, which are globally but unevenly located, hampering the determination of a detailed global pattern of these variations. For the past two decades, satellites have allowed global surveys of the field and its SV. Their data has been used to derive global spherical harmonic models through data selection schemes to reduce external field contributions. There however remain discrepancies between ground measurements and field predictions by these models, which do not reproduce small local spatial scales of the SV. This study attempts to extract temporal variation time series from satellite measurements as it is done at observatory locations. We follow a Virtual Observatories (VO) approach, defining a global mesh of VOs at satellite altitude. For each VO and a given time interval we apply an Equivalent Source Dipole (ESD) technique to reduce all measurements to a unique location, leading to time series similar to those available at ground observatories. Synthetic data is first used to validate the approach. We then apply our scheme to the first two years of the Swarm mission and locally compare the VO-ESD derived time series to ground observations as well as to satellite-based model predictions. The approach is able to describe the field temporal variations at local scales. For the first time, a global mesh of VO times series with a lateral 2.5 degree resolution is built. This global mesh is used to derive global main field spherical harmonic models. For a simple parametrization the model describes well the trend of the magnetic field both at satellite altitude and at the surface. As more data will be made available, longer time series can be derived and used to study temporal variation features such as geomagnetic jerks.

Keywords: Earth's magnetic field, satellite measurements, Swarm mission, virtual observatories, ESD

*Speaker

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Transdimensional modelling of archeomagnetic data

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Abstract

One of the main goals of archeomagnetism is to document the secular changes of Earth's magnetic field by laboratory analysis of the magnetization
carried by archeological artefacts (Gallet et al., 2009). Typical techniques for creating a model of temporal change include assuming a prescribed temporal discretisation which, when coupled with sparse data coverage, requires strong damping in order to ensure smoothness. Because such damping is often chosen arbitrarily, and applied to the entire time series, interpretation and detection of rapid changes and frequency content may be difficult.
Key to proper modelling (and physical understanding) is a method that places a minimum level of regularisation on any fit to the data.
Here we apply the transdimensional Bayesian technique (e.g. Sambridge et al., 2013) to sparse archeointensity datasets, in which the temporal complexity of the model is not set a priori, but is self-selected by the data. The method not only produces the posterior distribution of intensity as a function of time (a useful tool for archeomagnetic dating), but also allows the calculation of the posterior of the age of any individual contributing sample. We apply the technique to an archeomagnetic dataset centred in Paris, and confirm the _˜250 yr periodicity recently reported (Genevey et al., 2016).

Keywords: Archeomagnetism – Geomagnetic secular variation – Monte Carlo methods

*Speaker

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Stochastic Reanalysis of Transient Core Motions

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Abstract

We perform a re-analysis of transient core motions under spatial constraints derived from geodynamo simulations. The model is advected in time using stochastic equations coherent with the occurrence of geomagnetic jerks. The use of an Ensemble Kalman filter allows to estimate uncertainties on core flows as a function of length and time-scales. From synthetic experiments, we find crucial to account for subgrid errors to obtain an unbiased reconstruction. This is achieved through an augmented state approach. We show that a non-negligeable contribution from diffusion should be considered at the largest length-scales, even on short periods. We apply our algorithm to the COV-OBS.x1 model over the period 1940-2015. We estimate the reliability of the retrieved velocities, present probability densities for the several contributions to the dipole decay, and revisit decadal fluctuations of the westward gyre.

Keywords: Stochastic equations, augmented state Kalman filter, subgrid errors, geomagnetic data

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South Atlantic Anomaly throughout the solar cycle

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Abstract

The South Atlantic Anomaly (SAA) is a region of great concern in modern days. The growing reliance on satellites and space born instruments makes their protection an important area of study. The SAA is the region of space where the intensity of the magnetic field of the Earth is lowest and also, where the flux of energetic particles is highest.

High energetic particles trapped in the Van Allen radiation belts are the cause of many satellite problems. These energetic particles can penetrate the satellites and disturb the regular functioning of sensitive circuits, leading to bad data collection. This effect is nowhere better observed than in the South Atlantic Anomaly region. Here, the low intensity of the magnetic field leads to an increase in particle flux at lower altitudes, namely at satellite altitude.

Although a big reason why the particle flux patch is located where it is, is the low intensity of the internal magnetic field, this is not the only one. The influence of the Sun is clearly observed as well, as the variations in population of different radiation belts can be associated with the solar cycle.

To study the evolution of this particle flux anomaly, the Principal Component Analysis (PCA) method was used. This method, together with a knowledge of the radiation belts and the way particles behave in them, allowed us to properly describe the main aspects of the particle flux with only a few number of orthogonal components.

Using PCA we do not impose any restrictions in the shape of the anomaly, as previous studies do, and were able to identify separate modes with the different physical mechanics that affect the evolution of the particle flux SAA. By this, meaning both the mechanics derived from the interaction of the particles with the magnetic field of the Earth, and with the interaction with the Sun. The westward drift of the magnetic field is observed and we were able to clearly relate it with the shift in most populated radiation belts. And the 11 year cycle of the Sun is seen in the time series of the main PCA modes, those explaining the variation in total intensity and area of the particle flux.

*Speaker

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Keywords: Space Weather, South Atlantic Anomaly, Particle Flux, Magnetic Field, Radiation Belts, PCA

On the fine structure of geomagnetic secular variation foci

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Abstract

Our previous studies showed that the secular variation (SV) of the geomagnetic field is composed of several high-frequency constituents, which we called the _˜80-year, the 22-year, and the 11-year variations, superimposed on a so-called steady variation. In this study we look at the appearance, structure, and dynamics of the SV foci from the perspective of these constituents. Data from geomagnetic observatories with long time series of annual means, as well as from long time-span geomagnetic models, such as *gufm1* (1590-1990) and COV-OBS (1865-2010), have been used to separate these constituents by means of Hodrick-Prescott (HP) and Butterworth filtering. To get information on temporal displacement (speed included) of the constituents and of the SV foci, Latitude-Azimuthal-Speed (LAS) and Longitude-Meridional-Speed (LAM) power plots were constructed.

Keywords: secular variation foci, multi, decadal timescaels

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The geomagnetic field evolution from the perspective of sub-centennial variations. Consequences

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Abstract

The temporal evolution of the geomagnetic field shows the existence of several (quasi)oscillations at decadal, inter-decadal, and sub-centennial timescales that superimpose on a so-called steady variation. We discuss some issues concerning the geomagnetic field evolution, from the perspective of long time-span main field models (*gufm1* – Jackson et al., 2000; COV-OBS – Gillet et al., 2013) that are used to retrieve time series of geomagnetic elements in a 2.5x2.5∘ network. A special attention is given to the decadal constituent, separated as the cyclic component of a Hodrick-Prescott filtering applied to data, that can offer information on several issues: contamination of main field models, the geomagnetic jerk concept, geomagnetic field predictability, information on geoeffectivity of solar activity back to 1600, Earth's rotation fluctuations.

Keywords: secular variation constituents

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Investigating the core surface magnetic flux patches at sub-centennial time scale. Insights regarding the travelling speeds

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Abstract

The spatial and temporal evolution of the sub-centennial, about 80-year variation constituent of the radial field at the core-mantle boundary, shown to exist in geomagnetic observatory data by Demetrescu & Dobrica (2005; 2014), is investigated. The *gufm1* (Jackson et al., 2000) main field model is used to retrieve time series of the 80-year radial field in a grid of 2.5x2.5○ latitude/longitude, after separating it from higher-period (quasi)oscillations. Time-Longitude and Time-Latitude plots for various latitudes, respectively longitudes with a step of 2.5○ were constructed in order to investigate the spatial and temporal characteristics of the 80-year variation radial field at the core surface. A Radon transform method (Finlay, 2005) applied to the two types of plots shows a dominant westward movement of magnetic flux patches of about 17 km/year (0.27 deg/year) in the equatorial band and a northward dominant migration of 40 km/year at 70○W. Areas characterized by important displacements and intensity changes in the last 400 year are highlighted by means of geographical distribution of the time averaged energy of the secular variation. Our results regarding the westward movement of radial flux patches are similar to those obtained by Finlay and Jackson (2003) and Finlay and Jackson (2007) for a much larger time-window of 400 years, after removing the time-averaged axisymmetric component of the core radial field and then high-pass filtering the data with a 400-year cut-off window.

Keywords: main radial geomagnetic field, core surface, westward movement, travelling speeds

*Speaker

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Separation of core and lithospheric magnetic fields by co-estimation of equivalent source models from Swarm data

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Abstract

Observations of the Earth's magnetic field provide valuable information on core processes. The signal from the core is however mixed with signals from other magnetic sources, including that due to magnetized material in the lithosphere. Spherical harmonic analysis provides a means to separate sources internal and external to the measurement point, but it is unable to distinguish between core and lithospheric sources, both of which are internal. Spherical harmonic spectra indicate that degrees higher than 14 are likely dominated by the lithospheric field, while those below 14 are assumed to be core field. It has become standard practice to truncate internal field models at degree 13 or 14, refer to this as the core field, and ignore the higher degrees. Since the spectrum of the field at the CMB is almost flat, we are thereby prevented from seeing the detailed structure of the core field which leads to large errors when performing core flow inversions. In addition, even the low degree field will to some extent be contaminated by the lithospheric field.

Here, we present experiments exploring an alternative approach of co-estimating separate equivalent source models for the core and lithospheric fields. These involve equal-area distributions of monopoles sources placed at depths just below Earth's surface, and just below the core surface. We seek models that fit quiet-time, dark, vector magnetic field data collected by the Swarm satellite constellation, and simultaneously minimize L1 norm measures of the radial magnetic field at the Earth's surface (for the lithospheric part of the model) and at the core surface (for the core part of the model). The obtained models have spherical harmonic spectra of the form expected for the core and lithospheric field. However, maps of radial field at the core surface show surprisingly weak radial fields in many regions (particularly in the South Atlantic), punctuated by localized intense field concentrations. The lithospheric field model on the other hand is comparatively poor, and is polluted by unmodelled external fields. Further work is required on including more relevant prior information regarding the core and lithospheric sources in order to improve the separation, and on better quantifying the model uncertainties.

Keywords: Core, Magnetic field, Swarm, Inverse Problem

*Speaker

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Local Averages of the Core-mantle Boundary Magnetic Field: A Backus-Gilbert approach

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Abstract

The morphology and time evolution of the geomagnetic field at the core-mantle boundary (CMB) provide important constraints on the dynamics of the Earth's core. We present an approach to estimate local averages of the CMB field, based on recent satellite observations from CHAMP and the *Swarm* constellation. The method can be used to map the field locally over regions of particular interest and to construct time series of the field evolution at chosen sites on the CMB.
The CMB field is usually modelled globally by fitting a truncated spherical harmonic expansion to observations and downward continuing. However, the global support is a major disadvantage because all spherical harmonic coefficients are affected by high amplitude noise from the polar regions, as well as shortcomings in the global data distribution. Here, we take an alternative approach based on using the Green's functions for the Neumann boundary value problem to link satellite data to the radial field on the CMB, and use a Backus-Gilbert inversion approach to obtain optimized local estimates. Our approach builds on the SOLA (Subtractive-Optimally-Localized-Averages) method from helioseismology, seeking averaging kernels as close as possible to a target function that we choose to be a Fisher distribution on the CMB.
We present first results of our method as applied to sums and differences of vector magnetic field data along-track (and across track for Swarm), from geomagnetically quiet and dark times. A map of the radial field at the CMB derived applying the SOLA method to a grid of one degree resolution is found to compare well with conventional maps, but importantly it comes with estimates of the associated spatial averaging function and the model variance as a function of position. We also present example time-series of monthly means of the CMB radial field at locations of interest. These are free from the degree-dependent temporal regularization that plagues conventional time-dependent field models. Further work is required on data selection, the data covariance matrix, and fine tuning of the SOLA target function.

Keywords: Geomagnetism, Core Magnetic Field, Swarm, Backus Gilbert, Inverse Theory

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From Russia with Low Dipole Moment: Characterisation and Implications of an Exceptionally Weak Time-averaged Geomagnetic field in the Devonian (360-420 Ma)

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Abstract

Variations in the time-averaged dipole moment of Earth have the potential to inform us about the long-term state of the geodynamo and its response to mantle forcing and the thermal evolution of the core. Rocks of Devonian age (360-420 Ma) are well-known for occasionally producing erratic palaeomagnetic directions but measurements defining the intensity of the magnetic field during this period are sparse and of limited reliability. Recent collaborations between the Universities of Liverpool, Alberta and the Russian Academy of Sciences have produced a wealth of new palaeointensity data from this time period using samples collected from northern and southern Siberia and the Kola Penninsula. With near universality, the palaeointensities recovered from these rocks are lower than the field strength observed anywhere on Earth today. In many cases, the recovered palaeointensities are exceptionally low ($< 10\ \mu$T) and produce virtual dipole moments of less than 20% of today's value. These results, together with the general tendency of Devonian palaeomagnetic directions to be erratic, suggest that the geomagnetic field had, at this time, a time-averaged state similar to that found in more recent times only close to or during reversals and excursion events when the dipole diminishes and becomes comparable to the non dipole field. This view is further strengthened by a recently made observation that magnetic reversal frequency was high in the late Devonian. When considered in light of the subsequent transition of the time-averaged field to a highly stable state within the Permo-Carboniferous Reversed Superchron (265-310 Ma), these observations are highly significant. More complete palaeomagnetic records support a similar unstable-stable transition in the long-timescale field behaviour occurring approximately 200 Myr later between the Jurassic and Cretaceous and approximately 200 Myr earlier during the Cambrian and Ordovician. We therefore have increasing evidence of a recurring phenomenon in palaeomagnetic behaviour that most likely reflects a quasi-periodic process in the lower mantle producing changes in the pattern and/or magnitude of core-mantle heat flow. Superplume growth and collapse and the occurrence of major episodes of true polar wander are two plausible mechanisms which could potentially be causally linked and certainly deserve further investigation.

*Speaker

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Keywords: Palaeomagnetism, long timescale geomagnetic variations, geodynamo, mantle convection

Hydromagnetic sources of four centuries observed dipole and quadrupole in the Earth's core

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Abstract

Using IGRF (1900-2015) and gufm1 (1590-1990) geomagnetic models we roughly evaluated direct hydromagnetic sources of first eight Gauss components corresponding to magnetic dipole and quadrupole. To do so we first obtained the smoothed time derivatives of those components. The derivatives' values are determined by balance between their hydromagnetic sources (or averaged vortex of vector product of velocity and magnetic field) and correspondent magnetic diffusions. This balance is described by approximate mean-field equations those we obtained expanding the magnetic induction equation in term of spherical harmonics and diffusion egenfunctions. We argue that the obtained hydromagnetic sources are dependent mainly on higher degree ($n > 14$) expansion components those are principally unobservable, while we, perhaps for the first time, evaluated their average physical properties. Among those properties we first investigated their spectra and amplitudes allowing us to estimate various typical geodynamo parameters from the direct observations.

Keywords: geomagnetic observations, dipole and quadrupole, hydromagnetic source, geodynamo

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6-year variation in Earth's rotation: An update

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Abstract

For many years, power in the signal of the variation in Earth rotation at intradecadal periods has been identified as likely to originate in Earth's core. In earlier work, we identified that it is possible to model the signal as an oscillation with period about 6 years and remarkably coherant phase, plus a more slowly varying longer period signal. Detailed analysis of the signal is hampered by the non-unique nature of its modelling. here, we extend the analysis by a further four years, demonstrating that the 6 year periodic signal has well predicted the intermediate evolution of the signal. Prior to 1962, estimates of LOD variation exist through records of observations of lunar occulations. This database has recently been updated and cleaned, and a new signal for its predictions of length-of-day has been developed. This record is highly consistent with the higher-resolution data from 1962, showing the ability of the lunar data to constrain Earth rotation. A clear peak at around 6 year period is also seen for 1820 to 1962 (L Morrison, pers. comm); we investigate the coherance of this signal with that of the modern period.

Keywords: Earth rotation, core oscillation

*Speaker

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Core Flows inferred from Geomagnetic Field Models and the Earth's Dynamo

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Abstract

We test the ability of large scale velocity fields inferred from geomagnetic secular variation data to produce the global magnetic field of the Earth. Our kinematic dynamo calculations use large-scale, quasi-geostrophic (QG) flows inverted from geomagnetic field models, which, as such, incorporate flow structures that are Earth-like, as the large eccentric gyre and the anticyclone under North Pacific. Furthermore, the QG hypothesis allows straightforward prolongation of the flow from the core surface to the bulk.
We confirm that a simple QG flow is not able to sustain the magnetic field against ohmic decay.
Additional complexity is introduced in the flow, inspired by the action of the Lorentz force. Indeed, on centenial time-scales, the Lorentz force can balance the Coriolis force and strict quasi-geostrophy may not be the best ansatz. When our columnar flow is modified to account for the action of the Lorentz force, magnetic field is generated for Elsasser numbers larger than 0.25 and magnetic Reynolds numbers larger than 100. This suggests that our large scale flow captures the relevant features for the generation of the Earth's magnetic field and that the invisible small scale flow may not be directly involved in the process. Near the threshold, the resulting magnetic field is dominated by an axial dipole, with some reversed flux patches. We notice the footprint of the inner-core in the magnetic field generated deep in the bulk of the shell, although we did not include one in our computations. Time-dependence is also considered, derived from principal component analysis applied to the inverted flows. We find that time periods from 120 to 50 years do not affect the mean growth rate of the kinematic dynamos.

Keywords: geodynamo, kinematic dynamo, core, flows

*Speaker

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NanoMagSat, a nanosatellite concept for permanent space-born observation of the geomagnetic field and the ionospheric environment

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Abstract

Space-borne observation of the Earth's magnetic field and of the ionospheric environment started early on in the history of space exploration. But only since 1999 has continuous low Earth orbiting observation successfully been achieved, thanks, in particular, to the Oersted, CHAMP and Swarm missions. These missions have demonstrated the usefulness of long-term continuous observation from space for a wealth of applications, ranging from understanding the fast and small scales of the Earth's core dynamo, to investigations of still poorly understood ionospheric phenomena, all of which also have important societal applications.

In this poster, we will discuss the possibility of building a nanosatellite that could be used as a baseline for a series of low-cost satellites aiming at a permanent space-born observation of the Earth's magnetic field and of the ionospheric environment. This "NanoMagSat" concept, currently under investigation within CNES, is based on the possibility of using a miniaturized version of the absolute magnetometer designed by CEA-LETI, which currently operates on the Swarm mission. This instrument is capable of simultaneously providing absolute scalar and vector measurements of the magnetic field at 1 Hz sampling rate, together with higher frequency (250 Hz sampling rate) absolute scalar data. NanoMagSat would use this instrument, coupled with star imagers for attitude restitution, together with other instruments providing additional measurement capabilities for ionospheric science and monitoring purposes (vector field measurements beyond 1Hz, plasma density, electron temperature, TEC, in particular).

Because Swarm will very likely ensure data acquisition on a polar orbit for at least another 10 years, the orbit currently under consideration for NanoMagSat is that of an inclined orbit (within the 60◦ range), aiming at a launch before 2021. Such an orbit has been identified as particularly useful to complement polar orbits and provide a much- needed fast local time coverage of all sub-auroral latitudes (the so-called "Swarm Delta" mission concept). Beyond this maiden mission, NanoMagSat could then next be used as a baseline for the progressive establishment and maintenance of a permanent international network of a small number of

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similar satellites, operated and coordinated in a way analogous to the Intermagnet network of ground magnetic observatories.

Keywords: Magnetic Field, Satellite

Invisible dynamo in 2D Parker's dynamo model

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Abstract

We consider the inverse problem for the 2D Parker's mean field dynamo equations (the alpha-omega-approximation) in the spherical shell with the simple algebraic form of the alpha-quenching. These equations are still the good approximation for the modelling of the mean magnetic fields in the planets and stars. This approach is based on minimization of the cost-function which describes deviation of the model field properties from the desired ones. The cost function depends on the 2D Fourier coefficients of the alpha and omega profiles, which are itself functions of the radius and latitude. Then, minimization of the cost function gives the Fourier coefficients which can be used for reconstruction of the spatial distribution of alpha and omega dynamo energy sources. The cost-function can accumulate different properties of the magnetic field. So far it can have local minima the robust methods of minimization are required. For this aim we use the Monte-Carlo method. This method with help of MPI is realized at the cluster supercomputer, where at each node the dynamo equations were solved for the unique set of the Fourier coefficients. Then the best realization was selected. The process repeated till the cost function reached the desired value.

