A deep dive into the interior structure of Mercury and Mars
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Mercury and Mars, the innermost and outermost terrestrial planets in our Solar System, formed from material originating primarily in the inner part of the system. Despite sharing similar processes during their formation, these two planets exhibit striking differences in structure, composition, and evolution.

Mercury's core is about 2000 km in radius, it is composed predominantly of iron, which accounts for 65% of the planet's mass. Its core likely contains not much more than 10 wt% of light elements. In contrast, Mars has a 300 km smaller core, with over double the amount of light elements. The total iron content of Mars is less than half that of Mercury, with 70% of it residing in Mars's core. This difference in iron fractionation between the mantle and core suggests that Mercury formed under significantly more reducing conditions than Mars did. This difference impacts the nature and concentration of light elements in their cores and affects their present-day structures and thermal states. For instance, Mercury has growing inner core, and it maintains an active dynamo, while Mars very likely lacks an inner core, and its dynamo ceased around 3.7 billion years ago.

Until recently, our understanding of the interior structure of both planets relied primarily on gravity and rotational observations. This knowledge was at least for Mars significantly extended by seismic observations obtained during the InSight mission. I will discuss the most important results deduced from InSight and orbiter observations that have improved our current understanding of Mars' deep interior structure and I will review new questions that have arisen from those findings. Furthermore, I will also discuss new questions related to the interior structure of Mercury that largely follow from data acquired during the MESSENGER mission and recent laboratory results. Specifically, I'll focus on the present-day thermal state and structure of Mercury's core, as well as its relationship to dynamo action and its effect on the planets libration.

Farside Seismic Suite (FSS): A new part of the Moon, and a new way to do lunar seismology

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The Farside Seismic Suite (FSS) will represent some of the first new seismometers on the Moon since the Apollo era. They will return the first ever seismic data from the farside of the Moon when they are landed in Schrödinger Basin aboard a commercial lander provided by Draper Laboratory currently scheduled for 2026. FSS was selected to fly under the PRISM (Payloads and Research Investigations on the Surface of the Moon) program, which NASA introduced to provide scientific payloads for the Commercial Lunar Payload Services (CLPS) program.

FSS consists of two seismometers, both flight-proven on the Mars InSight mission: the vertical Very BroadBand (VBB) seismometer (the most sensitive seismometer ever built), and the Short Period (SP) sensor, the most mature compact triaxial sensor available for space applications. They are packaged together as a self-sufficient, lander-mounted payload that can survive independently, with power, communications and thermal control allowing continuous operation over multiple lunations. Thus FSS will outlive the delivery lander, and provide a long-lived seismic experiment capable of:

1. Investigating deep lunar structure and the difference between near and farside activity.
2. Understanding how the lunar crust is affected by the development of an impact melt basin.
3. Evaluating the current micrometeorite impact rate and local tectonic activity.

FSS is now fully built and tested to demonstrate thermal performance and tolerance to launch vibration. When combined with planned delpoyments by Artemis astronauts, FSS can serve as an important model for long-lived lunar science in the CLPS and Artemis era. FSS serves as a model for a small package with independent power and comms, allowing for placement by commercial landers without requiring large long-lived landers. The development process is also a key test of taking advantage of the different risk posture inherent in using commercial landers while still maximizing science return. With the potential for long-lived seismic stations based on the FSS model, and the expected cadence of CLPS and Artemis landings over the next decade, this approach shows great promise for building a network of seismic stations that can achieve key science goals outlined in the planetary science decadal survey.

The influence of heterogeneous seafloor heat flux on the cooling patterns of Ganymede's and Titan's subsurface oceans