We considered the case where the cost function was minimal if the total magnetic field (toroidal and poloidal counterparts) disappeared at the outer core boundary. Note that poloidal part should not be exactly zero at the boundary, but can be in order of magnitudes smaller than in the inner region. The profiles of alpha and omega are constructed for these dynamo regimes.
The resulting distributions of alpha and omega lead to the generation of the oscillating magnetic field, concentrated in the inner part of the liquid core. It is shown that due to the magnetic diffusion magnetic field during polarity reversal does not have enough time to get out to the surface. It is the skin-effect which is responsible for localisation of the magnetic field near the zone of generation of the magnetic field. The ratio of the maximal magnetic energy in the liquid core to its value at the outer boundary reaches two orders of magnitude or more. This result is important in the interpretation of the observed planetary and stellar magnetic fields. The proposed method for solving of the inverse problem of the non-linear dynamo equations can be easily adapted for the wide class of the mathematical physics problems.

Keywords: dynamo, Monte Carlo method, cost function

*Speaker

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Analytical solutions for inertial modes and onset of thermal convection in rapidly rotating spheroids

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Abstract

The flows in the fluid cores of rapidly rotating planetary bodies can be conveniently described as being invariant along the direction parallel to the rotation axis. This description, also referred to as columnar, is based on the quasi-geostrophic approximation and it holds for timescales longer than the rotation period as long as other forces acting on the fluid are of secondary importance with respect to rotation. A significant effort of the community is presently spent in the development of quasi-geostrophic numerical models of planetary cores, the final goal being to run numerical simulations in realistic parameters regimes. The development of such models has proven fundamentally challenging, especially when magnetic forces are present. Therefore, analytical solutions to simple dynamical problems will be of paramount importance for benchmarking purposes.
We present an analytical and explicit solution to the problem of the columnar inertial modes in rapidly rotating sphere and spheroids in absence of viscosity. We find that the oblateness of the spheroid significantly alters the frequency of the low order inertial modes for high azimuthal wavenumbers. However the geometry of the flow is the same as for the spherical case. Excellent agreement with known 3-D solutions has been found. Typically, given the geometry of the columnar flows, the axial vorticity equation is assumed to be a valid description of the dynamics of quasi-geostrophic flows. Based on a recently developed projection technique, we found the axial vorticity equation to be appropriate only in the case of highly oblate spheroids.
This analytical solution can be used to calculate the critical Rayleigh number and the shape of the flow at the onset of thermal convection. We do so by following an asymptotic procedure already applied to the spherical case and for 3-D flows.

Keywords: quasi geostropy, inertial modes, thermal convection, outer core

*Speaker

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Self-consistent thermal structure at the inner core boundary in dynamo simulations

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Abstract

Resent seismic observations suggests that inner core has a seismic anisotropy. This seismic anisotropy suggests aspherical growth of the inner core, and slow viscous deformation of the inner core and latent heat distribution by flow motion are expected to be the origin of the aspherical growth of the inner core. To explain inner core anisotropy and aspherical growth of the inner core, a number of dynamo simulations has been performed with prescribed boundary conditions at ICB to take into account the inner core heterogeneity. To represent thermal structure of the ICB self-consistently, geodynamo simulations are performed with considering the heat equation throughout the inner and outer core.
In the present study, we assume that the inner core is electrically insulated and co-rotate with mantle to compare the results with the simulation without considering the inner core. We also assumed that no heat sources in the outer core and set a homogeneous heat flux at the outer boundary of the shell as a thermal boundary condition at CMB, and the same thermal diffusivity is applied for the inner core and outer core. To sustain the average temperature in the outer core, a constant heat source is introduced in the inner core. We compare the simulations results with the simulations results using fixed heat flux or temperature condition at ICB. We performed four cases of the simulations with changing Rayleigh number to investigate dependency of the thermal structure on the Rayleigh number.
The results show that the time averaged thermal structure at ICB is likely to the simulation results with homogeneous heat flux boundary conditions. The time averaged lateral temperature variation is approximately 26% of the average temperature difference between ICB and CMB, while lateral heat flux variation is only 6% of the average heat flux at the ICB. We also observe small scale temperature and heat flux variations; however, these components vary with time. In addition, the length scale of the heat flux variation is smaller than the temperature variation at ICB. Furthermore, Y_1^1 component, which can generate a translation mode in the inner core, is approximately 0.1 times of the Y20 component. There is small dependence of the Y_2^0 component of the temperature variation on the Rayleigh number.

Keywords: geodynamo simulation, inner core boundary

*Speaker

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Frequency spectrum of the geomagnetic field harmonic coefficients from dynamo simulations

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Abstract

The construction of geomagnetic, archeomagnetic or paleomagnetic field models requires some prior knowledge about the actual field, which can be gathered from the statistical properties of the field over a variety of length scales and time scales. We use numerical simulations of the geodynamo to supplement the information about the temporal power spectra (or equivalently the auto-covariance functions) of the individual Gauss coefficients that describe the geomagnetic field outside the Earth's fluid outer core. Our three simulations are quite different, but they all exhibit relevant features of the secular variation. We interpret the time series of spherical harmonic coefficients in our simulations as realizations of stationary and differentiable stochastic processes, namely order 2 autoregressive processes. We discuss to what extent their time spectra can be deduced from the spatial power spectra of the magnetic field and of its first time derivative both averaged over a short time span. In this framework, the statistics of all but the axial dipole of the coefficients are fully constrained by their variance and their correlation times. These two quantities are mainly function of the spherical harmonic degree (with possible dependence on the order). Characterizing the axial dipole requires a more sophisticated process, with a second distinct timescale, possibly related to magnetic diffusion or non-linear effects. We discuss how these results bear on analyses of the actual geomagnetic field.

Keywords: Dynamo simulations, Magnetic field, Rapid time variations, Probability distributions, Time series analysis, Inverse theory

*Speaker

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Studying asymmetric growth and decay of the geomagnetic dipole field using geodynamo simulations

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Abstract

Studying direct magnetic and paleomagnetic field variations at Earth's surface provide a means to deepen our understanding of the dynamo operating in the liquid outer core. PADM2M is a reconstruction of the 0 to 2 Ma paleomagnetic axial dipole moment (ADM), based on global paleointensity data. It can resolve ADM variations on timescales of about 10ky and longer. When high frequency variations are filtered out the geomagnetic dipole on average grows more rapidly than it decays. This asymmetric behavior is not just associated with polarity reversals, and appears to be an important characteristic of secular variation visible from paleofield observations. We use a suite of numerical dynamo simulations (generated by the Boussinesq Leeds Dynamo Code) to investigate what core processes are responsible for this behavior. Simulations do not suffer the same limitations of spatial and temporal resolution as paleomagnetic records. The magnetic and velocity fields, are completely known; however, the simulations cannot yet run with Earth-like diffusivities or rotational rates. We analyzed multiple magnetic diffusion times because we are interested in long time scales (10ˆ4-10ˆ5 years). Our simulations include a range of Rayleigh and Roberts numbers with a variety of heating modes and outer boundary thermal conditions resulting in dipole-dominated dynamos some of which reverse. For each simulation we conducted the same analysis as was applied to PADM2M: a series of smoothed ADM models were constructed using low-pass filters to determine which timescales (if any) exhibited asymmetry in rate of change. We examine the coherence spectra between the ADM at the Earth's surface with the L=1 magnetic energy and the total magnetic energy integrated over the outer core to determine the frequency range over which internal field variations are coherent with surface ADM variations. By combining the rates of change of magnetic and kinetic energies, with ohmic and viscous heating computed directly during the simulations we recover time series of the work done by the Lorentz and buoyancy forces. Using the power spectral density and the coherence spectra we assess changes in the force balance as a function of frequency. At long periods, as expected, the dynamos are usually in steady state with little variability in kinetic and magnetic energies. In some frequency bands and some simulations asymmetry between growth and decay similar to that in PADM2M occurs and it is associated with more powerful Ohmic heating than work done by the Lorentz force in that frequency band.

*Speaker

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Keywords: Geomagnetic field, Changes in Axial Dipole Moment, Outer core force balance

An accelerating high-latitude jet in Earth's core

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Abstract

The structure of the core-generated magnetic field, and how it changes in time (its secular variation or SV), supplies an invaluable constraint on the dynamics of the outer core. At high latitude, previous studies have noted distinctive behaviour of secular change, in particular suggesting a polar vortex tied to the dynamics within the tangent cylinder region. Recent high-resolution observational models that include data from the Swarm satellites have refined the structure of observed SV, to a rapidly changing circular daisy-chain configuration centred on the north geographic pole, on or very close to the tangent cylinder itself. Motivated by theoretical considerations of the likely dynamical regime of the core, we demonstrate that this feature can be explained by a localised westwards cylindrical jet of 420 km width centred the tangent cylinder, whose amplitude appears to have increased in strength by a factor of three over the period 2000–2016 to about 40 km/yr. The current accelerating phase may be a short fragment of decadal fluctuations of the jet strength linked to both torsional wave activity and the rotation direction of the inner core.

Keywords: geomagnetism, core flows

*Speaker

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The effects of Ekman pumping on quasi-geostrophic convection

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Abstract

Numerical simulations of three-dimensional rotating Rayleigh-Bénard convection are performed using an asymptotic quasi-geostrophic model that incorporates the effects of no-slip boundaries through (i) parameterized Ekman pumping boundary conditions, and (ii) a thermal wind boundary layer that regularizes the enhanced thermal fluctuations induced by pumping. The fidelity of the model, obtained by an asymptotic reduction of the Navier-Stokes equations, is explored for the first time by comparisons of simulations against the findings of direct numerical simulations (DNS) and laboratory experiments of rotationally constrained convection that establish Ekman pumping as the mechanism responsible for significantly enhancing the vertical heat transport. For maximal values of the rotation rate attainable in experiments and DNS, as measured by Ekman number E is about 10ˆ{-7}, excellent agreement is achieved for fluids with Prandtl number Pr=1 and good qualitative agreement is achieved for Pr > 1. Similar to studies with stress-free boundaries, four spatially distinct flow morphologies exists, each in geostrophic balance. Despite the presence of frictional drag at the upper and lower boundaries, a strong non-local inverse cascade of barotropic (*i.e.*, depth-independent) kinetic energy persists in the final regime of geostrophic turbulence and is dominant at large scales. For mixed no-slip/stress-free and no-slip/no-slip boundaries, Ekman friction is found to attenuate the efficiency of the upscale energy transport and, unlike the case of stress-free boundaries, rapidly saturates the barotropic kinetic energy. For no-slip/no-slip boundaries, Ekman friction is strong enough to prevent the development of a coherent dipole vortex condensate. Instead vortex pairs are found to form intermittently before being destroyed frictionally. For all combinations of boundary conditions, a Nastrom-Gage type spectrum of kinetic energy is found where the power law exponent changes from about -3 to -5/3, *i.e.* from steep to shallow, as the spectral wavenumber increases.

Keywords: Rapidly Rotating, thermal convection

*Speaker

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Anisotropic Turbulent Heat Flux Models in the Earth's Core and Rotating Magnetoconvection

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Abstract

The local linear analysis of turbulence in the Earth's outer core by Braginsky & Meytlis (1964, GAFD 55, 71-87) is revisited for regions where the buoyancy force is not parallel to the rotation axis. The resulting dispersion relations are examined for varying Ekman and Rayleigh numbers. The analysis compares the growth rates of turbulent anisotropic plate-like cells, elongated in the directions of the magnetic field and the rotation axis, with the growth rates of isotropic cubic cells. At low Rayleigh and high Ekman numbers plate-like and cubic cells typically have comparable growth rates. However, for Rayleigh and Ekman numbers appropriate for the Earth's core, anisotropic plate-like cells grow much faster than isotropic cubic cells. These findings are consistent with Matsushima et al. (1999, Earth Planets Space 51, 277–286) at low Rayleigh and high Ekman numbers, but with Braginsky & Meytlis (1964) at core Rayleigh and Ekman numbers, supporting the Braginsky-Meytlis picture of core turbulence in which viscous and thermal diffusivities are enhanced in directions of strong magnetic field and the rotation axis up to the molecular magnetic diffusivity. The effects of anisotropic turbulence on the mean magnetic, velocity and temperature fields are studied in magnetoconvection models with thermal diffusion enhanced in the direction of the magnetic field and rotation. The perturbed mean fields are linearized about azimuthal basic state magnetic and velocity fields. The azimuthal basic state velocity is chosen to balance the Lorentz force to leading order in the non-diffusive momentum equation. The linearized perturbation equations are solved numerically in a rotating sphere with electrically-insulating exterior for different Ekman, Elsasser and Rayleigh numbers. The efficiency of the resulting mechanism in enhancing instability is compared for controlled total diffusivity in different models using the critical Rayleigh number.

Keywords: heat transport, anisotropic diffusion, dynamo, magnetoconvection

*Speaker

Spherical convective dynamos in the rapidly rotating asymptotic regime

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Abstract

Self-sustained convective dynamos in planetary systems operate in an asymptotic regime of rapid rotation, where a balance is thought to hold between the Coriolis, pressure, buoyancy and Lorentz forces (the MAC balance). Classical numerical solutions have previously been obtained in a regime of moderate rotation where viscous and inertial forces are still significant. We define a unidimensional path in parameter space between classical models and asymptotic conditions from the requirements to enforce a MAC balance and to preserve the ratio between the magnetic diffusion and convective overturn times (the magnetic Reynolds number). Direct numerical simulations performed along this path show that the spatial structure of the solution at scales larger than the magnetic dissipation length is largely invariant. This enables the definition of large-eddy simulations resting on the assumption that small-scale details of the hydrodynamic turbulence are irrelevant to the determination of the large-scale asymptotic state. These simulations are shown to be in excellent agreement with direct simulations in the range where both are feasible, and can be computed for control parameter values far beyond the current state of the art, such as an Ekman number E=1e-8. We obtain strong-field convective dynamos approaching the MAC balance and a Taylor state to an unprecedented degree of accuracy. The physical connection between classical models and asymptotic conditions is shown to be devoid of abrupt transitions, demonstrating the asymptotic relevance of classical numerical dynamo mechanisms. The fields of the system are confirmed to follow diffusivity-free, power-based scaling laws along the path.

Keywords: Geodynamo, Dynamo theory, MHD turbulence, convection, numerical simulations

*Speaker

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Geomagnetic forecasts driven by thermal wind dynamics in the Earth's core

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Abstract

There exists a fundamental as well as practical interest in being able to accurately forecast the future evolution of Earth's magnetic field at decadal to secular ranges. This work enables such forecasts by combining geomagnetic data with an Earth-like numerical model of a convection-driven fluid dynamo. The underlying data assimilation framework builds on recent progress in inverse geodynamo modelling, a method which estimates an internal dynamic structure for Earth's core from a snapshot of the magnetic field and its instantaneous rate of change at the surface. Here the method is further evolved into a single-epoch ensemble Kalman filter, in order to initialise at a given epoch an ensemble of states compatible with the observations and representative of the uncertainties in the estimation of hidden quantities. The ensemble dynamics, obtained by subsequent numerical integration of the prognostic model equations, are found to be governed by a thermal wind balance or equilibrium between buoyancy forces, the Coriolis force and the pressure gradient. The resulting core fluid flow pattern is a quasi-steady eccentric gyre organised in a column parallel to Earth's rotation axis, in equilibrium with a longitudinal hemispheric convective density anomaly pattern. Predictions of the present magnetic field from data taken within the past century show that the ensemble has an average retaining good consistency with the true geomagnetic evolution and an acceptable spread well representative of prediction errors, up to at least a secular range. The assimilation generally outperforms the linear mathematical extrapolations from a 30-yr prediction range onwards, with a 40 per cent improvement in Earth-surface error at a secular range. The geomagnetic axial dipole decay observed over the past two centuries is predicted to continue at a similar pace in the next century, with a further loss of 1.1 ± 0.3 μT by year 2115. The focal point of the South Atlantic geomagnetic anomaly is predicted to enter the South Pacific region in the next century, with the anomaly itself further deepening and widening. By year 2065, the minimum intensity is predicted to decrease by 1.46 ± 0.4 μT at the Earth surface and the focal point to move 12.8 ± 1.4 deg westwards with a slight northward component. This corresponds to a drift rate of 0.26 deg yr–1, similar to the westward drift observed over the past four centuries. The same drift rate is also predicted until 2115 with a further (but more uncertain) intensity decrease.

Keywords: Inverse theory, Dynamo: theories and simulations, Magnetic anomalies: modelling and interpretation, Rapid time variations, Satellite magnetics.

*Speaker

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Flow States in the Derviche Tourneur experiment

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Abstract

The Derviche Tourneur Sodium Experiment (DTS) is a spherical Couette flow experiment with a liquid sodium medium between inner and outer spheres of copper and stainless steel, respectively. The apparatus has the same aspect ratio as the Earth, and a strong dipole magnetic field imposed from the inner sphere. The operation of the experiment reveals a collection of flow states dependent on the balance of inertial, Coriolis, and magnetic forces (represented by the Elsasser and Rossby numbers). The experimental diagnostics register the change between states, but don't provide a full picture of what these states actually look like inside the sphere. To rectify this the XSHELLS code has been run in a similar range of Rossby (Ro) and Elsasser () numbers. For Ro close to 1 (where the inner sphere rotates faster than the outer sphere) the mean flow is mostly quasigeostrophic, while counterrotating spheres transition from a regime dominated by an instability centered in the still point between outward and inward flowing jets to an instability occupying the return flow along the outer sphere as the differential rotation increases (Ro $\in$ (-2, -1)). This poster will aim to explain these simulations, in particular the balances between the Coriolis and Lorentz forces (aka magnetostrophic regime), their underlying assumptions, and how their outputs relate to the physical system of the DTS.

Keywords: dynamo, direct numerical simulation, experiment

*Speaker

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Penetration of mean zonal flows into an outer stable layer excited by MHD thermal convection in rotating spherical shell

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Abstract

Penetration of steady magneto-hydrodynamic (MHD) disturbances into an upper strongly stratified stable layer excited by MHD thermal convection in rotating spherical shells is investigated. An analytic expression of penetration distance is derived by considering perturbations to a stably stratified rotating MHD Boussinesq fluid in a semi-infinite region with the rotation axis and uniform magnetic field tilted relative to the gravity axis, respectively. Linear dispersion relation shows that the penetration distance with zero frequency depends on the amplitude of Alfven wave speed. When Alfven wave speed is small, viscous diffusion becomes dominant and penetration distance is similar to the horizontal scale of the disturbance at the lower boundary. In contrast, when Alfven wave speed becomes larger, disturbance can penetrate more deeply, and penetration distance becomes in proportion to the Alfven wave speed and inverse proportion to the geometric average of viscous and magnetic diffusion coefficients and to the total horizontal wavenumber. The analytic expression of penetration distance is in good agreement with the extent of penetration of mean zonal flow induced by finite amplitude convection in a rotating spherical shell with an upper stably stratified layer embedded in the axially uniform basic magnetic field.

Keywords: Alfven waves, secular variation of geomagnetic field, dynamo

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Subcritical convection in a numerical model of planetary cores

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Abstract

We study nonlinear convection for low Prandtl number fluids (such as liquid metals, Pr=0.01-0.1) in a rapidly rotating sphere with internal thermal heating. Our model assumes that the velocity is invariant along the axis of rotation due to the rapid rotation of the system, while the temperature is computed in 3D. We identify two separate branches of convection near the onset of convection: a well-known weak branch for Ekman numbers greater than 1e-6, which is continuous at the linear onset of convection, and a novel strong branch at lower Ekman numbers, which is discontinuous at the onset with large values of the convective and zonal velocities. For small Ekman numbers (Ek< 1e-7), the strong branch is subcritical.

Keywords: convection, zonal flows, rotating flows, outer core dynamics

*Speaker

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The signature of inner core nucleation on the geodynamo

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Abstract

Energetics of the core indicate that the power delivered to the present-day geodynamo comes mainly from the growth of the solid inner core, through light element and latent heat release, and that nucleation of the inner core occurred within 1.5 Ga. We use numerical dynamo simulations linked by thermochemical evolution of the core to investigate the effects of inner core nucleation (ICN) on the geodynamo, and to identify possible ICN footprints in the paleomagnetic field. Our results predict little footprint of ICN on surface magnetic field intensity, consistent with the enigmatic lack of a long-term trend in paleointensity. We find that the time average dipole moment increases slightly with age from present-day to ICN, despite a reduction of two orders of magnitude in the dynamo power. We also find that the surface field is dominated by an axial dipole before and after ICN, plus a smaller axial octupole that strengthens with age due to changes in polar flows as the inner core shrinks. The ratio of axial octupole to axial dipole field presents an observable for tracking inner core growth.

Keywords: geodynamo, inner core nucleation, state of the Earth's core, geomagnetic field on long timescales, paleointensity, core evolution

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Geodynamo Models With a Thick Stable Layer and Heterogeneous CMB Heat Flow

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Abstract

The upward revision of the thermal conductivity in the Earth's core makes it plausible that the mean heat flow at the core-mantle boundary (CMB) could be only a fraction of what can be conducted down the core adiabat. The upper part of the fluid core would be stably stratified to substantial depth. Heat flow at the CMB is likely very heterogeneous and would still be superadiabatic in some regions of the CMB. The dynamics of such a system is unclear. Gubbins et al. (2015) suggest that the locally unstable gradient would mix up the stable layer as a whole and replace it by a weakly convecting one. We study dynamo models driven by a codensity flux from the inner core. On the outer boundary an inverse (on average) gradient is imposed, leading to stable stratification of the top 1/5 to 1/3 of the fluid shell. In addition to control cases with homogeneous CMB flux, we run models with heterogeneous and locally unstable heat flow distributions. In the latter cases a predominantly horizontal circulation in a thin layer immediately below the outer boundary redistributes the heat that is conducted radially upward in the stable layer and transports it towards the high heat-flow spots. Radial flow below these spots does not penetrate deeply into the stable layer, nor does the layer become mixed up to a significant degree. A scaling theory for the velocity and penetration depth of the shallow circulation agrees with the numerical results. Extrapolated to core conditions, it predicts a thickness of 0.1-1 km for the recirculation layer. A dynamo operates in the convecting deep interior of the models, however, its dipole moment is low in comparison to the Earth value. Heat flow heterogeneity at the CMB does not seem to solve the problems that exist for the geodynamo when the average heat flux is substantially subadiabatic.

Keywords: Geodynamo model, Core, mantle boundary, Core heat flow

*Speaker

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Inertial effects on thermochemically driven hydromagnetic dynamos in spherical shells

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Abstract

Mechanisms of rotating convection play a fundamental role in the generation of the Earth's magnetic field. In order to get a better understanding of these mechanisms, we investigate the isolated problems of rotating thermal,chemical and thermochemical convection, and then thermally, chemically and thermochemically driven hydromagnetic dynamos in spherical shells. The underlying model equations describe the evolution of the flow, thermal and compositional fields in the first case, and flow, thermal, compositional and magnetic fields in the second case within the Boussinesq approximation. A uniform distribution of heat sources within the shell are assumed. The effects of solidification at the inner core boundary are accounted for by prescribing the latent heat and solutal fluxes at the bottom of the shell. In the limit of small Ekman and Prandtl numbers, we provide asymptotic results for the onset of convection and dynamos, in which case the system can be approximated to leading order by an inertial-wave convection and dynamos. The full set of governing equations is then solved numerically.

Keywords: inertial waves, thermochemical convection, codensity, solidification processes

*Speaker

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Magnetostrophic Convection: At the Heart of Planetary Dynamo Action?

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Abstract

The concept that planetary dynamos evolve to a magnetostrophically balanced state was first posited following Chandrasekhar's (1954, 1961) linear stability analysis of plane layer rotating magnetoconvection. In this poster, I will compare linear theoretical results against planetary dynamo modeling results to test under what conditions, if any, magnetostrophically balanced states exist in present dynamo experiments. In addition, I will then consider under what more extreme conditions, if any, magnetostrophic dynamo action might occur.

Keywords: Magnetostrophic, Convection, Dynamo

*Speaker

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Excitation of Torsional Waves in the Earth's Core

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Abstract

Axisymmetric torsional waves have been detected in the Earth's core, both by measurements of the secular variation and through length of day changes. Both signals have a strong 6 year component, which is consistent with a magnetic field having a strength of around 2mT in the outward direction perpendicular to the rotation axis, the direction in which torsional waves propagate. There is some observational evidence that the torsional waves are travelling outward from the tangent cylinder parallel to the rotation axis touching the inner core. There is a theoretical expectation that the fluid inside the tangent cylinder will be more thermally and compositionally buoyant than the fluid outside the tangent cylinder. At the tangent cylinder, there will be strong thermal and compositional gradients, exciting convection in the form of travelling magnetic Rossby waves. These magnetic Rossby waves can have periods close to that of the torsional Alfven waves in the core, provided they have components with a wavelength of around 350 km perpendicular to the convection roll axis. These waves can trigger trains of torsional waves travelling outwards from the tangent cylinder region.

We have investigated this resonant excitation mechanism using a magnetoconvection based approach, which has been adapted from a spherical shell convection driven dynamo code. This enables us to get to a regime of strong fields and very low Ekman numbers, at the cost of specifying the form of the magnetic field at the boundaries rather than allowing it to arise naturally from the dynamo model. Low Ekman number is essential to see the wave excitation, as the tangent cylinder convecting layer is expected to be only a few hundred kilometres thick, and viscosity must be small enough to allow convection on these scales. Under some circumstances the torsional waves can be almost periodic, locked to a trapped torsional wave mode inside the tangent cylinder. This is therefore a possible source of the 5.9 year period in the length of day signal. We are currently exploring the conditions under which the resonance between the convection and the torsional oscillations can occur.

Keywords: core convection: torsional waves: length of day changes

*Speaker

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A particle-in-cell method to study double-diffusive convection in the liquid layers of planetary interiors.

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Abstract

Numerous planetary bodies contain internal liquid layers in the form of either partially molten iron cores, buried water oceans (Khurana et al., 1998; Kivelson et al., 2002) or post-accretion primitive magma oceans (Labrosse et al., 2007). Convection in these layers is usually driven by the combination of two sources of buoyancy: a thermal source directly related to the planet's secular cooling, the release of latent heat and possibly the heat generated by radioactive decay, and a compositional source due to some process of cristallisation or fusion, for example the growth of a solid inner core which releases light elements into the liquid outer core (Braginsky and Roberts, 1995). The molecular diffusivities of the thermal and compositional fields typically differ by several orders of magnitude: the Lewis number (ratio of the thermal to the compositional molecular diffusivity) has an estimated value of 1000 in the Earth's outer core (Braginsky and Roberts, 1995). This can produce significant differences in the convective dynamics compared to pure thermal or compositional convection due to the potential occurrence of double-diffusive phenomena. However, the weak diffusivity of the compositional field makes it technically difficult to handle in current geodynamo codes and requires the use of a semi-Lagrangian description to produce minimal numerical diffusion.

We implemented a "particle-in-cell" (PIC) method into a pre-existing geodynamo code (PARODY, J. Aubert, E. Dormy) to properly describe the compositional field. We successfully tested our new code on two benchmark cases (Christensen et al, 2001; Breuer et al, 2010) which validate its applicability to the study of double-diffusive convection in the internal liquid layers of planets.

In addition, the thermochemical boundary conditions are distinct and coupled at the inner core boundary and this cannot be described in a codensity formulation. Therefore, we also implemented the corresponding coupling equations in our new tool which allows for the fields

*Speaker

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to be treated separately.
As a first application, we study a case of non-magnetic double-diffusive convection at infinite Lewis number and compare the convection's properties to that of simulations with finite Lewis numbers. We also present work in progress addressing the inner core's dichotomy. Our study builds on previous simulations by (Aubert et al, Nature 2008) and includes both coupling of the boundary conditions at the inner core boundary and varying Lewis number.

Keywords: double diffusive convection, geodynamo, core dynamics, numerical methods

Core flows inside and below a viscous boundary layer at the core surface

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Abstract

Fluid flows near the core surface provide valuable information on, for example, realistic geodynamo processes, features of the core-mantle boundary (CMB), and core-mantle coupling in relation with length-of-day (LOD). Such core flows can be estimated from the spatial distribution and secular variation of the geomagnetic field, and many core-surface flow models have been obtained on the basis of the frozen-flux approximation (Roberts and Scott, 1965). It should be noted, however, that the no-slip boundary for the flow at the core surface would give rise to a significant viscous boundary layer. This implies that time variations of the geomagnetic field should be caused by the magnetic diffusion at the CMB; that is, the so-called frozen-flux hypothesis could be invalid. Hence, a new method of estimating fluid flows near the core surface has been presented (Matsushima, 2015); inside the boundary layer at the CMB, balance is presumed among the viscous force, the Coriolis force, and the pressure gradient, and it is reasonable that the magnetic diffusion contributes to the time variations of the geomagnetic field; below the boundary layer, the tangentially geostrophic constraint is imposed on the flow, and the magnetic diffusion is neglected as in the frozen-flux approximation. The radial component of magnetic field in the core is inferred using the radial component and its partial derivatives with respect to the radius derived from the continuity and the geomagnetic diffusion at the CMB. In this presentation, a core surface flow model between 1840 and 2015 has been derived from a geomagnetic field model, COV-OBS.x1 (Gillet et al., 2015).

High correlation between vortices and upwellings/downwellings in the boundary layer at mid and high latitudes is noticeable. The positional relation of upwellings and downwellings inside and below the boundary layer at low latitudes suggests existence of columnar convective cells. Upwellings of cyclonic and anticyclonic columnar flows give rise to flux expulsion, which seems to be a cause of intense magnetic flux spots seen in equatorial regions. Furthermore, temporal variations of the flow model possibly contain information on phenomena in relation with core-mantle coupling, such as the LOD, and spin-up/spin-down of core flows. The present new method would lead to a new insight on core surface flows.

Keywords: core surface flow, viscous boundary layer, geomagnetic field

*Speaker

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Scaling regimes in spherical shell rotating convection

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Abstract

Rayleigh-Bénard convection in rotating spherical shells can be considered as a simplified analogue of many astrophysical and geophysical fluid flows. Here, we use three-dimensional direct numerical simulations to study this physical process. We construct a dataset of more than 200 numerical models that cover a broad parameter range with Ekman numbers spanning 3e-7 < E < 0.1, Rayleigh numbers within the range 1e3< Ra < 2e10 and a unity Prandtl number. We investigate the scaling behaviours of both local (length scales, boundary layers) and global (Nusselt and Reynolds numbers) properties across various physical regimes from onset of rotating convection to weakly-rotating convection. Close to critical, the convective flow is dominated by a triple force balance between viscosity, Coriolis force and buoyancy. For larger supercriticalities, a small subset of our numerical data approaches the asymptotic diffusivity-free scaling of rotating convection Nu _˜ Ra^(3/2)E^(2)Pr(-1/2) in a narrow fraction of the parameter space delimited by 6Ra_c < Ra < 0.4E^(-8/5). Using a decomposition of the viscous dissipation rate into bulk and boundary layer contributions, we establish a theoretical scaling of the flow velocity that accurately describes the numerical data. In this regime, the fluid bulk is controlled by a triple force balance between Coriolis, inertia and buoyancy, while the remaining fraction of the dissipation can be attributed to the viscous friction in the Ekman layers. Beyond Ra = E^(-8/5), the rotational constraint on the convective flow is gradually lost and the flow properties continuously vary to match the regime changes between rotation-dominated and non-rotating convection. We show that the quantity Ra E^(12/7) provides an accurate transition parameter to separate rotating and non-rotating convection.

Keywords: Geostrophic turbulence, Rotating flows, Geophysical and geological flows

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Magnetic to magnetic and kinetic to magnetic energy transfers at the top of the Earth's core

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Abstract

We develop the theory for the magnetic to magnetic and kinetic to magnetic energy transfer between different spherical harmonic degrees due to the interaction of fluid flow and radial magnetic field at the top of the Earth's core. We show that non-zero secular variation of the total magnetic energy could be significant and may provide evidence for the existence of stretching secular variation, which suggests the existence of radial motions at the top of the Earth's core - whole core convection or MAC waves. However, the uncertainties of the small scales of the geomagnetic field prevent to have a definite conclusion. Combining core field and flow models we calculate the detailed magnetic to magnetic and kinetic to magnetic energy transfer matrices. The magnetic to magnetic energy transfer shows a complex behavior with local and non-local transfers. The spectra of magnetic to magnetic energy transfers show clear maxima and minima, suggesting an energy cascade. The kinetic to magnetic energy transfers, which are much weaker due to the weak poloidal flow, are either local or non-local between degree one and higher degrees. The patterns observed in the matrices resemble energy transfer patterns that are typically found in 3D MHD numerical simulations.

Keywords: Dynamo: theories and simulations, Geomagnetic induction, Magnetic field, Rapid time variations, Core, outer core and inner core.

*Speaker

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TROCONVEX: An extreme laboratory approach to geostrophic turbulence

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Abstract

The Earth's dynamo is likely powered by vigorous thermochemical convection of molten iron in the outer core, in the presence of strong rotational and magnetic forces. In present-day numerical models of the dynamo, Earth-like magnetic field morphologies are reproduced when the flows are organized into axially-aligned, quasi-laminar columnar structures. However, recent experimental and numerical rotating convection studies have shown that these structures become decreasingly stable as the governing parameters approach Earth-like values (e.g., Cheng et al., 2015; Julien et al., 2016). Instead, regimes of so-called geostrophic turbulence (GT) are more likely relevant to the core. Here, stronger thermal forcing causes the flow field organization to break down, but not yet into buoyancy-dominated, nonrotating-style turbulence. This resembles conditions in the core, where the Rossby number (inertia / Coriolis) is very small (_~1e-6), but the Reynolds number (inertia / viscosity) is very high (_~1e8). Developing a greater understanding of GT will therefore aid our understanding of the underlying fluid physics in the Earth's dynamo. However, modern rotating convection experiments have yet to reach extreme enough parameter ranges for distinctive GT heat transfer and velocity trends to fully manifest (cf. Ecke & Niemela, 2014). We present here an upcoming experimental device, TROCONVEX, designed to characterize geostrophic turbulence at significantly more extreme conditions than previously possible. Specifically, we will conduct rotating convection experiments in a 4 meter high right cylindrical tank, reaching Ekman numbers (viscous / Coriolis forces) as low as 5e-9 and Rayleigh numbers (buoyancy / diffusion) as high as 1e14. These values are each an order of magnitude more extreme than achievable in other rotating convection setups. Using thermal diagnostics, we will scan through a wide array of Rayleigh, Ekman and Nusselt number (total heat transfer / conductive heat transfer) values, allowing us to fit precise scaling trends between these governing parameters in the GT regime. We will also test the myriad existing predictions for the location of the transition to GT. Finally, using Stereo Particle Image Velocimetry (SPIV), we will make detailed measurements of the three-dimensional velocity field. These diagnostics will advance our knowledge of turbulent rotating convection in more geophysically-relevant settings than previously possible.

Keywords: rotating convection, dynamo, laboratory experiments, geophysical fluid dynamics, outer core, turbulence

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Tests of diffusion-free scaling behaviors in numerical dynamo data sets

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Abstract

In attempting to describe the underlying physics of the dynamo generating regions of planets, geoscientists often make use of a set of scaling laws proposed in the seminal work of Christensen and Aubert (2006). These scalings are built around specially-constructed parameters that are independent of fluid diffusivities, anticipating that large-scale turbulent processes will dominate the physics in planetary dynamo conditions. Here, we examine the validity of these diffusion-free heat transfer scaling laws by constructing synthetic heat transfer datasets and testing their scaling properties alongside those proposed by Christensen and Aubert (2006). Our tests demonstrate that the seemingly robust collapse of heat transfer data using diffusion-free parameters is not indicative of fully turbulent, diffusion-free physics, but is instead an *a priori* consequence of the way such parameters are constructed. In fact, the diffusion-free heat transfer scaling is determined by convective onset, which is itself determined by the viscous diffusivity of the fluid. Our results, in conjunction with those of Stelzer and Jackson (2013), show that diffusion-free scalings are not validated by current-day numerical dynamo datasets, and that the conditions under which dynamo generation becomes free of fluid diffusivities remain to be established.

Keywords: outer core, dynamo modeling, heat transfer

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Performance and accuracy benchmarks for a next generation numerical dynamo model

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Abstract

Geodynamo simulations have successfully represented many observable characteristics of the geomagnetic field, and yield insight into the fundamental processes that generate magnetic fields in the Earth's core. Because of limited spatial resolution, however, the diffusivities in numerical dynamo models are much larger than those in the Earth's core. Consequently, questions remain about how realistic these numerical dynamo models are. The typical strategy used to address this issue has been to continue to increase the resolution of these quasi-laminar models with increasing computational resources, thus pushing them toward more realistic parameter regimes. We assess which methods are most promising for the next generation of supercomputers, which will offer access to the order of a million processor cores for large problems. We report performance and accuracy benchmarks from 15 dynamo codes that employ a range of numerical and parallelization methods. Computational performance is assessed on the basis of weak and strong scaling behavior up to 16,384 processor cores. Extrapolations of our weak scaling results indicate that dynamo codes that employ two- or three-dimensional domain decompositions can perform efficiently on up to a million processor cores, paving the way for more realistic simulations in the next model generation.

Keywords: Geodynamo simulation, Benchmark

*Speaker

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Magnetic confinement of polar vortices in the Earth's core

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Abstract

Spherical shell dynamo models based on rotating convection show that the flow in the tangent cylinder is dominated by an off-axis plume that extends from the inner core boundary to the polar region and drifts westward. The formation of such a plume has been attributed to the effect of the magnetic field that significantly reduces the wavenumber of convection in a rotating plane layer. However, the assumption of a uniform axial magnetic field in the tangent cylinder is unrealistic, and also does not help explain the formation of isolated plumes. This study examines the onset of rapidly rotating convection in a fluid layer of finite aspect ratio subject to a laterally varying magnetic field. While a uniform axial magnetic field permeating the fluid layer produces a finite number of equally unstable modes, a laterally inhomogeneous field gives rise to a unique mode of instability where convection is entirely confined to the peak-field region. The localization of the flow by the magnetic field occurs even when the field strength (measured by the Elsasser number) is small and viscosity controls the smallest lengthscale of convection. The lowest Rayleigh number at which an isolated plume appears in the tangent cylinder in a nonlinear dynamo simulation agrees closely with the viscous-mode Rayleigh number in linear magnetoconvection. The lowest Elsasser number for plume formation in the simulation is higher than that in magnetoconvection, which indicates that the viscous–magnetic mode transition point with inhomogeneous fields is displaced to higher Elsasser numbers. Our study supports the idea that the magnetic field locally excites tangent cylinder convection in the viscous mode.

Keywords: Rapid rotation, magnetoconvection, tangent cylinder, geodynamo

*Speaker

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The observational signature of modelled torsional waves and comparison to geomagnetic jerks

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Abstract

Torsional Alfvén waves involve the interaction of zonal fluid flow and the ambient magnetic field in the core. Consequently, they perturb the background magnetic field and induce a secondary magnetic field. Using a steady background magnetic field from observationally constrained field models and azimuthal velocities from torsional wave forward models, we solve an induction equation for the wave-induced secular variation (SV). We construct time series and maps of wave-induced SV and investigate how previously identified propagation characteristics manifest in the magnetic signals, and whether our modelled travelling torsional waves are capable of producing signals that resemble jerks in terms of amplitude and timescale. Fast torsional waves with amplitudes and timescales consistent with a recent study of the 6 yr ΔLOD signal induce very rapid, small (maximum ˜2 nT/yr at Earth's surface) SV signals that would likely be difficult to be resolve in observations of Earth's SV. Slow torsional waves with amplitudes and timescales consistent with other studies produce larger SV signals that reach amplitudes of ˜20 nT/yr at Earth's surface. We applied a two-part linear regression jerk detection method to the SV induced by slow torsional waves, using the same parameters as used on real SV, which identified several synthetic jerk events. As the local magnetic field morphology dictates which regions are sensitive to zonal core flow, and not all regions are sensitive at the same time, the modelled waves generally produce synthetic jerks that are observed on regional scales and occur in a single SV component. However, high wave amplitudes during reflection from the stress-free CMB induce large-scale SV signals in all components, which results in a global contemporaneous jerk event such as that observed in 1969. In general, the identified events are periodic due to waves passing beneath locations at fixed intervals and the SV signals are smoothly varying. These smooth signals are more consistent with the geomagnetic jerks envisaged by Demetrescu and Dobrica than the sharp 'V' shapes that are typically associated with geomagnetic jerks.