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Abstract

Several icy moons of Jupiter and Saturn are known to possess deep water oceans. Heating in the rocky mantle underneath often produces heterogeneous heat flux patterns at the ocean's seafloor. How this internal ocean dynamically relates the seafloor to the surface ice shell is a crucial question to understand the long term evolution of icy moons. Here we investigate how a heterogeneous seafloor heat flux pattern affects the convection and heat transfer in the subsurface ocean of large icy worlds involving a high pressure ice layer beneath the seafloor such as Titan or Ganymede. We perform rotating convection simulations in a thin 3D spherical shell with a prescribed heterogeneous bottom heat flux inferred from 3D convection simulations of the underlying mantle (Choblet et al., 2017b). In our simulations, although the amplitude of imposed inner boundary heat flux heterogeneity is rather moderate, preferred longitudes of intense outer boundary heat flux are highly correlated with longitudes of intense inner boundary heat flux. In addition, a small imposed inner boundary large-scale order 2 pattern is amplified at the outer boundary heat flux by the convection in the thin shell. Lastly, deviations from axisymmetry and equatorial symmetry in the outer boundary heat flux increase with the main convection vigor and the amplitude of the inner boundary heterogeneity. In our models polar vs. equatorial cooling is mostly controlled by inertial effects, as was found by Amit et al. (2020) for homogeneous boundary conditions, with the latitudinally equilibrated inner boundary heterogeneity acting to reduce the amplitude of this effect. Our results support polar cooling for Titan's sub-surface ocean.

Keywords: Icy moons, Titan, Ganymede, Hydrodynamics, Heat transfer

Electrical resistivity of liquid iron-sulfur alloy and its implications for Martian dynamo

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Mars has no magnetic field today, but probably had an early field generated by a dynamo effect in its metallic fluid core. The primary mechanisms driving core convection are generally thought to be thermal and compositional. Sulfur (S) may be an important light element in the Martian core, which is mainly composed of iron (Fe), and the influence of S on the conductivity of liquid Fe has important implications for the ancient dynamo action and thermal evolution of the Martian core. However, all conductivity measurements of Fe-S alloys made under Martian core pressure conditions were limited to the solid phase, and the effect of melting on Fe-S conductivity was unknown (Hsieh et al., 2024; Suehiro et al., 2017).

We studied the electrical resistivity of liquid Fe-S alloy up to 36 GPa and 3890 K in a laser-heated diamond anvil cell combined with millisecond time-resolved simultaneous measurements of electrical resistivity, X-ray diffraction, and temperature of instantaneously melted Fe-S alloy (see Ohta et al., 2023 for methods). The starting material is Fe_3S synthesized in a multi anvil apparatus. The experiments were conducted at BL10XU, SPring-8. Our results showed that the resistivity of liquid Fe-S shows a strong temperature dependence relative to that of pure Fe, implying enhanced electron-electron scattering. The thermal conductivity is calculated from the obtained electrical resistivity of the liquid Fe-S alloy, and the thermal conductivity and thermal history of the Martian core are discussed.

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OSCILLATORY THERMAL-INERTIAL LAYER FORMATION IN THE MOLECULAR ENVELOPES OF GAS GIANTS

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Abstract

The paradigm system for modeling the turbulent thermal convective flows occuring inside planets is rotating Rayleigh-Bénard convection (RBC). It is theoretically described by the Navier-Stokes equations augmented by the temperature equation, commonly employing the Oberbeck–Boussinesq (OB) approximation. The OB approximation assumes all the material properties to be constant, except for the density that varies linearly with temperature in the buoyancy term. However, in realistic planetary flows, the material properties can vary strongly with pressure and temperature, thus, a more faithful model is to consider non-Oberbeck–Boussinesq (NOB) effects. Yet only little work has been devoted to rotating NOB convection[1], and arguably the biggest gap in in our knowledge is the impact of NOB effects on rotating oscillatory convection which only occurs for Prandtl numbers $\mathrm{Pr} = \nu/\kappa \leq 0.68$[2,3], where ν is the kinematic viscosity and κ the thermal diffusivity. Indeed, κ and Pr can vary by more than an order of magnitude in Jupiter, in such a way that one may expect regions where oscillatory convection is permitted and others where it is forbidden.

I will present results from direct numerical simulations (DNS) of rotating RBC with temperature-dependent and height-dependent material properties that are Jovian-inspired. The DNS are conducted in a cylindrical geometry as a model for the polar region of a gas giant. Different NOB models are considered to capture the fundamental behaviours of co-existing oscillatory and non-oscillatory layers and compared to the OB reference model. Locally Pr varies in the DNS and the fluid changes from being water-like to liquid metal-like, very much as is the case in gas giants. Figure 1 shows the temperature field for the OB and three different NOB cases with temperature-dependent κ, which visualises the formation of distinct layers in the system. I will show the consquences of the different functional dependencies of the material properties on the types of convection focusing in particular on the layer formation due to locally different supercriticalities for the onset of stationary, oscillatory, and wallmode convection when compared to the OB case. I will further discuss how these different flow morphologies may influence the mixing efficiency and, thus, concentration of heavier elements in the outer part of the molecular enevelope of gas giant.