Keywords: Torsional waves, geomagnetic jerks, core dynamics

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Bulk triggerring of travelling torsional modes

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Abstract

The proximity between the 6 to 8 years recurrence time of the torsional Alfven waves that have been inferred in the Earth's outer core over 1940-2010 and their 4 years travel time across the fluid core is nicely explained if these traveling waves are to be considered as normal modes. We discuss to what extent the emergence of free torsional modes from a stochastic forcing in the fluid core is compatible with some dissipation, specifically with an electromagnetic torque strong enough to account for the observed length of day variations of 6 years period. When the mantle is electrically insulating, the torsional normal modes that are excited are standing modes. In the presence of a conducting mantle, they transform into outward traveling modes very similar to the torsional waves that have been detected in the Earth's outer core. With such a resonant response a periodic forcing is not required; neither is the search for a source of motions in the vicinity of the cylindrical surface tangent to the inner core, where traveling waves seem to emerge.

Keywords: torsional waves, core, mantle coupling, length, of, day

*Speaker

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Polar vortices and their associated magnetic minima

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Abstract

Polar magnetic minima have been inferred from geomagnetic field observations. These minima may be related to anticyclonic vortices also inferred to exist near the poles. However, the physical mechanism for the connection between the two has not been well identified or quantified. One commonly invoked explanation asserts that the meridional circulation associated with the anticyclonic polar vortices advects magnetic flux away from the polar regions, thereby creating the polar magnetic minima. Here we quantify the magnetic effects of meridional circulation driven by Ekman and gyroscopic pumping. This is accomplished by solving the axisymmetric MHD equations for Earth's outer core under the magneto-geostrophic approximation (zero-inertia in the momentum equation). In our numerical experiments, a fixed thermal wind forcing is adopted, poloidal magnetic fields with different geometry and amplitude are imposed, and the Ekman number are varied from 10^{-3} to 10^{-6}. From our results, we infer that the polar magnetic minimum resulting from the meridional circulation in Earth's core is on the order of 10%. This is far smaller than the polar magnetic minimum observed at Earth's core- mantle boundary, which indicates that polar geomagnetic minima are not likely caused by large-scale polar vortex flows.

Keywords: Core Flow, Polar Vortices, Gyroscopic Pumping, Polar Magnetic Minima

*Speaker

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Coupling the Earth's Rotational and Gravito-Inertial Modes

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Abstract

Wave motions in the Earth's fluid core, supported by the restoring action of both buoyancy (within the stably stratified top layer) and the Coriolis force, lead to the existence of global oscillation modes, the so-called gravito-inertial modes. These fluid modes can couple with the rotational modes of the Earth by exerting torques on the mantle and the inner core. Viscous shear stresses at the fluid boundaries, along with pressure and gravitation, contribute to the overall torque balance. Previous research by Rogister & Valette (2009) suggests that indeed rotational and gravito-inertial modes are coupled, thus shifting the frequencies of the Chandler Wobble (CW), the Free Core Nutation (FCN) and the Free Inner Core Nutation (FICN). Here we outline a plan to develop a more accurate numerical model of the Earth's fluid core by considering a generalised eigenvalue problem that solves simultaneously the Liouville equation for the rotational modes, and the Navier-Stokes equation for the inertial modes.

Keywords: gravito inertial modes, rotation

*Speaker

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Heat Transfer and Velocity Field Behaviors of Core-Style Convection

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Abstract

Accurate models of planetary core dynamics require robust descriptions of core flows. Towards this end, we have designed and fabricated what is presently the world's largest experimental rotating convection device using water as the working fluid. Capable of accessing a broad range of parameters (e.g., Ekman numbers ranging between 1e-8 $<$ E $<$ 1e-2 and Rayleigh numbers between 1e4 $<$ Ra $<$ 1e13), this device provides the opportunity to characterize the heat transfer and velocity field behaviors necessary to build and test next-generation models of planetary core dynamics. Velocity data is obtained within the described parameter space using high-resolution Laser Doppler Velocimetry (LDV), allowing us to measure convection velocities that can range between 1e2 $<$ Re $<$ 1e5. Our heat transfer and velocity measurements span different behavioral regimes of rapidly-rotating convection in order to determine the scaling trends and transitions between columnar style convection and geostrophic turbulence. Further, with future Particle Image Velocimetry (PIV) measurements, it will be possible to correlate velocities, helicities, and length scales in order to quantify the detailed dynamics of turbulent convention existing in planetary cores.

Keywords: core dynamics, convection, turbulence

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The turbulent response of planetary fluid interiors to tidal and librational forcing

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Abstract

The turbulence generated in the liquid metal cores and subsurface oceans of planetary bodies may be due to the role of mechanical forcing through precession/nutation, libration, tidal forcing, and collisions. Here, we model the response of an enclosed fluid to tidal forcing by combining laboratory equatorial velocity measurements with selected high-resolution numerical simulations to show, for the first time, the generation of bulk filling turbulence. The transition to saturated turbulence is characterized by an elliptical instability that first excites primary inertial modes of the system, then secondary inertial modes forced by the primary inertial modes, and finally small-scale turbulence. The amplitude of this saturated turbulence scales with the body's elliptical distortion, while a time-averaged zonal flow scales with the square of the body's elliptical distortion. The results of the current tidal experiments are compared with recent studies of the libration-driven turbulent flows studied by Grannan *et al.* 2014 and Favier *et al.* 2015. Tides and libration, correspond to two end-member types of geophysical mechanical forcings. For satellites dominated by tidal forcing, the ellipsoidal boundary enclosing the internal fluid layers is elastically deformed while, for librational forcing, the core-mantle boundary possesses an inherently rigid, frozen-in ellipsoidal shape. We find striking similarities between tidal and librational forcing in terms of the transition to bulk turbulence and the enhanced zonal flow, hinting at a generic fluid response independent of the mechanical forcing. In planetary bodies where the elliptical distortion is _˜1e-4, while the zonal flow velocity is usually considered negligible, the presence of much larger turbulent saturation velocities driven by tidally- or librationally-driven flow instabilities may play a crucial role in global processes like planetary dissipation and magnetic field generation.

Keywords: Tidal forcing, librational forcing, elliptical instability, turbulence

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SiO2 Saturation in the Outer Core

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Abstract

Laser heated diamond-anvil cell experiments in the Fe-Si-O system show textures in recovered samples that indicate oversaturation in SiO2 and crystallization of silica. Si and O are candidate light elements in the Earth's core. Hence crystallization of SiO2 is a possible energy source for the geodynamo from the gravitational potential energy released by crystallization. In order to quantify the likelihood for operating a dynamo this way, we thermodynamically model melting experiments in the Fe-Si-O system to determine saturation conditions. Our model shows that solubility of SiO2 increases with temperature and decreases with pressure. We apply the model to present core-mantle boundary conditions ($P = 135$ GPa, $3500 \leq T \leq 4500$ K), and find that recent core composition models all are oversaturated in SiO2 and entail crystallization. Dynamos operating for the age of the Earth require only cooling of 50-150 K if driven by SiO2 precipitation.

Keywords: core, sio2 crystallization

*Speaker

Impact of paleomagnetic field model on forecasting of modern era geomagnetic fields

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Abstract

In this work we demonstrate how geomagnetic data assimilation can be used to connect paleomagnetic field models with the more recent gufm1 and CM4 field models, generated from more recent observatory and satellite measurements. We can use this to determine what information content in the paleomagnetic data can be carried forward to the present time. We have carried out a series of nearly 2000 year assimilation runs using the NASA geomagnetic data assimilation system, MoSST-DAS. The assimilation uses data from the *cals3k.4* model from 10 CE until 1590 CE, *gufm1* from 1590 until 1960 and CM4 from 1960 to 1990. For each run, the observation errors are modeled as a fraction of each Gauss coefficient. For the *gufm1* and CM4 field models, an error of 30 % is used in all runs, while the error estimates for *cals3k.4* are varied in each assimilation run. The runs are evaluated by comparing the RMS difference between the CM4 model and a 20 year forecast (O-F), both in 1990. Smaller RMS differences are an indication that the paleomagnetic observations are utilized in a more optimal manner, thereby resulting in an inproved geomagnetic forecast. We show how this can lead to a better understanding of how accuracy in a palemagnetic field model changes with Gauss coefficient degree, and use this to improve current era geomagnetic forecasts.

Keywords: geomagnetic data assimilation, field models

*Speaker

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Towards a 4D-Var MHD assimilation framework

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Abstract

The generation of Earth's magnetic field occurs in its outer core and it is known as dynamo action. In the last decades, various numerical and experimental studies have been carried out in this field of research. Limited by their computational complexity, numerical simulations are far away from the estimated parameter regime of the Earth's dynamo system. In contrast, physical experiments can be performed in a much larger range of control parameter, specifically, for very small E_k and P_m . It is though very difficult to design representative physical systems and to sample the physical processes, which occur inside its apparatus. 4-dimensional variational (4D-Var) assimilation is a framework developed in the field of optimal control theory, which demonstrated its power to capture the inner working of a dynamic system, to retrieve and optimize its pivotal quantities, and to better predict their evolution in time.

Keywords: Adjoint problems, Spherical Couette flow, Inverse problems, prediction theory

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Characteristics and interpretations of simulated geomagnetic field excursions

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Abstract

Numerical dynamo simulations can be used to study spatial and temporal characteristics of geomagnetic field excursions. Excursions occurred numerous times in Earth's magnetic field history and may be considered to have severe implications for Earth's biosphere. In this study we analyze a large set of simulated field excursions resulting from different numerical dynamo parameterization. The results of the simulations agree with observations of Earth's magnetic field, such as reversal/excursion rates and field dipolarity, but differ in the parameters describing the importance of the physical processes generating Earth's magnetic field. The deficiency of the numerical experiments is discussed based upon arguments derived from theoretical scaling laws. A comparison with recent findings for the Laschamp and Mono Lake excursions highlights the similarity between observations and numerical simulations. We explore possible interpretations for the current and future states of Earth's magnetic field.

Keywords: Geomagnetic field excursions, numerical dynamo simulations, Geomagnetic field modelling

*Speaker

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Low-dimensional models and data assimilation for geomagnetic field variations and coarse predictions of dipole reversals – assessments and prospects

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Abstract

Low-dimensional models for Earth's magnetic dipole have attracted attention recently because they may be a powerful tool to study dominant dipole dynamics over geological time scales, where direct numerical simulation remains challenging. We investigate the extent to which several low-dimensional models can explain Earth's dipole dynamics by calibrating them against the signed relative paleointensity over the past 2 million years. Our model calibrations are done by "data assimilation" which allows us to incorporate nonlinearity and uncertainty into the computations. We find that the data assimilation is successful, in the sense that a relative error is below 8% for all models and data sets we consider. The successful assimilation of paleomagnetic data into low-dimensional models suggests that, on millennium time scales, the occurrence of dipole reversals mainly depends on the average, large-scale behavior of the dipole field, and are rather independent of the detailed morphology of the field. This, in turn, suggests that large-scale dynamics of the dipole may be predictable over long time-scales of thousands of years, longer than the detailed morphology of the field, which is predictable for about one century. We explore these ideas by performing coarse predictions with low-dimensional models, and quantify the quality of predictions by hindcasting and Brier scores. We find that the precise timing of reversals is difficult to predict. However it appears feasible to predict a time-window of 4 kyr during which a reversal is likely to occur. Applying our approach leads us to tentatively predict that no reversal of the Earth's magnetic field is to be expected within the next 4 kyr. Perhaps more importantly, we present a series of tests that can be applied to assess the quality of coarse predictions based on low-dimensional models.

Keywords: data assimilation, dipole reversals, predictability

*Speaker

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Slow magnetic Rossby waves in the Earth's core

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Abstract

The westward drift component of the secular variation is likely to be a signal of waves riding on a background mean flow. By separating the wave and mean flow contributions, we can infer the strength of the "hidden" azimuthal part of the magnetic field within the core. We explore the origin of the westward drift commonly seen in dynamo simulations and show that it propagates at the speed of the slow magnetic Rossby waves with respect to a mean zonal flow. Our results indicate that such waves could be excited in the Earth's core and that wave propagation may indeed play some role in the longitudinal drift, particularly at higher latitudes where the wave component is relatively strong, the equatorial westward drift being dominated by the mean flow. We discuss a potential inference of the RMS toroidal field strength within the Earth's core from the observed drift rate.

Keywords: Geomagnetic secular variation, Waves, Toroidal field, Dynamo simulations

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Latest news of the DTSOmega experiment

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Abstract

We have conducted major instrumentation improvements on our magnetized spherical Couette experiment. We can now measure 200 signals simultaneously in the rotating frame (hence its new DTSOmega denomination). We typically measure the three components of the magnetic field at the surface along two meridians, the electric potential differences along two other meridians, and the radial dependance of the magnetic field in a sleeve inside the liquid sodium shell. We have calibrated each of our 150 magnetic probes over the range of temperature and magnetic field we have in the experiments. We have run measurement campaigns up to the maximum inner sphere spin rate ($\pm$30 Hz) and two outer sphere rotation rates (5 and 10 Hz). Our data demonstrate the strong inhibition of fluctuations when both global rotation and strong magnetic field are present. We characterize the fluctuations we observe for absolute values of the Rossby number above 1. The properties of the statistically dominant fluctuation modes are compared to numerical simulations. The latest campaigns have revealed that the coupling between sodium and the inner copper shell has degraded. The entrainment of the liquid by the spinning inner magnet is thus strongly reduced. We will discuss some peculiarities of the flows we observe in these conditions. We plan to replace our aging liquid sodium with fresh one.

Keywords: MHD, DTS, experiment, sodium, Grenoble

*Speaker

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Tilted Coriolis Modes in Ellipsoids

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Abstract

We consider a simple basic model planetary core. The incompressible flow of a uniform fluid, which fills a rigid ellipsoid (sphere, spheroid, tri-axial ellipsoid) rotating about an arbitrary axis fixed in an inertial frame, is dominated at small Rossby and Ekman numbers by the rotation via the Coriolis force. The Coriolis force modified by a pressure gradient can then be treated as a skew-symmetric bounded linear operator C acting on smooth inviscid incompressible flows in the ellipsoid. The space of incompressible polynomial flows of a fixed degree or less in the ellipsoid is invariant under C. The symmetry of -iC thus implies the Coriolis operator C is non-defective with an orthogonal set of Coriolis eigenmodes (inertial and geostrophic modes) on the finite-dimensional space of ellipsoidal polynomial flows. The eigenmodes are tilted if the rotation axis is not aligned with a principal axis of the ellipsoid. It enables enumeration of the modes and proof of their completeness using the Weierstrass polynomial approximation theorem. The fundamental tool is that the solution of Poisson's equation with Neumann boundary condition and polynomial data in an ellipsoid is a polynomial. The Coriolis modes of degree one and all geostrophic modes are explicitly constructed. Only the Coiolis modes of degree one have non-zero angular momentum in the boundary frame.
We consider three methods to compute Coriolis modes in ellipsoids: a weak form of Poincare's equation, which incorporates the incompressible condition and the boundary condition, is solved for the pressure; a form of the momentum equation with isotropic inertia but anisotropic pressure gradient is solved for the pressure and velocity; and a form of the momentum equation with anisotropic inertia but isotropic pressure gradient is solved for the velocity. All methods use a polynomial spectral method and the QZ algorithm. Finally the exact solution of Poincare's equation for the tilted inertial modes in an ellipsoid in terms of Lame functions is described, including solution of the boundary condition.

Keywords: inertial modes, geostrophic modes

*Speaker

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Precession-driven dynamos in a full sphere and the role of large scale cyclonic vortices

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Abstract

Precession has been proposed as an alternative power source for planetary dynamos. Previous hydrodynamic simulations suggested that precession can generate very complex flows in planetary liquid cores [Lin et. al., Physics of Fluids 27, 046601 (2015)]. In the present study, we numerically investigate the magnetohydrodynamics of a precessing sphere. We show that precession can drive dynamos in different flow regimes, laminar and turbulent. In particular, we highlight the role played by large scale cyclonic vortices in the magnetic field generation, which has not been explored previously. In this regime, dynamos can be sustained at relatively low Ekman and magnetic Prandtl numbers, which paves the way for planetary applications.

Keywords: precession, dynamo, LSV

*Speaker

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Progress towards the inertialess inviscid dynamo

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Abstract

The Taylor state dynamo is understood as an excellent approximation to Earth's dynamo system, in which the Coriolis, pressure and Lorentz forces dominate in Earth's core and the inertial force and viscous force are negligible. Taylor (1963) first proved the rationale of this theoretical limit and provided the mathematical proof and the initial numerical recipe for solving it. However, this approach exhibits considerable difficulties for a numerical scheme. We introduce a new approach for computing the Taylor state dynamo by utilizing the concept of the optimal control theory, such that Taylor state is satisfied in the entire simulation time window. We demonstrate our method in an illustrative 2D mean field dynamo and compare the numerical solution with the solution from torsional wave model of very small inertial.

Keywords: Dynamo theory

*Speaker

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Ultrasonic velocimetry using integrated time of flight

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Abstract

Many common techniques in flow diagnostics rely on the presence 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 scatters 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 a novel technique based on the time of flight principle to perform velocity measurements in the absence of scattering particles.

Keywords: liquid sodium experiments, flow, diagnostics, time of flight

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Dissipation of free torsional eigenmodes and conductivity of the lowermost mantle

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Abstract

Torsional Alfvén waves propagating in the Earth's core have been inferred by inversion techniques applied to geomagnetic models. They appear to propagate across the core but vanish at the equator, exchanging angular momentum between core and mantle. We find that an electrically conducting layer at the bottom of the mantle can lead to total absorption of torsional waves that reach the equator. We show that the reflection coefficient depends on the dimensionless number Q=$\sqrt{}(\mu 0\rho)$GBr , where $\mu 0$ is magnetic permeability of free space ρ the fluid density Br the strength of the radial magnetic field at the equator, G the conductance of the lower mantle and Br the strength of the radial magnetic field at the equator. Torsional waves are completely absorbed when they hit the equator if Q=1, which corresponds to G 1.3 10ˆ8 S for Br =7. 10–4 T. For larger or smaller Q, reflection occurs. As Q is increased above unity, there is less attenuation and more angular momentum exchange. These results directly translate into properties of free torsional eigenmodes. Increasing Q from Q=0 (insulating mantle), the period of the eigenmodes changes by half the fundamental period at Q=1 whereas dissipation peaks for Q=1 also. Finally, we find that it is important to ensure consistency between models for the magnetic field in the core interior and at its surface. For example, models for torsional waves allow for deviations from axial symmetry. In this case, we have to make certain that the magnetic field sources are internal to the core. Our study paves the way for a new estimation of the strength of the magnetic field in the core interior.

Keywords: mantle conductivity, core mantle coupling, torsional waves

*Speaker

On the persistence of a stably stratified layer at the top of the core

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Abstract

The controversial idea that regions of the outer core may be stably stratified arose decades ago. Several plausible stabilizing effects either thermal or chemical have been debated. As suggested by recent experiments, the thermal conductivity of liquid-iron might be so high near the CMB that heat would be transferred by conduction only, so that the adjacent region tends toward stratification. It could also stem from an enrichment of light alloying species released during the inner core growth or dissolved from the mantle. However, stably stratified fluids adjacent to convective regions (e.g. in the Sun) often experience thermal plume penetration. We would like to question the persistence of such a layer subjected to this *penetrative convection*. To this end, we performed an analogue experiment: a volume of water initially at ambiant temperature was cooled from below at 0 degrees Celsius. Due to the maximum density of water near 4 degrees, a convective region develops and grows below a purely conductive region. A laser sheet crosses the experimental cell, illuminating both neutrally buoyant particles and a thermosensitive fluorescent dye, which allows to monitor the velocity and temperature fields respectively (PIV-LIF technique), giving access to the local convective and conductive heat flux. The apparatus is placed on a rotating table to inspect the effect of the Coriolis force on the interfacial region. This region is studied in detail, with special focus on the role of rotation and stratification, as their effects are thought to prevail in the Earth's outer core. A simple model where a conductive layer is forced from below by convective structures has also been developed and confirms their respective role. We find that increasing the rotation rate deepens the penetration of vortices into the conductive region, thus changing the structure of the interfacial layer. As a consequence, the perturbation from the convective outer core could induce vertical motions in the hypothetical stratified region or could even erode it.

Keywords: stratification, penetrative convection, analogue experiment

*Speaker

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Precessional-convectional instabilities in a spherical system

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Abstract

Generally, the Earth's dynamo is attributed to thermo-compositional convection, which is supported by numerical simulations in a range of parameters far from core conditions. Meanwhile, numerical studies (Tilgner, 2005; Wu and Roberts, 2009; Lin et al., 2016) have shown that precession is also a plausible forcing mechanism to drive a dynamo. Additionally, large-scale vortices in rotating turbulent convection can sustain large-scale magnetic fields (Guervilly et al., 2015), and recent investigations of the coupled convection precession forcing (Wei, 2016; Wei and Tilgner, 2013) have revealed some unexpected features. In the present study we aim at investigating in greater detail the coupled precession-convection dynamo starting with the purely hydrodynamical regime.

Keywords: precession, convection, computational fluid dynamics

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Experimental Compressible Convection

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Abstract

Compressible convection, in particular in Earth's outer core dynamics, is usually described with the anelastic approximation. A number of theoretical and numerical studies have been done about this approximation but there is no experimental work on it. We present here an experiment especially designed to study compressible convection in the lab. For significant compressible convection effects, the parameters of the experiment have to be optimized. We use a centrifuge to artificially increase the apparent gravity. Moreover, compressibility is higher with a gas and in particular with xenon. With these choices, we can obtain an adiabatic gradient of 10 K/cm and the dissipation number αgL/C_p is equal to 0.2 which is close to the value of 0.5 in the outer core.
A first version of the experiment allowed us to measure an adiabatic gradient and to study pressure fluctuations. A new version, with new sensors and with an higher rotating speed, should reach a larger adiabatic gradient, better temperature measurements and increase the time resolution.
Moreover, due to the high rotating speed, effects of the Coriolis force will be important. So, we will study how the stratification caused by compressible convection will change geostrophy and inertial waves in the special case where gravity and rotation vector are orthogonal.

Keywords: convection, anelastic approximation, adiabatic gradient, experiment

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A two-dimensional approach to modelling the short timescale zonal flow in Earth's core

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Abstract

Reconstructions of flow in Earth's outer core based on surface magnetic data predict mean zonal accelerations on several timescales. Since accelerations in the core couple to the angular momentum of the mantle, their existence has been confirmed by length-of-day observations. Recent studies suggest that free modes of torsional oscillations are responsible for relatively weak signals with a 5-6 year period. The mechanisms responsible for stronger decadal signals are less well understood. To address the problem, we construct a quasi-geostrophic model of magnetoconvection, with thermally-driven flows perturbing a steady, imposed background magnetic field. This approach is justified by the Taylor-Proudman theorem, in which velocities in a rapidly rotating system vary little parallel to the rotational axis. Using only two dimensions allows a much more rapid exploration of parameter space than traditional three-dimensional approaches.

Our model is capable of producing mean zonal accelerations similar to those predicted by the geomagnetic reconstructions of Earth. In particular, we produce a separation between short- and long-period oscillations in the zonal flow. We then explore the model's behaviour in a variety of parameter regimes, attempting to extrapolate our results to the conditions found in Earth's core.

Keywords: magnetoconvection, quasigeostrophic, torsional oscillations

*Speaker

Archeomagnetic field modeling based on statistical information from dynamo simulations

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Abstract

Archeomagnetic observations are key to recovering the behavior of the geomagnetic field over the past few millennia. The heterogeneous spatial and temporal character of the archeomagnetic data catalog, however, does not allow for a well-constrained inversion of the core field. Instead, the inverse problem is generally regularized by imposing prior constraints limiting the complexity of the field. Here we introduce the concept of using prior information derived from numerical models of the Earth's dynamo. The prior information, built on a dynamo model, is connected to the surface data in terms of the directions and intensity of the field, by means of the corresponding observation operators. Within these two pieces of information and the archeomagnetic dataset from the last three thousand years, we are able to develop field models of the magnetic field at the top of the core and quantify the archeomagnetic data resolution. Our results show that the archeomagnetic field is well-resolved up to spherical harmonic degree 3 for the first millennium BC, up to degree 4 for the first millennium AD and close to degree 5 for the past thousand years. This study paves the way for further incorporation of dynamo-based constraints on archeomagnetic field modeling.

Keywords: archeomagnetism, inverse modeling, dynamo simulations

*Speaker

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Sequential assimilation of geomagnetic data into dynamo models, an archeomagnetic study

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Abstract

The core field is generated by a natural dynamo mechanism, which evolves on a variety of time scales. Its longer term dynamics is only accessible by indirect observations, the archeomagnetic data. However, the archeomagnetic dataset presents a highly heterogeneous distribution in both space and time. To supplement the information provided by the sparse archaeomagnetic dataset, we consider the extra information on the magnetic field given by numerical simulations of the geodynamo. In this study, we explore how a sequential data assimilation framework can help improving the estimation of the field in the archeomagnetic context. We use the Ensemble Kalman Filter, which considers the propagation in time by an ensemble of numerical dynamo models in a sequence of forecast-and-analysis cycles. This methodology allows for the estimation of not only the observable, but also of the hidden variables of the dynamo system, the magnetic field in depth, the flow throughout the core and the density anomalies for instance. The assimilation, tested in the framework of closed-loop experiments for archeomagnetic-like synthetic observations, shows good performance in terms of accuracy and precision of the core state estimation. In particular, the assimilation is robust even in the case where observations are only available over one hemisphere. This work opens the possibility for the assimilation of real archeomagnetic observations and the subsequent estimation of the physical processes operating in the core on millennial time scales.

Keywords: acheomagnetism, data assimilation, dynamo simulations

*Speaker

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Compressible Rayleigh-Benard stability

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Abstract

The stability analysis of the Rayleigh-Benard configuration (Rayleigh 1916) is a landmark of fluid mechanics. This was made possible thanks to the Oberbeck-Boussinesq approximation. However, this approximation is only valid when the imposed temperature difference is small compared to the absolute temperature and when compressible effects are negligible compared to thermal effects on density. Those conditions can be expressed as conditions on two dimensionless numbers, the dimensionless temperature gradient and the dissipation parameter: a = Delta T / T << 1 and D = alpha g L / cp << a.

An important contribution by Jeffreys (1930) was to show that the Rayleigh criterion for stability still holds, provided the Rayleigh number is changed for the superadiabatic Rayleigh number, in the limit of small values of a. Further contributions by Busse (1967), Paolucci and Chenoweth (1987), Frohlich et al. (1992) show that the critical superadiabatic Rayleigh number departs quadratically in a and D from its 'Rayleigh' limit.

We have computed numerically the stability analysis, for different equations of state, for a range of values of a and D. Moreover, we have extended Rayleigh's analysis (for stress-free boundary conditions) by considering that the temperature eigenvector is the sum of the traditional cos (pi z) even function with an additional contribution proportional to the odd function sin (2 pi z) function. That analysis is not exact, contrary to Rayleigh's analysis, but its results fit the numerical solution very well. Given an equation of state, we show that the quadratic departure of the critical Rayleigh number from Rayleigh's solution depends on the expansion up to the degree 3 of density rho in terms of pressure p and temperature T around a reference value.

In addition to the full compressible equations, we have considered two simplified models, the quasi-Boussinesq model in which density disturbances around the base profile are considered to depend on temperature disturbances only, and a quasi-ALA (Anelastic Liquid Approximation) model in which entropy disturbances are a function of temperature disturbances only. The quasi-ALA model is a better approximation than the quasi-Boussinesq model in general.

Keywords: linear stability, mantle convection, core convection

*Speaker

Instabilities induced by the precession of spherical shell

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Abstract

The dynamics of the liquid core is known to be crucial to the planetary dynamics through angular momentum exchange with the surrounding mantle, kinetic energy dissipation and in some cases dynamo processes. It has been shown that mantle perturbations such as forced precession-nutations, librations can drive complex flows strongly influenced by the rotation in the form of parametric instabilities. In the present study we aim at shedding some light on the influence of an inner core onto the precesssional instabilities. We investigate numerically the flow in the outer liquid core at moderate Ekman numbers (_˜1e-5) driven by the precession of the mantle and the inner core. We aim at deriving the stability diagram and at characterising the mechanism underlying the onset of the instabilities.

Keywords: precession, parametric instability

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Studying the CMB topography variation by using PcP and PKiKP phases from IMS Arrays

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Abstract

The core mantle boundary (CMB) of the earth is very important for understanding the evolution of our planet, and its small-scale structure variation is a key constrain to study the core-mantle dynamic process. This research mainly uses PcP and PKiKP data from IMS arrays to study the topography variations and velocity anomaly on CMB. Comparing PcP and PKiKP and analyzing amplitude ratios as well as differential travel time residuals of the two phases from IMS arrays, we find small-scale topography variations of CMB in some regions. A convex CMB topography beneath North Mexico is found by comparing NVAR and PDAR records. Distinctive PKiKP/PcP amplitude ratios and PcP waveform appear for two nearby regions at CMB which indicates rapid topography variations. We also confirm a case that shows CMB focusing effect by observing anomaly low PKiKP/PcP amplitude ratios and large minus PKiKP-PcP travel time residuals beneath Kenai peninsula, Alaska, which agrees well with previous study. Our studies show that CMB topography can have significant effects on PcP and it is a main source that contributes to the scatter of PKiKP/PcP amplitude ratio. All observations in this study may imply a complex core-mantle dynamic process. The research is supported by the National Natural Science Foundation of China (41125015 and 41474040).

Keywords: CMB topography variation, PcP, PKiKP

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The easternmost Pacific Anomaly in the Earth's lowermost mantle: a metastable structure

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Abstract

Seismic tomography studies have shown a broad, seismically low velocity anomaly in the Earth's lower mantle beneath the Pacific (we term it the "Pacific Anomaly"), surrounded by the circum-Pacific high velocity zone. Previous waveform modeling and travel time analysis further revealed the geometries, structural features and velocity structures of the northwestern, northern and northeastern Pacific Anomaly. The northwestern Pacific Anomaly extends 700 km above the core-mantle boundary (CMB) and has a box-shaped structure with nearly vertical sides that is expected to be metastable. The northeastern and northern Pacific Anomaly reach 500 km above the CMB and have bell-shaped structures with sloped sides, implying that they are stable and long-lived structures. Here, we constrain the detailed structure of the easternmost Pacific Anomaly on the basis of three-dimensional forward waveform modeling of the seismic data. Two typical earthquakes occurred in Tonga-Fiji Islands and recorded in South America have raypaths sampling the whole easternmost Anomaly. Waveform analysis validates the geographic boundary of the easternmost Anomaly previously deduced by differential-travel-time-residual data, and suggests that the easternmost Anomaly reaches approximately 600 km above the CMB with steeply dipping edges and surrounded by high velocity structures. Those inferred features suggest that the easternmost Anomaly is a metastable structure.

Keywords: Pacific Anomaly, waveform modeling, shear wave

*Speaker

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Effects of core-mantle chemical coupling in a coupled core-mantle evolution

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Abstract

Here we show preliminary results on effects of core-mantle chemical coupling in a coupled core-mantle thermo-chemical evolution model. In order to include the core-mantle chemical coupling in a coupled core-mantle thermal evolution model, we assume several assumptions. 1. The infinite silicate reservoir in the mantle. 2. Element partitioning (e.g. O and Si) of the metallic core caused by the equilibrium partitioning with imposing the boundary condition at the core-mantle boundary (CMB) of core thermo-chemical evolution model [e.g. Buffett and Seagle, 2010]. 3. As a result of element changes across the CMB, chemically stable layer allows growing below the CMB. With those assumptions, we modify the chemical evolution of Earth's core into thermo-chemical evolution of Earth's core. Moreover, the sub-adiabatic shell growth is also included in the model if the CMB heat flow is sufficiently low compared to the adiabatic heat flow. The important accomplishments are as follows: 1. The initial CMB temperature is no longer very high, which is nearly 4900 K, when the stable region beneath the CMB allows growing. 2. Thickness of stable region below the CMB would be 100 to 120 km. This is consistent with that suggested from observational data analysis [Buffett, 2014]. 3. The core thermo-chemical evolution might not be strongly sensitive to the CMB heat flow if the stable layer below the CMB was found, which suggested that the core thermal conductivity, that is the adiabatic heat flow across the well-mixed region below the interface of stable region would be a key quantities for understanding core thermo-chemical evolution. 4. The CMB temperature would not be cooled very much because a stable region may be worked for the stronget heat buffer for heat transfer across the CMB and the CMB heat flow would not be changed with time, which indicates nearly 12 TW. 5. The magnetic evolution of Earth's core before inner core onset would be explained by the mechanical forcing caused by tidal effect or precision of rotating axis rather than he convecrive motion in Earth's core.

Keywords: Stable region, Core, mantle boundary, Core, mantle chemical coupling, Thermo, chemical evolution

*Speaker

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Major Disruption of D" beneath Alaska

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Abstract

D" represents one of the most dramatic thermal and compositional layers within our planet. In particular, global tomographic models display relatively fast patches at the base of the mantle along the circum-Pacific which are generally attributed to slab-debris. Such distinct patches interact with the bridgmanite (Br) to post-bridgmanite (PBr) phase boundary to generate particularly strong heterogeneity at their edges. Most seismic observations for the D" come from the lower mantle S wave triplication (Scd). Here, we exploit the US-Array waveform data to examine one of these sharp transitions in structure beneath Alaska. From west to east beneath Alaska, we observed three different characteristics in D": 1) The western region with a strong Scd, requiring a sharp δVs = 2.5% increase; 2) The middle region with no clear Scd phases, indicating a lack of D" (or thin Br-PBr layer); 3) The eastern region with strong Scd phase, requiring a gradient increase in δVs. To explain such strong lateral variation in the velocity structure, chemical variations must be involved. We suggest that the western region represents relatively normal mantle. In contrast, the eastern region is influenced by a relic slab that has subducted down to the lowermost mantle. In the middle region, we infer an upwelling structure that disrupts the Br-PBr phase boundary. Such an interpretation is based upon a distinct pattern of travel time delays, waveform distortions, and amplitude patterns that reveal a circular-shaped anomaly about 5○ across which can be modeled synthetically as a plume-like structure rising about 400km high with a shear velocity reduction of _˜5%, similar to geodynamic modeling predictions of upwellings.

Keywords: D" layer, S wave triplication

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Core-Mantle Boundary Complexities beneath the Mid-Pacific

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Abstract

Seismic data from deep earthquakes in the Fiji-Tonga region recorded by stations of USArray provide great sampling of the core-mantle boundary (CMB) beneath the Mid-Pacific. Here we explore the USArray data with different seismic phases to study the CMB complexities beneath the Mid-Pacific. The Sdiff data recorded by stations at central US shows variation in multi-pathing, that is, the presence of secondary arrivals following the S phase at diffracted distances (Sdiff) which suggests that the waveform complexity is due to structures at the eastern edge of the mid-Pacific Large Low Shear Velocity Province (LLSVP). This study reinforces previous studies that indicate late arrivals occurring as long as 26 secs after the primary arrivals. A tapered wedge structure with low shear velocity allows for wave energy trapping, producing the observed waveform complexity and delayed arrivals at large distances. Such structures having characteristic properties of, for example, a height of 70 km, in-plane extent more than 1000 km, and shear wave velocity drop of 3% at the top to 15% at the bottom relative to PREM. The arrivals of the SPdKS phase support the presence of an ultra-low velocity zone within a two-humped LLSVP. A sharp _˜10 secs jump of the differential travel time between S and SKS (TS-SKS) across distance range of 5○ is observed. The associated SKS waveform distortions suggest that the differential travel time anomaly is mainly controlled by the SKS, which is explained by a sharp slab subducted to the lower mantle. We also examined the TScS-S for data at western US and confirm the northeastern boundary of the mid-Pacific LLSVP. Identification of Scd phases sampling this region suggests that a slab structure with thick phase boundary layer bonds the east edge of the mid-Pacific LLSVP.

Keywords: LLSVP

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Chemical reaction between a basally molten mantle and core

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Abstract

Core-mantle disequilibrium was originally introduced to the Earth by the process of core formation, in which metals and silicates equilibrated in a magma ocean at temperatures and pressures different than those that later prevailed at the core-mantle boundary (CMB). Models have been proposed in which this original disequilibrium drives dissolution of oxygen from the solid mantle into the top of the core, resulting in a buoyant slightly O-enriched layer that floats on top of the deeper core. However, the predicted O-enrichment may be too weak to explain seismic inferences of outermost core layering, which suggest a low velocity layer at least 100 km thick atop the core, with some recent studies suggesting even thicker layers. Furthermore, such a reaction depletes the base of the solid mantle in iron, which may be incompatible with observations of dense CMB structures such as the ultra-low velocity zones (ULVZs). On the other hand, estimates of secular core cooling suggest an ancient dense basal magma ocean in the lowermost mantle that underwent slow fractional crystallization to produce ULVZ-like structures at the present. Here we show that the existence of a basal magma and a secular change in its composition driven by fractional crystallization produces a strong outermost core stratification while also enriching the base of the mantle in iron, thus resolving this paradox. Furthermore, the predicted fractionation trend depletes the magma in SiO2 but enriches it in FeO, and correspondingly produces an outermost core layer that is relatively depleted in Si and enriched in O. According to recent ab initio models of iron alloy compressibility, a simultaneous depletion in Si and enrichment in O is a simple way to produce a reduction in outermost core seismic velocities, thus resolving another paradoxical observation regarding outermost core layering.

Keywords: Core, Mantle Boundary, Core, Mantle Reaction, Basal Magma Ocean, Outermost Core Stratification

*Speaker

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P and S waves reflected in the lowermost mantle under the mid Central Atlantic Ocean

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Abstract

The D" region (the lowest 200-400 km of the Earth's mantle) has a complex seismic structure and several explanations, including thermo-chemical anomalies, phase transition and anisotropy, have been proposed in order to explain the observed seismic data. Global tomographic imaging provides "long wavelength" structures information for the bottom of the mantle which, in turn, seems to have a key role in the flow mantle convection system, acting as a lower thermal boundary layer. Fast and slow regions at these depth are usually associated to ancient descending subducted slab, settled at D", and upwelling of hot materials up to the Earth's surface, respectively. In the last decades, seismological observations focused on both these regions and complex seismic pattern have been found, spanning from strong heterogeneities and scattering to polarities variation for reflected waves and shear waves splitting with related anisotropy. Few studies focus on the lowermost mantle structure between fast and slow regions. Using Central to South American earthquakes recorded in Morocco, we study the core mantle boundary under the mid-Central Atlantic Ocean employing array methods. This region lies between a fast anomaly in a more western region (under Caribbean and Cocos plates) and the African LLSVP (Large Low Shear Velocity Province) towards east. Amplitude ratios and polarities comparison between P(S), PdP(SdS) and PcP(ScS) have been measured on stacked waveforms. Reversal polarities for PdP phases have been detected, while SdS show normal polarities. We also found deviations from the great circle path, perhaps as result of 3D structure in the D" under the mid-Central Atlantic Ocean. In order to test whether the polarity changes could be due to anisotropy, we are looking for different cross-path sampling the region under study, with the attempt to improve our understanding of both structure and anisotropy in the D" and the related link with lowermost mantle deformation, rheology and microstructures.

Keywords: core mantle boundary, D", anisotropy

*Speaker

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The vortex magnetic field, the velocity and scales under the surface of the Earth's core

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Abstract

Basing on currently defined conductivity, 115 years observed evolution of the geomagnetic dipole, Faraday's and Ohm's laws I estimate averaged radial derivatives of the vortex magnetic field hidden just below the surface of the Earth's core.
This allows to formulate a simple model of vortex field beneath the surface of the core and to evaluate typical scale of the field, which determines the major geodynamo parameters and the adequacy range of the proposed simple model.

Estimated scale of the vortex field (about 60 km) is much less than the typical scale resulting from the extrapolation of the observed field to the core-mantle boundary.

This agrees well with the modern planetary dynamo theory, allowing observational estimation of the typical velocity field just beneath the surface of the Earth's core.

The proposed new approach to determine the subsurface characteristics of the hidden in the depths of the physical object of the vortex magnetic field and velocity from the observed evolution of the potential field can be used for both astrophysical and for technical objects with hardly accessible electric current systems.
This work was partly supported by Russian RFBR grant No 16-05-00507.

Keywords: magnetic dipole evolution, vortex magnetic field, velocity, subsurface of the Earth's core, geodynamo

*Speaker

Scaling Laws in Models of Boundary Forced Rotating Convection

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Abstract

The temperature variations that drive convection in the Earth's mantle also result in a heterogeneous pattern of heat flux extracted from the core. Previous work has shown that core-mantle boundary (CMB) heat flux heterogeneity may influence the structure of the magnetic field and its secular variation; furthermore, changes in the pattern and amplitude of the CMB heat flux may be linked to changes in the intensity and reversal frequency of the magnetic field. If CMB heterogeneity can reorganise flow throughout the fluid core, it could also influence the growth of the inner core. However, it remains uncertain how important these effects might be in the Earth's core where rapid rotation and strong convection is expected.
We undertake a systematic investigation of the role of heterogeneous boundary forcing in numerical models of non-magnetic convection in a rotating spherical shell. The dynamics of the homogeneous system are determined by the Rayleigh number (Ra), measuring the strength of the basal thermal driving force, the Prandtl number (Pr), the ratio of viscous and thermal diffusion, and the Ekman number (E), measuring the strength of the Coriolis force. We consider models with Pr=1, E=10^{-4} - 10^{-6}, Ra up to 500 times the critical value for the onset of homogeneous convection, which is approaching the degree of supercriticality estimated for Earth's core. Boundary forcing is described by a pattern g(theta,phi), taken to be Y_{1,1} and Y_{2,2}, and an amplitude q*, with values 2.3 and 5.0 chosen to promote strong boundary effects.
In this poster we focus on the fluid mechanical implications of the boundary forcing. We present results on the scaling behaviour of the heat transfer, characteristic length scale, and flow speeds of the system. The flow speeds and length scales of the heterogeneous models approach those of the equivalent homogeneous case as Ra is increased. The exponent of the Nu v Ra scaling is indistinguishable between the various boundary conditions; however, heterogeneity at the CMB does result in larger Nu compared to the homogeneous case. The differences in heat transport arise because the heterogeneous boundary condition modifies the dynamics of the flow near the top of the core.

Keywords: core dynamics, CMB heterogeneity

*Speaker

Geomagnetic spikes on the core-mantle boundary

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Abstract

Extreme variations of Earth's magnetic field occurred in the Levantine region around 1000 BC, where the field intensity rose and fell by a factor of 2-3 over a short time and confined spatial region. There is presently no coherent link between this intensity spike and the generating processes in Earth's liquid core. Here we test the attribution of a surface spike to a flux patch visible on the core-mantle boundary (CMB), calculating geometric and energetic bounds on resulting surface geomagnetic features. We show that the Levantine intensity high must span at least 60∘ longitude. At the CMB the spikes in our preferred models are 5-30∘ wide with peak values of O(100)mT. We propose that any Levantine spike grew in place before migrating northward and westward, contributing to the growth of the axial dipole field seen in Holocene field models. Estimates of Ohmic dissipation suggest that diffusive processes, which are often neglected, likely govern the ultimate decay of such a spike.

Keywords: magnetic field, temporal variations

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Constraining the interior of Titan from its polar motion

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Abstract

The presence of a global ocean under a thin ice shell is supported by the large tidal Love number k2 of Titan (Iess et al. 2012), its larger than expected obliquity (e.g. Baland et al. 2014) and by magnetic measurements in the atmosphere of Titan (e.g. Béghin et al. 2012). This presence has a large impact on the rotational state of Titan as, with a subsurface ocean, the rotation of the interior of Titan can differ from the rotation of its surface, leading to torques between the different layers. The effect of periodic elastic deformations on the polar motion is also taken into account (see Coyette et al. 2016).
As the observed shape of Titan (see Zebker et al. 2009) does not fit to the expected hydrostatic shape deduced from the gravitational coefficients (Iess et al. 2012, in particular, the polar flattening of Titan is larger than expected with hydrostatic equilibrium), we here construct a large set of non-hydrostatic interior models of Titan to study how its polar motion is influenced by its internal structure.

The polar motion of Titan is mainly forced by its dense atmosphere (the effect of the lake is four orders of magnitude smaller) and follows an anticlockwise trajectory. The main period and the amplitude of the polar motion depend on whether the interior model considered is close to or far from a resonance. For an interior model far from a resonance (thick ice shelL), the polar motion presents a main annual period while, close to a resonance, the main period of the polar motion corresponds to the resonant period.
If observed during a large period of time, the variation of the polar motion amplitude could help us constraining some parameters of the interior of Titan, in particular the ice shell thickness and the ocean density.

Keywords: Titan, Polar Motion, Atmosphere

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Scattering attenuation profile of the Moon: implications for shallow moonquakes and the structure of the megaregolith

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Abstract

We report measurements of the attenuation of seismic waves in the Moon based on the quantitative analysis of envelope records of lunar quakes. Our dataset consists of waveforms corresponding to 62 events, including artificial and natural impacts, shallow and deep moonquakes, recorded by the seismometers deployed during four Apollo missions. To quantify attenuation and distinguish between elastic (scattering) and inelastic (absorption) mechanisms, we measure the arrival time of the maximum of energy tmax and the coda quality factor Qc. The former is controlled by both scattering and absorption, while the latter is an excellent proxy for absorption. Consistent with the strong broadening of seismogram envelopes in the Moon, we employ diffusion theory in spherical geometry to model the propagation of seismic energy in depth-dependent scattering and absorbing media. To minimize the misfit between predicted and observed tmax for deep moonquakes and impacts, we employ a genetic algorithm and explore a large number of depth-dependent attenuation models quantified by the scattering quality factor Qsc or equivalently the wave diffusivity D, and the absorption quality factor Qi.
The scattering and absorption profiles that best fit the data display very strong scattering attenuation (Qsc = 10), or very low wave diffusivity (D = 2 km2/s) in the first 10 km of the Moon. These values correspond to the most heterogeneous regions on Earth, namely volcanic areas. Below this surficial layer, the diffusivity rises very slowly up to a depth of approximately 80 km where Qsc and D exhibit an abrupt increase of about one order of magnitude. Below 100 km depth, Qsc increases rapidly and reaches about Qsc = 2000 at depths of about 150 km. These scattering properties are similar to those found in the Earth's mantle but the absorption quality factor Qi = 2400 is about one order or magnitude larger than on Earth. Our results suggest the existence of an approximately 80 km thick megaregolith, which is much larger than what was previously thought. The rapid decrease of scattering attenuation below this depth is compatible with crack healing through viscoelastic mechanisms. Using our best attenuation model, we invert for the depth of shallow moonquakes based on the observed variation of tmax with epicentral distance. On average, they are found to originate from about 50 km $\pm$ 20 km deep, suggesting that these earthquakes are caused by the failure of deep faults in the fragile part of the Moon's lithosphere.

Keywords: Moon, seismology, seismic wave attenuation, megaregolith, scattering

*Speaker

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The forced precession of the Moon's inner core

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Abstract

The tilt angle of the 18.6 yr precession of the Moon's solid inner core is unknown but it is set by a balance between gravitational and pressure torques acting on its elliptical figure. We show here that, to first order, the angle of precession of the inner core of a planetary body is determined by the frequency of the free inner core nutation, w_{ficn}, relative to the precession frequency, W_p. If abs(w_{ficn}) < < abs(W_p), the inner core is blind to the gravitational influence of the mantle. If abs(w_{ficn} > > abs(W_p), the inner core is gravitationally locked to the mantle and is nearly aligned with it. If w_{ficn} _˜ W_p, large inner core tilt angles can result from resonant excitation. Viscous inner core relaxation and electromagnetic coupling can attenuate large tilt angles. For the specific case of the Moon, we show that w_{ficn} is to within a factor of 2 of W_p = 2 pi / 18.6 yr^{-1}. For a rigid inner core, this implies a tilt of 2 to 5 deg with respect to the mantle, and larger if w_ficn is very close to W_p. More modest tilt angles between 0 and 0.5 deg result if viscous relaxation within the inner core occurs on a timescale of one lunar day. Predictions from our model may be used in an attempt to detect the gravity signal resulting from a tilted inner core, to determine the past history of the inner core tilt angle, and to assess models of dynamo generation powered by differential rotation at the core-mantle and inner core boundaries.

Keywords: Moon, inner core, dynamo

*Speaker

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A time-averaged regional model of the Hermean magnetic field

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Abstract

We derive a time-averaged model of the magnetic field of Mercury with the Revised Spherical Cap Harmonic Analysis (R-SCHA) to 770 km horizontal spatial resolution using the observations acquired by the MESSENGER spacecraft above the northern hemisphere and over the entire mission's lifetime. The model explains 97% of the magnetic signa and the remaining signal seems have regular time variations. At the studied length scales we find no convincing evidence for systematic crustal fields. The planetary centered dipole moment is 214.1Rmˆ3. The internal magnetic field is mostly axisymmetric and has a dipole tilt of about 1.4◦ with respect to the rotation axis. The magnetic equator is shifted northward to about 14◦ at Mercury's surface where the field strength is 410 nT. The spatial power spectrum suggests that the top of the outer core is below 280 km depth where the field intensity is about 660 nT. In spherical harmonics, we find an axial quadrupole to axial dipole ratio of g20/g10 = 0.25, lower than previous estimates. Furthermore, some non-zonal field contributions seem discernible at depth. These aspects possibly broaden the class of dynamo regimes for Mercury.

Keywords: Mercury, core field, magnetism

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A New Hermean Magnetic Field Model

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Abstract

MESSENGER spacecraft MAG measurements provide crucial information on the magnetic field of Mercury. Due to the spacecraft eccentric orbit and the small magnetosphere of Mercury, measurements close enough to the planet's surface and therefore suitable for internal magnetic field studies are acquired only over the northern hemisphere. This configuration is a limitation to standard global modeling methods such as Spherical Harmonics. We use a local modified Equivalent Source Dipole method to model the magnetic field above the surface from measurements partially distributed. Here, the dipoles are placed deep inside the planet. This method is first applied to single sidereal day data periods. We find small-scale features varying in time which may be interpreted as fields of external origin. Note that in this study, we do not attempt to model explicitly the external field. As the planet is in 3:2 resonance the Sun does not cover all local longitudes during one sidereal day. We therefore consider only one-solar-day models because most external features tend to be averaged out. We find a dominantly axisymmetric field for each solar-day models. However, comparing successive models we observe a strong large-scale variability of the field. This is probably due to some large-scale external sources. Further studies are needed to confirm whether these differences are due to spatial or temporal variability. We finally compute a unique model with all the data considered above (about three terrestrial years) to describe the Hermean magnetic field. This model confirms the large-scale and close-to-axisymmetry structure of the internal magnetic field of Mercury. It also displays the northward offset magnetic equator crossings previously detected. However, our magnetic equator latitude varies with altitude in contrast with the altitude-independent equator latitude of the purely dipole offset hypothesis. Fitting SH coefficients to our model we obtain an axial quadrupole to axial dipole ratio up to 0.48 that decreases to _˜0.2 if the poorest data coverage are not considered. These results suggest that the magnetic field of Mercury may be explained by a range of possible hemisphericities enlarging the domain of possible dynamical regimes for Mercury's dynamo.

Keywords: Planetary magnetic field, Mercury, MESSENGER mission, Axisymmetric field

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A forward look to Juno and possible information on Jovian secular variation

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Abstract

Juno is approaching Jupiter, and is due to arrive at Jupiter on July 4th. Using a modelled prediction of the mission trajectory, we examine the possible constraint that the mission will provide on Jovian field and its variation (secular variation). We perform synthetic experiements using output of a dynamo model constructed to represent Jupiter. We find that given an assumption of isotropic measurement error of 100 nT, it might be possible to recover the field to spheric harmonic degree 18, and secular variation (SV) perhaps to degree 5. To identify the separation between the recovered SV and noise, we make use of a relation for the Earth for which secular variation at the surface of the core has a simple algebraic form (Holme et al, 2011). We find that this relationship argrees very well for low degree field for the dynamo model, and also for other dynamo models. It will be of great interest to see whether this also shows up at Jupiter, which might suggest a universal dynamo scaling relationship. The magnitude of the SV in the model is of a similar magnitude to that estimated from all available pre-Juno data (Ridley and Holme, 2016). Using secular variation, it is possible to estimate flow in the core. We examine this estimation for the dynamo model to explore what models of flow might be sensible. Our analysis is optimistic, and relies on the error characterisation - we consider how this may be disrupted by non-isotropic noise (from external current systems and the aurora), and consider briefly the implications of these sources for induced magnetic fields.

Keywords: Jupiter, secular variation, flow

*Speaker

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Direct measurement of thermal conductivity in solid iron at planetary core conditions

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Abstract

The conduction of heat through minerals and melts at extreme pressures and temperatures is of central importance to the evolution and dynamics of planets. In the cooling Earth's core, the thermal conductivity of iron alloys defines the adiabatic heat flux and therefore the thermal and compositional energy available to support the production of Earth's magnetic field via dynamo action. Attempts to describe thermal transport in Earth's core have been problematic, with predictions of high thermal conductivity at odds with traditional geophysical models and direct evidence for a primordial magnetic field in the rock record. Measurements of core heat transport are needed to resolve this difference. Here we present direct measurements of the thermal conductivity of solid iron at pressure and temperature conditions relevant to the cores of Mercury-sized to Earth-sized planets, using a dynamically laser-heated diamond-anvil cell. Our measurements place the thermal conductivity of Earth's core near the low end of previous estimates, at 18–44 watts per metre per kelvin. The result is in agreement with palaeomagnetic measurements indicating that Earth's geodynamo has persisted since the beginning of Earth's history, and allows for a solid inner core as old as the dynamo.

Keywords: iron thermal conductivity, iron electrical conductivity, inner core age

*Speaker

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Constraints on the thickness of Enceladus's ice shell from Cassini's libration measurements

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Abstract

The recent measurements of the librations, or spin rate variations, of Saturn's moon Enceladus from Cassini images suggest that it could have a global subsurface ocean (Thomas et al. 2016), buried under a thin ice shell of average thickness 14-26 km (Van Hoolst et al. 2016).

One complication in the modelling arises from the pronounced nonhydrostatic structure of Enceladus (Iess et al. 2014, McKinnon 2015). Detailed models of librations are therefore required to properly interpret the measurements in terms of interior structure. Here we compare the ice shell thickness estimates from the 'classical', separate tide and libration models with those from our combined tide+libration model, both extended to account for nonhydrostatic structure.

Keywords: Enceladus, interior structure, libration, nonhydrostatic structure

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Fully determined scaling laws for volumetrically heated systems : a tool for assessing the thermal states of natural systems

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Abstract

We develop fully theoretical scaling laws giving the thermal structure of the Thermal Boundary layer (TBL) as a function of the Rayleigh number (Ra) in volumetrically heated systems. Our approach is based on the dynamics of the TBL at the onset of convection and provides an analytical explanation for the variations of thermal structure with changing boundary conditions. The scaling laws agree with independent numerical simulations conducted for Ra ranging between 10ˆ3.7 – 10ˆ9 and for both free slip and rigid surfaces, whereas previous studies failed to explain results for both low and high Ra with a single law. We then apply the scaling laws to planetary systems.
We first consider an application to Pluto. The New Horizons spacecraft provided the first high resolution pictures of Pluto's surface, where a nitrogen glacier, informally named Sputnik Planum, has been detected. The unique character of Sputnik Planum stems on the fact that its surface is divided into polygonal cells. Here, we test the hypothesis that the polygonal structure is a surface expression of volumetrically heated convection. Using the surface observation of Sputnik Planum coupled to the surface planform of numerical simulations, we constrain the Rayleigh number of the glacier. Next, appropriate scaling laws allow us estimating the interior temperature of the glacier as a function of its thickness. We conclude that volumetrically heated convection is a plausible explanation, and that, if this explanation is correct, the glacier should be 2–13 km thick.
We then present the application to exoplanets. We combine the scaling laws with solidus and liquidus profiles of a terrestrial peridotite to obtain a regime diagram giving the thermal state of an exoplanet (liquid, solid or partially molten) as a function of physical parameters that can be observed, e.g., the radius of the planet, or that can be constrained using available information for solar system material, e.g., the mantle heating rate. Our results indicate that old and cold planets did not preserve their primitive atmosphere and are probably not habitable. During the early thermal history of large planets, on the other hand, primordial heating by collisions induces a magma ocean, whose thermal conditions prevent the apparition of life. The contribution of primordial heating appears as a key factor in the generation of volcanism in terrestrial planets.

Keywords: Convection, Scaling Laws, Pluto, Exoplanet

*Speaker

Evolution of an Initially Stratified Liquid Core on Mars and Dynamo activity

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Abstract

Mars magnetic history was discovered after Mars Global Surveyor lowered its orbit and recorded the remanent magnetization of the crust [1]. Remanent magnetization varies with terrane, with strong field associated with ancient, heavily cratered southern highlands. Differences in crustal ages permitted to estimate that any dynamo activity ceased by the early Noachian epoch, about 4 billion years ago, which has since been confirmed by direct measurements on SNC meteorites [2,3]. Depending on the early state of Mars, such a short lived dynamo can be hard to explain. Various authors have proposed mechanisms such as a primordial superheated core that can sustain a thermal dynamo for a few 100 million years [4], or suppression of core cooling by a series of large impact which would have heated the mantle and changed its dynamic state [e.g., 5].

Several workers [6-8] proposed recently that the core of terrestrial planets are likely to be formed stratified. The accretion and differentiation of terrestrial bodies occur on similar time scales, with metal segregation occurring shortly after each impacts. The metal equilibrates with the silicates at a pressure and temperature similar to the conditions at the bottom of the surrounding magma ocean before sinking through the solid mantle, either by dykes or diapirs. Because the body is growing with each addition of material, the temperature and pressure of equilibration increase after each accretion steps. The metal merging with the core at each steps is thus hotter and lighter that the previously-segregated material, forming a layered core. In this presentation, we investigate the thermal evolution of such an initially stratified core, with special interest on the onset of convection and dynamo action on Mars.

Acuña et al., Science (1999), [2] Weiss et al., Earth Planet. Sci. Lett. (2002), [3] Chassefière et al., Planet Space Sci. (2007), [4] Williams and Nimmo, Geology (2004), [5] Roberts et al., J. Geophys. Res. (2009), [6] Jacobson et al., AGU Fall Meeting (2015), [7] Helffrich and Brasser, AGU Fall Meeting (2015), [8] Arkani-Hamed, AGU Fall Meeting (2015).

Keywords: mars, dynamo, core

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Scaling and stability of the compositional convection in a rotating spherical layer with asymptotically small transport coefficients

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Abstract

An optimal asymptotical scaling is suggested for the compositional convection that dominates in the deep interiors of the Earth and many other planets and moons. The scaling is based on the self-consistent estimations of the typical physical parameters under the conditions of fast rotation and small transport coefficients. New small characteristic number, which defines how fast the rotation is, is introduced as the ratio of the typical length-scale in the direction normal to the axis of rotation to the outer radius of the spherical layer in which the convection is being developed. Small viscosity and diffusion in the deep planetary interiors are usually characterized by the Ekman number E. The main length-scale of the linearly stable convection is defined by the product of the Ekman number and the radius of the spherical layer. The presence of this small parameter allows us using the asymptotic analysis to reduce the initial problem for the system of partial differential equations to the simplified two-point boundary value problem for a single second-order ordinary differential equation. Using the power series expansion of our new characteristic parameter we apply WKBJ approach and find analytical solution for the system of two ODEs for the vertical velocity and the pressure The critical Rayleigh numbers, frequencies and distributions of planetary/moons convection are obtained for the Prandtl number Pr=1 and values of geometrical parameters which are the most interesting for practical applications.

Keywords: compositional convection, fast rotation, WKBJ approach

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A laboratory model for deep-seated zonal jets in gas planets

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Abstract

Using a large-scale rotating fluid experiment, we report the formation of deep-seated Jovian-like jets due to topographical effects in 3Dimensional (3D) rotating turbulence. For the first time in a laboratory, a simple device brings together the physical ingredients require to reach the so-called "zonostrophic" regime, thought to be relevant to gas giant's atmosphere: rapid rotation, highly turbulent flow, and large depth variations. We show that the flow naturally generates multiple, alternating jets and that the strength and scale of the jets share the basic properties of those observed on the gas planets. Our findings demonstrate that long-lived jets occur and persist at high latitudes even under natural flow conditions including dissipation. For our experimental set up, we use a cylindrical container 1.4 meter high with a radius of 0.5 meter filled with up to 400 liters of water. The device is mounted on a rotating table and rotates up to 75 RPM. This leads to a very large paraboloidal deformation of the fluid layer after spin-up (topographic beta-effect with water depth variation of 70cm). A turbulent small-scale flow is driven via a basal injection/suction system generating a flow of high Reynolds number (Re=10ˆ4) and low Rossby number (Ro=10ˆ-3). Complementary 3D turbulent numerical simulation shows that due to the very low Rossby numbers, the basal forcing very quickly drives a nearly depth-invariant turbulent flow and attests that surface measurements are sufficient to characterize the whole system in a first approach. The steadiness of the resulting multiple jets system is an important qualitative feature shared by gas planets as well as our laboratory and numerical models. Kinetic energy spectrum analysis, performed on both the free surface in our set-up and from high-resolution images of Jupiter's clouds (Cassini space-craft mission), reveals similar feature of strong anisotropy and steep turbulent cascade which differ from classical Kolmogorov–Kraichnan law. Ultimately, by controlling basal friction in numerical simulation we evidence that boundary dissipation is a key-ingredient which determines the equilibrated scale and strength of jets. Based on the formation of jets in the presence of viscous boundaries, we hypothesize that deep planetary jets will also form in the presence of a magnetic dissipation region, as exists within the gas planets. These results open new perspectives in the debate between shallow versus deep models by successfully designing the first laboratory device carrying deep-seated Jovian-like jets.

Keywords: rotating turbulence, zonostrophic regime, zonal jets

*Speaker

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Laboratory experiments on rain-driven convection: implications for dynamos in cooling planet cores

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Abstract

Compositional convection driven by precipitating solids or immiscible liquids has been proposed as a dynamo mechanism in cooling planets and satellites throughout the solar system, including Mercury, Ganymede, and the Earth. Here we report laboratory experiments on turbulent rain-driven convection, analogs for the flows generated by precipitation within planetary fluid interiors. We subject a two-layer fluid to a uniform intensity rainfall, in which the rain is immiscible in the upper layer and miscible in the lower layer. Rain falls through the upper layer and accumulates as a two-fluid emulsion in the interfacial region between the layers. In experiments where the rain is denser than the lower fluid, rain-injected vortices evolve into small-scale plumes that rapidly coalesce into larger structures, resulting in turbulent convection throughout the lower layer. The turbulent convective velocity in our experiments increases approximately as the cube root of the rain buoyancy flux, implying little or no dependence on viscous and chemical diffusivities. Diffusion-free scaling laws for magnetic field generation indicate that precipitation-driven convection is an effective planetary dynamo mechanism provided the precipitation buoyancy flux is large and the convecting region is deep and nearly adiabatic.

Keywords: Rain, driven convection, planetary dynamos, iron snow, magnesium precipitation, convection experiments, scaling laws

*Speaker

Heat transport in the high-pressure ice mantle of large icy moons.

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Abstract

While the existence of a buried ocean sandwiched between surface ice and high-pressure (HP) polymorphs of ice emerges as the most plausible structure for the hundreds-of-kilometers thick water components within large icy moons of the Solar System (Ganymede, Callisto, Titan), little is known about the thermal structure of the deep HP ice mantle and its dynamics, possibly involving melt production and extraction. This has major implications for the thermal history of these objects as well as on the habitability of their ocean as the HP ice mantle is presumed to limit chemical transport from the rock component to the ocean. Here, we describe 3D spherical simulations of subsolidus thermal convection tailored to the specific structure of the HP ice mantle of large icy moons. Melt production is monitored and melt transport is simplified by assuming instantaneous extraction to the ocean above. The two controlling parameters for these models are the rheology of ice VI and the heat flux from the rock core. Reasonable end-members are considered for both parameters as disagreement remains on the former (especially the pressure effect on viscosity) and as the latter is expected to vary significantly during the moon's history. We show that the heat power produced by radioactive decay within the rock core is mainly transported through the HP ice mantle by melt extraction to the ocean, with most of the melt produced directly above the rock/water interface. While the average temperature in the bulk of the HP ice mantle is always cool ($\sim$ 5 K above surface temperature), maximum temperatures at all depths are close to the melting point, often leading to the interconnection of a melt path via hot convective plume conduits throughout the HP ice mantle. Overall, we predict long periods of time during these moons' history where water in contact with he rock core is transported to the above ocean. More precise evidence for such exchanges will be tested by infrared spectroscopy and mass spectroscopy performed by the ESA JUpiter ICy moon Explorer (JUICE) mission.

Keywords: Ganymede, Titan, Callisto, High, pressure ices

*Speaker

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Heat transfer, Core flows and Dynamos in tidally locked terrestrial exoplanets

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Abstract

It is assumed that a significant fraction of the detected terrestrial exoplanets orbit their host star in synchronous rotation. The stellar irradiation will thus induce an enormous temperature difference between the permanently exposed day and very cold night side of the exoplanet. Assuming that the emerging horizontal temperature gradient reaches as deep as the core mantle boundary (CMB), the heat flux due to cooling of the liquid, iron-rich core is suppressed at the front and enhanced at the back side. We therefore study the emerging flows, the heat transfer and the potential induction of a global magnetic field in a rapidly rotating core under a non-homogeneous CMB heat flux. The specific shape of the anomalous part of the heat flux pattern is spherical harmonic of degree and order unity (Y11).

Interestingly, also in the absence of thermal or compositional convection, azimuthal and radial flows are induced by the heat flux pattern seeking to equilibrate the differential cooling. However, the emerging two-cell flow pattern is azimuthally phase-shifted by the dominant Coriolis force such that radial flows are located at the day-night boundaries where the azimuthal temperature gradient is maximised. Increasing the non-linearities the emerging broad radial flows are deformed into thin, jet-like structures spiralling towards the inner core boundary.

If additionally the mean core heat flux is superadiabatic, the convective heat transfer is strongly modulated by the boundary enforced flows and temperature anomaly. Convection and hence dynamo action are then most energetic in the night side of the core, although the activity maximum is advected by ca. 30 degrees further east then the antipodal longitude relative to the host star.

Keywords: core dynamics, heat transfer, inhomogeneous CMB heat flux, dynamo

*Speaker

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A numerical method for reorientation of tidally deformed visco-elastic bodies

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Abstract

We developed a numerical method for calculating the time-history of the reorientation of tidally deformed rotating bodies. With the help of our model, we show the limitations of existing dynamic approaches for calculating the true polar wander: (i) linear dynamic approaches which use the linearised Liouville equation (e.g. Wu and Peltier [1984]) can have significant error for loadings near the poles or the equator. For instance, when the loading is placed at 10 degree colatitude on a model representing the Earth, the maximum allowed TPW is just 0.2 degree for the error of the linear method to remain below 1%. (ii) non-linear dynamic approaches which are based on the quasi-fluid approximation (e.g. Ricard et al. [1993]) is not suitable for modelling the transient TPW behaviour of Earth or other planets with significant slow relaxation modes. Furthermore, our method is able to give the dynamic solution for the reorientation of tidally deformed body. Compared to those static fluid-limit solutions which only give the final position of the reorientation (e.g. Matsuyama and Nimmo [2007]), we have a better insight of how the reorientation is accomplished. We show that at a tidally deformed body, positive mass anomalies are more likely to be found near the equator and the plane perpendicular to the tidal axis, while negative mass anomalies tend to be near the great circle with longitudes 0○ and 180○.

Keywords: True polar wander, Linear polar wander theory, Quasi, fluid approximation, Reorientation of tidally deformed bodies

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Top-down crystallization in Mercury's core

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Abstract

Planetary cores crystallize due to secular cooling. Where in the core solidification starts is a crucial question that has implications for the thermal and dynamical evolution of the planet. In smaller planets or moons like Mercury or Ganymede, the adiabatic profile may be steeper than the liquidus profile, so that solidification may start at the core-mantle boundary (Williams, 2009). Crystallization can then be via dendrites forming at the CMB (Haack and Scott, 1992) or via an iron crystal snow, the so-called "snowing core regime" (Hauck et al., 2006, Chen et al., 2008).
A major issue with crystallization in the interior of the core is nucleation: the energy barrier for homogeneous nucleation is prohibitive (Shimizu et al., 2005), and no obvious sites exist for heterogeneous nucleation. Homogeneous nucleation can occur only when a cluster of atoms (a so-called embryo) is large enough for the bulk free energy of the solid to overcome the energy penalty of the solid/liquid interface. This requires a large supersaturation of the solid phase, which is usually expressed in terms of the degree of undercooling required, i.e. the difference between the liquidus temperature and the temperature at which the embryo can survive and grow. For pure metals at ambient pressure, the critical undercooling is about 20% of the melting temperature (Turnbull, 1950). Recent molecular dynamics studies of iron at high pressure show that a similar degree of undercooling is required for nucleation at pressures up to 350 GPa. Homogeneous nucleation of solid iron in Mercury's core is hence likely to require an undercooling of at least 1000 K.
However, the core-mantle boundary can provide heterogeneous nucleation sites. Then, the crystallization can initiate at the CMB via the formation of dendrites and mushy layer (Haack and Scott, 1992; Williams, 2009; Scheinberg et al., 2015). The presence of such mushy layer below the core-mantle boundary raises important questions on the dynamic in the outer core. In the case of hypoeutectic Fe-S alloy, Fe-dendrite crystallization leads to release of a sulfur-rich liquid, which is partially trapped in the mushy layer with some released just below the interface. The released sulfur-rich liquid could be removed by thermal convection. Below the core-mantle boundary, an iron mushy layer will become unstable when grows beyond a critical thickness.

Keywords: Mercury, core, solidification, snowing core regime, nucleation

*Speaker

Global stability analysis of mechanically-driven flows in rigid rotating ellipsoids

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Abstract

Because of gravitational torques generated by orbital partners, most of planets and moons have ellipsoidal shapes. Gravitational interactions also give birth to mechanical forcings, such as precession or libration, which are associated with time-dependent rotating angular velocities. In ellipsoidal containers these forcings drive inertial instabilities, leading to turbulent flows. From a theoretical point of view, the former have been mainly studied in the limit of weak viscosities in weakly deformed spheres or in unbounded domains. On the other hand viscosity cannot be neglected in laboratory and numerical experiments and the deformation of the containers is large, such that the topographic effect may be dominant over viscous damping.

We investigate the hydrodynamic stability of incompressible, time-dependent flows of uniform vorticity in rotating rigid ellipsoids. First we use a generic method to estimate the uniform vorticity base flow, driven by a mechanical forcing in an ellipsoidal container. Then we analyse its global stability analysis by considering three-dimensional perturbations which belong to a finite-dimensional polynomial vector space in ellipsoids (Lebovitz, 1989, Wu and Roberts, 2011). By carefully combining symbolic and numerical computations, we are able to consider perturbations of higher spatial complexity than in the literature. To bridge the gap between theory and experiments, we have also included corrections due to viscous damping (both Ekman pumping and bulk dissipation), following the path drawn by Greenspan (1965). These corrections are self-consistent as they do not rely on adjustable parameters. Thus we can compute the linear growth rate (with or without viscous damping) and the flow structure of inertial instabilities driven by a mechanical forcing in ellipsoids. As applications we perform the viscous stability analysis of tidally-driven (Cébron et al, 2010) and libration-driven (Grannan et al, 2014) flows. We find good agreements between our predictions and lab / numerical simulations, even for moderate viscosities. This model is a first step toward a generic weakly nonlinear stability analysis of mechanically-driven inertial instabilities in ellipsoids.

Keywords: Inertial instabilties, Mechanical forcings, Tides, Libration, Laboratory experiments, Ellipsoids

*Speaker

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Elliptical instability in stably stratified fluid interiors

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Abstract

Self-sustained magnetic fields in celestial bodies (planets, moons, stars) are due to flows in internal electrically conducting fluids. These fluid motions are often attributed to thermo-solutal convection, as it is the case for the Earth's liquid core and the Sun. However some past or present dynamos may originate from (completely or partially) stably stratified fluid layers, where convective instabilities are inhibited. Thus alternative mechanisms to thermo-solutal convection are needed to understand the dynamo process in these celestial objects.

Turbulent flows driven by mechanical forcings (tides, precession...) seem very promising, since they are dynamo capable (Tilgner, 2005; Cébron and Hollerbach, 2014). However it has not been clearly shown that inertial instabilities, the key ingredient to explain the transition between laminar and turbulent flows driven by mechanical forcings, may grow in stably stratified fluids. It may have consequences for thermal evolution of celestial bodies (Labrosse, 2015). In the linear regime stable stratification has some destabilisation effects in cylindrical geometry (Kerwell, 1993), which also seems to be the case in some numerical simulations of precession in spherical geometry (Wei and Tilgner, 2013) and of tidally-driven flows in triaxial ellipsoids (Cébron et al, 2010). Finally the nonlinear behaviour of these flows is still unknown.

Using an approach similar to the one used by Cébron and Hollerbach (2014), we mimic an elliptical distortion (first effect of a mechanical forcing) in spherical geometry. It allows to keep the numerical efficiency of spectral numerical codes in spherical geometry. First we build a theoretical base flow with elliptical streamlines, consistent with a stable thermal stratification profile in a full sphere, which satisfies the stress-free boundary conditions at the outer boundary. Then we perform its stability analysis, using three-dimensional simulations with the spectral code xshells (Schaeffer, 2013) to perform both linear and nonlinear computations. Preliminary results are shown. Determining the dynamo capability is at reach and will be studied in a second step.

Keywords: Elliptical instability, stratification, planets, stars, dynamo

*Speaker

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Exploring planetary core dynamics with the SINGE and XSHELLS codes

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Abstract

The geodynamo group at ISTerre has developed several numerical codes for solving the incompressible Navier-Stokes equation (NSE) in rotating spheres, including Boussinesque buoyancy and magnetic induction (i.e. geophysical contexts). SINGE and XSHELLS discretize the fields using a radial grid of shells and decomposing fields within each shell into vector spherical harmonics. Various boundary conditions and forcings are implemented. Both codes are free and open source.

SINGE is a linear eigensolver for the NSE, using the SLEPc and PETSc (MPI parallelized) libraries to determine the eigenmodes of a sparse matrix representing gravito-inertial or thermally convecting systems. SINGE can thus find gravito-inertial modes or determine the onset of convection.

XSHELLS integrates up coupled differential equations from user specified initial states, including various forcing mechanisms (Couette flow, precession driven flow, nutation, thermal convection, and arbitrary bulk forcings). It is very fast, thanks to an efficient spherical harmonic transform library (SHTns) and a careful hybrid MPI/OpenMP parallelization. SHTns is highly vectorized and ready for the next generation of computer architectures (e.g AVX-512); XSHELLS is one of the fastest spherical code on the market, and it is used in production with more than 8000 cores.

These codes come with a mature suite of post-processing tools, which allow speedy and complex analyses of the computed velocity/magnetic/thermal fields. A gallery of nice-looking applications is shown, among which: (i) the spiraling of Rossby modes at low viscosity; (ii) inertial wave attractors in spherical shells; (iii) high resolution geodynamo simulations; (iv) precessing spheres.

Keywords: numerical simulations, geodynamo, convection, spherical shell, sphere, rotation, precession, inertial modes

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Plume-induced subduction: from laboratory experiments to Venus large coronae

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Abstract

Understanding the details of plate failure and the initiation of subduction remains a challenge due to the complexity of mantle rocks. We carried out experiments on convection in aqueous colloidal dispersions heated from below, and dried and cooled from above. The rheology of colloidal aqueous dispersions of silica nanoparticles depends strongly on the solid particle fraction, ϕp, deforming in the Newtonian regime at low ϕp, and transitioning to strain-rate weakening, plasticity, elasticity, and brittle properties as ϕp increases. So, as the system is dried from above, a dense skin grows on the surface, akin to a planetary lithosphere. If it is also heated from below, hot plumes develop.

When a hot plume impinges under the skin, it triggers a new mode of subduction: as the upwelling plume material breaks the lithosphere and flows above the denser skin, it forces it to sink. The subduction trenches are localized along the rim of the plumes and strong roll-back is observed. Subduction always occurs along partial circles, a situation very different from the purely viscous case. This is due to the brittle character of the upper part of the experimental lithosphere: it cannot deform viscously to accommodate roll-back and sinking motions. Instead, the plate tears, as a sheet of paper would do upon intrusion. The experiments further suggest that a weaker lithosphere than that present on Earth today is required for such a convective regime.

These experimental observations strongly resemble the association of large coronae with trenches that is observed on Venus. The surface deformation structures and the subsurface density variations predicted by the laboratory agree with radar image observations and subsurface density variations inferred from modeling the gravity and topography data at Artemis and Quetzelpetlatl Coronae. Evidence for geologically recent volcanism at Quetzelpetlatl suggests that subduction may be currently active on Venus.

Keywords: Venus, Mantle Plumes, Subduction, Laboratory experiments

*Speaker

Improved Particle-in-Cell advection for the modelling of planetary interiors using deformable particle kernels

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Abstract

Modeling numerically the evolution of the Earth and planetary interiors requires the accurate description of advective processes, often combined with a variety of motionless mechanisms acting on several quantities (temperature, composition, grain-size, magnetic field components). To this end, the particle-in-cell (PIC) method is a well-suited flexible hybrid approach that uses a network of Lagrangian particles superimposed on a Eulerian grid. The grid represents the discretization of the physical domain and is used to determine the velocity field and the quantities affected by motionless processes (diffusion, radiation, source, reactions...). The particles move through the grid and carry information about advected quantities. The latter are continuously transferred back and forth between the particles and the grid, through averaging, which involve particles kernels and grid shape functions. The method heavily relies on the choice of the particle kernels and on their meaning. Despite an effective spatial accuracy often confined to first-order, PIC approaches remain popular in many applications for geodynamics at various scales (mantle and lithospheric dynamics) and for MHD calculations, with interesting potential applications to liquid core dynamics, because the advection of Lagrangian particles significantly reduces numerical dissipation compared to purely Eulerian methods of higher-order.
In spite of their popularity, PIC approaches suffer from particle clustering and rarefaction in regions characterized by intense deformation. This phenomenon also concerns incompressible flows for which grid cells can become completely empty while others are over-sampled by particles. Typical remedies involve: (1) the increase of the number of particles, often generating a prohibitive computational cost; (2) particles re-meshing to maintain a homogeneous sampling of the domain, which induces numerical dissipation that progressively degrades the accuracy of the solution.
I will present an evolution of the PIC method based on a new formulation of the particle kernels that takes into account the strain history in the vicinity of the particles. This new method, named DPIC, allows for a considerably more uniform spatial sampling by the particles with a reasonable computational extra cost (_˜ 50% relative to the PIC approach using the same number of particles). The DPIC method with only 4 particles per cell (in 2D) generates a solution whose accuracy is comparable to the standard PIC approach with more than 64 particles per cell. Therefore, at comparable precision this new approach reduces the computational cost by more than one order of magnitude.

*Speaker

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Keywords: Advection, PIC method, Particle Kernel, Interface Tracking

Convective Dynamics of Icy Satellite Oceans

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Abstract

Icy satellites in the outer solar system can have liquid water oceans beneath their surfaces [1-2], making them potentially habitable. These oceans are thermodynamically possible because of the tidal heating that results from the satellites' proximity to their host planets. In combination with radiogenic heating and secular cooling, tidal heating in the mantle amounts to a sizeable fraction of the net heat flux emanated from these satellites that is transferred convectively through the ocean. Here, we investigate oceanographic processes in the ice-covered moons Europa and Enceladus.

Convection is able to efficiently redistribute heat and chemicals through fluid motions. Experiments have shown that convection characteristics depend critically on the relative importance of rotation [e.g., 3]. In turbulent, rotationally-constrained spherical systems, convection manifests as columnar vortices aligned with the rotation axis with multiple east-west currents that alternate in direction, similar to the zonal winds of Jupiter and Saturn [4]. These columns act to pump heat in the axial direction, which causes heat transfer to peak near the poles [5]. In sharp contrast, convection in weakly-constrained systems is no longer organized by the Coriolis force, leading to chaotic fluid motions. Here, three east-west currents develop, similar to the zonal winds of Uranus and Neptune [6]. Low latitude turbulence and Hadley-like cells enhance heat transfer near the equator [7]. Applying these results to icy satellites, we predict Europa's ocean to be characterized by three zonal currents with retrograde equatorial flow and two overturning cells at low latitudes [8]. Conversely, we hypothesize Enceladus' ocean to be characterized by multiple zonal currents with prograde equatorial flow and axially-aligned vertical flows.

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Keywords: icy satellites, ocean, convection

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Mercury's core evolution

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Abstract

Remote sensing data of Mercury's surface by MESSENGER indicate that Mercury formed under reducing conditions. As a consequence, silicon is likely the main light element in the core together with a possible small fraction of sulfur. Compared to sulfur, which does almost not partition into solid iron at Mercury's core conditions and strongly decreases the melting temperature, silicon partitions almost equally well between solid and liquid iron and is not very effective at reducing the melting temperature of iron. Silicon as the major light element constituent instead of sulfur therefore implies a significantly higher core liquidus temperature and a decrease in the vigor of compositional convection generated by the release of light elements upon inner core formation. Due to the immiscibility in liquid Fe-Si-S at low pressure (below 15 GPa), the core might also not be homogeneous and consist of an inner S-poor Fe-Si core below a thinner Si-poor Fe-S layer. Here, we study the consequences of a silicon-rich core and the effect of the blanketing Fe-S layer on the thermal evolution of Mercury's core and on the generation of a magnetic field.

Keywords: Mercury, thermal evolution, magnetic field, core composition

*Speaker

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Critical mode of anelastic thermal convection in a rotating spherical shell depends on radial distribution of thermal diffusivity

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Abstract

We perform linear stability analysis of anelasitc thermal convection in a rotating spherical shell with thermal diffusivities varying in the radial direction.
Many previous studies about anelastic thermal convection in rotating spherical shells assume that thermal diffusivity is constant for simplicity. However, location of occurrence of convection depends on radial entropy distribution of a basic state, it can be expected that the structure of convection will be changed with radial distribution of thermal diffusivity.

In order to illustrate this expectation, we investigate the structure of critical convection with three different radial distributions of thermal diffusivity; (1) is constant, (2) T is constant, (3) ρT is constant, where is the thermal diffusivity, T is the temperature of basic state, and ρ is the density of basic state, respectively. The ratio of inner and outer radii, the Prandtl number, the Ekman number, the polytrope index, and the density ratio are 0.35, 1, 10ˆ{-3}, 2, and 5, respectively.
In the case of (1), where the setup is same as that of the anelastic dynamo benchmark (Jones, et al, 2011), the structure of critical convection is concentrated near the outer boundary of the spherical shell around the equator. However, in the cases of (2) and (3), the convection columns locate at the mid-depth and near the inner boundary of the spherical shell, respectively.

Keywords: Critical Convection, Anelastic fluid, Jovian planets

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A parameter study of Jupiter-like dynamo models

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Abstract

The upcoming missions to Jupiter will provide new information about the outer flow dynamics and magnetic field of the planet. In the last few years, the interest in more accurate numerical models of the planet significantly increased and remarkably close models have been published which incorporate interior radial profiles obtained from ab initio equations of the interior of the planet. The solutions of these numerical models for the dynamics already show several surface features that closely reproduce the observational data available in the present. The future observational data will provide better constraints for numerical models, thus allowing comparisons at a much higher degree. In the mean time, the next step in the numerics is to develop parameter studies, which will provide us a broader range of models incorporating Jupiter's interior profiles. Simplifications are necessary when it comes to numerical modelling and so we present here an extensive parametric study of Jupiter models, along side other previously published polytropic models for comparison, where different Ekman numbers and Prandtl numbers at different supercriticallies are tested and presented. Furthermore, for a more detailed analysis we focus on different heating mechanisms and Jupiter-like density and electrical conductivity gradients. The density gradient is fixed for the Jupiter models, but the steep electrically conductivity profile cannot be achieved for a nearly full interior model (up to 1% below the surface) due to the limitations of current computational resources.
Jupiter's measured luminosity shows that the planet radiates more energy than what it receives from the Sun. This is commonly attributed to the fact that the primordial heat from the planet's formation is being released from the interior by convection. The second part of this work takes a closer look at this driving mechanism and its comparison with a more simple assumption of bottom heating. We conclude that there are no significant differences for the surface field by changing the heating mode, while the other parameters play a major role in finding Jupiter like dynamo solutions.

Keywords: Jupiter, dynamo, modelling, parameter study

*Speaker

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The thermochemical structure of Mars - a seismological perspective on phase transitions, low-velocity layers and dynamic processes in the deep interior

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Abstract

The deep thermal and chemical structure of Mars has been shaped by many processes, including impacts, core-mantle segregation, convection and volcanism. This structure is currently poorly constrained; improved constraints will help us better understand the planet's thermal, chemical, dynamic and magnetic evolution. The InSight mission landing on Mars in 2018 will deploy a seismometer on Elysium Planitia, providing us with single-station three-component measurements of Martian seismicity, illuminating its interior structure. These measurements are subject to perturbations due to the significantly aspherical structure of the Martian crust, source location uncertainties, lander and environment noise, waveform distortions due to yet unknown scattering properties of the Martian upper mantle and crust. In preparation for this mission, we build on earlier models of Mars structure (e.g. Mocquet et al, 1996; Sohl and Spohn, 1997; Gudkova and Zharkov, 2004; Khan and Connolly, 2008; Zharkov et al, 2009; Rivoldini et al, 2011) to investigate the effects of specific unknowns on seismic travel times and waveforms which we expect to be recorded during the mission. In this study, we link model parameters such as average crustal, lithospheric and mantle thickness, mantle temperature, composition and convective vigour with seismic observables such as travel times and ray parameters. We discuss the trade-offs between the model parameters based on ray theoretical predictions, focusing on the effects of low-velocity layers in the uppermost and lowermost mantle, the absence or presence of triplications indicating the sharpness of phase transitions within the Martian mantle and the effects of core size and composition on seismic observables.

Keywords: Mars, InSight, core, mantle, mineralphysics, seismology

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Resolution of the velocity and attenuation profile at the base of the outer-core and in the inner-core

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Abstract

We compiled records of more than three thousand, high quality differential travel-times and amplitude ratios measurements of PKPbc, PKPbc-diff, PKPab and PKPdf phases in the epicentral distance range [149○ ; 171○] and discuss the radial and lateral variation of the attenuation and velocity profiles at the base of the outer-core and in the inner-core. To better constrain the structure in the core, we included measurements of the M phase. The M phase is a large energy in the coda of the PKPbc and PKPbc-diff that is not predicted by 1D reference model and is originating at the base of the outer-core. We showed that, at 150km bellow the ICB, the eastern hemisphere is smaller than the western hemisphere and extends from ˜65○E to ˜165○E. Forward modeling, combined with a grid-search approach is used to model and search for the best-fitting attenuation and P-velocity profile in the eastern and western hemispheres. Results showed that Qkappa is close to 400 in the inner-core and 600 in the outer-core, with a very attenuated 100km-thick layer at the base of the outer-core. Relative travel-time and amplitude ratio measurements are best explained with 1% P-velocity increase or 0.8% P-velocity decrease at the ICB in the outer-core, respectively. In the inner-core, travel-time measurements are best explained with slower velocities in the deep inner-core while amplitude measurements are best explained with shallower P-velocity reductions. We also discussed the possibility of a mushy layer in the F-layer to explain the large M amplitude observations that are failed to be explained with attenuation or P-velocity perturbations.

Keywords: PKP, outer core, inner core, F layer, Qkappa, Vp, Vs

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Mushy layer and flow over a moving substrate

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Abstract

Analyses of the conditions at the inner core/ outer core boundary suggest that the liquid ahead of the interface is likely constitutionally supercooled. It is a well-known fact that during solidification of a binary alloy, constitutional supercooling usually leads to the formation of a so-called mushy layer, i.e. a region in which the solid and liquid phases coexist in a thermodynamic equilibrium. From the microscopic point of view, the mushy layer has a complicated microstructure made of highly convoluted solid structures, called dendrites. From the macroscopic point of view, the mushy layer is a reactive porous medium whose porosity changes in space and time upon the internal solidification/melting of the dendrites and due to the local effects of convective fluid flow. The full system of equations governing the mushy layer usually cannot be solved explicitly, especially when the effects of flow have to be taken into account. However, there are special situations, when that is possible. One of those situations is an experimental configuration in which the solidification occurs at a horizontally moving, cooled substrate. In such a configuration, one can study explicitly the effect of flow on the thickness of the mushy layer. From the point of mathematical modelling, there are some important features: the solidifying interfaces are stationary; the interfaces are not planar and there is a strong two-dimensional flow in the liquid phase. Models based on both local and global conservation laws are presented. The explicit solutions of the governing equations are found and analysed via the asymptotic methods. The assessment of how the boundary-layer flow influences the physical characteristics of the mushy layer is given.

Keywords: solidification, binary alloy, mushy layer, moving substrate, boundary layer

*Speaker

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Solid iron snow in the F-layer

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Abstract

Seismic observations of the Earth's core reveal a complex structure: radial and lateral heterogeneities in seismic anisotropy and attenuation in the solid inner core, but also discrepancies between observed P-wave velocity and homogeneous PREM model in the deep liquid outer core. In this work, we focus on the 200km anomalous layer at the bottom of the outer core that exhibits seismic velocities lower than the PREM model. It has been interpreted as a layer depleted in light elements, whereas the usual model considers that light elements are expelled at the surface of the inner core by freezing of the outer core alloy. Recent models of core formation argued for an early stratified liquid core, and the stratified layers at the top and bottom of the outer core could be a vestige of this primordial stratification. However, freezing of the inner core at the inner core boundary releases light elements that provide buoyancy fluxes that would mix the stratified liquid above with small scale buoyant plumes. We consider here that the freezing of iron alloy and thus releasing of light elements occurs in volume in the liquid and not at the inner core boundary. We consider the dynamics of such a mixture of iron solid particles and iron liquid, and show that this is a stable state for some area of the parameters space. The fall of particles through the stratified layer is destabilizing the layer, while the equilibrium between solid and liquid particles stabilizes the compositional stratified profile. This mechanism is thus a very good candidate to explain the stability of the F-layer, under a vigorously convective outer core.

We developed a theoretical framework to study instabilities in such snow mechanisms, and this work can be extended to study similar processes in either primitive core (for early freezing of oxides) or in other planetary bodies.

Keywords: F, layer, outer core, inner core, cristallization

*Speaker

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Measuring the seismic velocity in the top 15 km of Earth's inner core

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Abstract

The inner core is growing as the Earth cools. The uppermost layer has been formed most recently and is therefore related to current solidification processes. However, little is known about this layer and previous studies have constrained the seismic velocity only at depths greater than 15 km below the inner core boundary. Previously, the inner core has been shown to have a distinct hemispherical structure. The eastern hemisphere is seismically faster, more attenuating and less anisotropic. The reason behind this hemispherical structure is as yet undetermined; it could be the result of different freezing rates in the two hemispheres due to thermochemical coupling with the mantle, or crystallization in the West and melting in the East resulting in the lateral translation of the inner core. By studying the velocity structure at the very top of the inner core, light may be shed on which of these processes is occurring. Differential travel time measurements between the inner core seismic phase PKIKP and inner core boundary phase PKiKP are used to determine inner core velocity structure. PKIKP waves travelling through the upper 15 km of the inner core arrive at a very similar time to PKiKP and the two phases interfere, making it difficult to obtain a differential travel time measurement. We have generated synthetic seismograms to model the overlapping signals of PKIKP and PKiKP. We assign different parts of the waveform to each phase, and compare real and synthetic data to calculate the differential travel time residual. As proof of concept, we have applied this method to data from a single event. Ray paths from this event traverse the inner core in the region where hemispherical boundaries have been observed in lower layers. We have created a velocity model for this region of the inner core, and found a lower velocity for deeper, more easterly ray paths. There are two explanations for this, one of which is a high velocity upper layer in this region. There may also exist a hemisphere boundary similar to those seen at lower depths, but with a different location. These are the first direct observations of the uppermost inner core, and as such open the possibility of further research into the inner core boundary.

Keywords: Seismology, inner core, body waves

*Speaker

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New complex inner core features

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Abstract

The structure of Earth's inner core provides a key to understand its evolution and the generation of the Earth's magnetic field. Numerous studies have shown great complexities of the inner core structure. The anisotropy of the inner core changes laterally and with depth. Strong anisotropy is found for the bulk of the inner core, but the topmost of the inner core is nearly isotropic. The lateral variation of the inner core structure is just as pronounced with hemispherical variation in seismic anisotropy, in isotropic velocity of the topmost inner core, and in attenuation. All the previous inner core anisotropy models have assumed a cylindrical anisotropy with the symmetry axis parallel (or nearly parallel) to the Earth's spin axis. In this presentation, I highlight two new complexities of the inner core we've recently discovered. First, using a new method of noise correlation, which allows us to sample the very center of the earth, we have recently found that the fast axis in the inner part of the inner core is close to the equator (Wang et al., Nature Geosci. 2015), compared with the north-south fast axis in the outer inner core. The equatorial fast axis is near Central America and Southeast Asia. Assuming the age of the inner core of around 1 billion years, the time of the change of the anisotropy axis coincides roughly with the proposed equatorial geomagnetic dipole in Ediacaran (a controversial hypothesis). Second, using a new careful waveform inversion technique, we've found significant higher degree (degrees 2 and 3) structure at the topmost inner core (than the degree 1 hemispherical structure). Both the velocity and attenuation structures correlate well with the long-wave features of the lowermost mantle. The results provide clear evidence for strong mantle and core coupling.

Keywords: inner core, anisotropy, geodynamo, geomagnetism

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Topography of a Solidifying and Melting Inner Core

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Abstract

Lateral variations in the freezing and melting of Earth's inner core can induce variations in the topography of its boundary. Topography of the inner core boundary (ICB) can affect the amplitude, phase, and coda of incident seismic body waves. P waves incident on models of a rough inner core boundary, synthesized by boundary element and pseudospectral methods, are compared with observed waveforms for evidence for these effects at ranges from near vertical to grazing incidence. At near vertical, pre-critical, incidence a plausible upper bound of 1 km for 10-20 km wavelength topography can be established from the amplitude and lack of a strong coda in observed PKiKP 1 Hz waveforms. Assuming topography at this scale is on the order of the compaction scale length of a solidifying inner core, it is consistent with a relatively high inner core viscosity of 10**19 Pa-sec. This small upper bound can still smooth over the minima and zeros of the ICB reflection coefficient predicted by standard Earth models in the 50o to 60o distance range. In the critical-reflection range (108-130 deg), the plausible upper bound does not strongly affect the amplitude and phase of the PKIKP + PKiKP waveform, requiring a mechanism other than ICB topography combined with inner core super rotation to explain strong variations in PKiKP amplitudes observed in the waveforms of some earthquake doublets. In the diffracted distance range (> 152 deg), plausible topography does not affect the travel time or decay with distance of the PKP-Cdiff waveform, leaving its observed behavior to be explained by velocity gradients and intrinsic attenuation in the F region of the lowermost outer core.

Keywords: inner core boundary, seismic body waves, solidification, melting

*Speaker

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Coupled dynamics of Earth's geomagnetic westward drift and inner core super-rotation

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Abstract

The geomagnetic westward drift and the inner core differential rotation relative to the mantle are two remote observables of the Earth's core rotational dynamics. We present here a study of their long-term/time-average behavior in numerical simulations of the geodynamo. The natural link between the two arises when including gravitational coupling between the inner core and the mantle, in addition to electromagnetic coupling at the inner core and core–mantle boundaries in the model.
We show that the global shear available in the fluid shell does not depend on the strength of these couplings, it is thus fully determined by the vigor of convection.
This shear is distributed between the long-term westward drift and the long-term differential rotation of the inner core, in proportions controlled by the relative magnitudes of the electromagnetic and gravitational couplings.
As present-day estimate of this available shear is close to that of the observed westward during the last 400 yrs, the long-term inner core differential rotation must be close to zero. Assuming a lower mantle conductance of order 10ˆ8 S, this in turn sets a constraint on the minimum stiffness of the inner core, the viscosity of which should be larger than 2.10ˆ17 Pa for the westward drift to dominate.

Keywords: dynamo: theories and simulations, outer core, inner core, core–mantle coupling, westward drift, super, rotation

*Speaker

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P-wave reflection coefficients at the inner core boundary beneath the central America observed by USArray

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Abstract

Complex frequency characteristics of the P-wave reflection coefficients at the inner core boundary beneath the eastern Asia observed by Hi-net were reported by Tanaka and Tkalčić (2015). Although the observed pattern of frequency variation is very complex, spectral peaks and holes are frequently detected at frequencies larger and smaller than 2 Hz, respectively. To expand the survey area to the quasi-western hemisphere of the inner core, we examine the data recorded by USArray. Although Li et al. (2014) have already reported PKiKP phases from several earthquakes observed by USArray, our rigorous data selection permits only the Guatemalan event from May 3rd, 2009 as a suitable data set for our analysis so far. Li et al. (2014) concluded that the amplitude ratios of PKiKP/PcP are less affected by a focal mechanism solution. However, the PKiKP/PcP ratios from the Guatemalan events generally show very large values compared to the theoretical ones. We find that the CMT solution can be useful to adjust this anomaly rather than the USGS MT solution. After the division into 4 sub-arrays and thorough corrections for geometrical spreading, Q values in the mantle, the focal mechanism, and the fluctuation in the reflection coefficient at the core-mantle boundary, we find the areas indicating both normal and abnormal reflection coefficients at the inner core boundary. The normal means that the reflection coefficients are close to a theoretical value and almost constant as a function of frequency. In the "abnorma" area, we find a spectral peak and hole at frequencies less and greater than 2 Hz, which is an opposite feature to that recorded by Hi-net in the quasi-eastern hemisphere. This observation suggests the existence of a large scale variation in the surface condition of the inner core.

Keywords: ICB, USArray, quasi, western hemisphere

*Speaker

Partial melting of a Pb-Sn mushy layer due to heating from above, and implications for regional melting of Earth's directionally solidified inner core

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Abstract

Superimposed on the radial solidification of Earth's inner core may be hemispherical and/or regional patches of melting at the inner-outer core boundary. Little work has been carried out on partial melting of a dendritic mushy layer due to heating from above. Here we study directional solidification, annealing, and partial melting from above of Pb-rich Sn alloy ingots. We find that partial melting from above results in convection in the mushy layer, with dense, melted Pb sinking and re-solidifying at a lower height, yielding a different density profile than for those ingots that are just directionally solidified, irrespective of annealing. Partial melting from above causes a greater density deeper down and a corresponding steeper density decrease nearer the top. There is also a change in microstructure. These observations may be in accordance with inferences of east-west and perhaps smaller scale variations in seismic properties near the top of the inner core.

Keywords: inner core, solidification, partial melting, seismic attenuation, translation

*Speaker

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Double-diffusive inner core convective translation

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Abstract

The hemispherical asymmetry of the inner core has been interpreted as resulting form a high-viscosity mode of inner core convection, consisting in a translation of the inner core. With melting on one hemisphere and crystallization on the other one, inner core translation would impose a strongly asymmetric buoyancy flux at the bottom of the outer core, with likely strong implications for the dynamics of the outer core and the geodynamo. The main requirement for convective instability in the inner core is an adverse radial density gradient. While older estimates of the inner core thermal conductivity favored a superadiabatic temperature gradient and the existence of thermal convection, the much higher values recently proposed makes thermal convection very unlikely. Compositional convection might be a viable alternative to thermal convection: an unstable compositional gradient may arise in the inner core either because the light elements present in the core are predicted to become increasingly incompatible as the inner core grows (Gubbins *et al.* 2013), or because of a possibly positive feedback of the development of the F-layer on inner core convection. Though the magnitude of the destabilizing effect of the compositional field is predicted to be similar to or smaller than the stabilizing effect of the thermal field, the huge difference between thermal and chemical diffusivities implies that double-diffusive instabilities can still arise even if the net density decreases upward. We propose here a theoretical and numerical study of double diffusive convection in the inner core that demonstrate that a translation mode can indeed exist if the compositional field is destabilizing, even if the temperature profile is subadiabatic, and irrespectively of the relative magnitude of the destabilizing compositional gradient and stabilizing temperature field. The predicted inner core translation rate is similar to the mean inner core growth rate, which is more consistent with constraints from the geomagnetic field morphology and secular variation (Aubert *et al.*, 2013) than the higher translation rate predicted for a thermally driven translation (Alboussière *et al.*, 2010).

Keywords: inner core, double diffusive convection

*Speaker

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Subducted eclogite identified 1800 km beneath South America

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Abstract

Broadband USArray waveforms of the July 21, 2007 MW=6.0 (depth = 633 km) western Brazil earthquake include high-amplitude S-wave to P-wave conversions (*i.e.* S x P) at 1150 km (S1150P), 1500 km (S1500P), and 1800 km (S1800P) depth. These phases are formed within a high-velocity slab due to Nazca Plate subduction into the lower mantle beneath western South America. The S1800P conversion is the clearest signal. It has the same polarity as the S wave and an amplitude that is about 0.24 x the S amplitude on vertical component waveforms. 2D Spectral-element method waveform modeling in a 3D axisymmetric domain demonstrates that S1800P can be explained by a 10-km thick block beneath the event with a shear velocity that is about 1.6% lower and a density that is about 2% higher than the ambient mantle. These properties are consistent with the bulk elastic parameters of eclogite and indicate entrainment and preservation of crustal fragments that have been brought into the lower mantle.

Keywords: body wave, eclogite, subduction, lower mantle

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