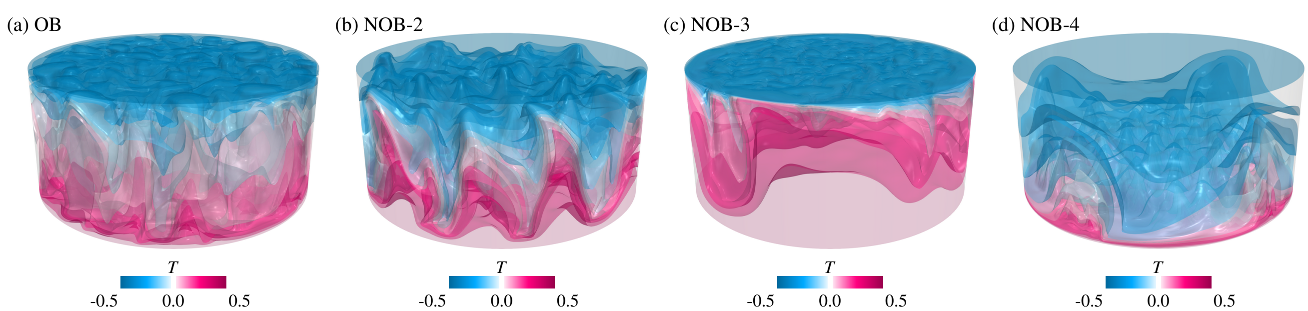

Figure 1: Temperature fields T for (a) OB conditions; (b–d) three different NOB cases with temperature-dependent κ, (b) $\kappa(T)$ is chosen to be symmetric with respect to the mean temperature $T_m = 0$, such that, $\mathrm{Pr}(T_m) = 1$ and $\mathrm{Pr}(T_b) = \mathrm{Pr}(T_t) = 0.025$, i.e. at the top and bottom boundary the fluid is liquid metal like permitting oscillatory convection, the region where convection is only stationary with $\mathrm{Pr} > 0.68$ is sandwiched in between these layers, (c) $\kappa(T)$ is chosen such that the fluid behaves water-like close to the top and liquid metal-like close to the bottom boundary, (d) similar to (c), but top and bottom are reversed.

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Semi-convective planetary cores

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The recent Juno and Cassini space missions delivered a wealth of observations of Jupiter and Saturn. Constraints from gravity data and ring seismology suggest that these planets host a dilute core of substantial size, in which the concentration of heavy material increases with depth. This stabilising compositional gradient coexists with a destabilising thermal gradient induced by the secular cooling of these planets. As thermal anomalies diffuse on time scales much shorter than compositional anomalies, this configuration is prone to fluid instabilities termed semi-convective instabilities. Semi-convection has been studied in the context of oceanography and astrophysics. Results from local models in Cartesian geometry show that semi-convection can take the form of internal gravity waves or layered convection, in which sharp interfaces separate well-mixed regions that can eventually merge. In order to check to which extent these results can be applied to the interior of giant planets, we have conducted a parametric study of semi-convective dynamics in a non-rotating, non-magnetised sphere, using the MagIC code.

We identify three distinct regimes of semi-convection from our catalogue of 69 simulations. In the first regime, close to onset, gravity waves emerge, with a large-scale azimuthal structure near the centre of sphere, and finer-scale structure near the surface (Fig. 1a). The fluid remains stably stratified, and the transport of composition and temperature across the domain is weak. Triadic interactions between small-scale, unstable gravity modes and large-scale, stable gravity modes explain the overall stability of this regime.

The second regime is reached upon further increase of the thermal driving: internal gravity waves initially emerge but a convective core eventually develops at the centre (Fig. 1b). This core grows with time and finally occupies the whole fluid volume, which makes the transport of composition and heat more efficient than in the first regime. Lastly, for the most driven simulations, convective layering occurs (Fig. 1c). In this third regime, the number of layer increases with the level of thermal driving. These layers have a finite lifetime and they ultimately merge to yield a state of global overturning convection.

We discuss the application of our findings to the interior of Jupiter, that could operate either in the second or third regime, based on a tentative extrapolation of our results.

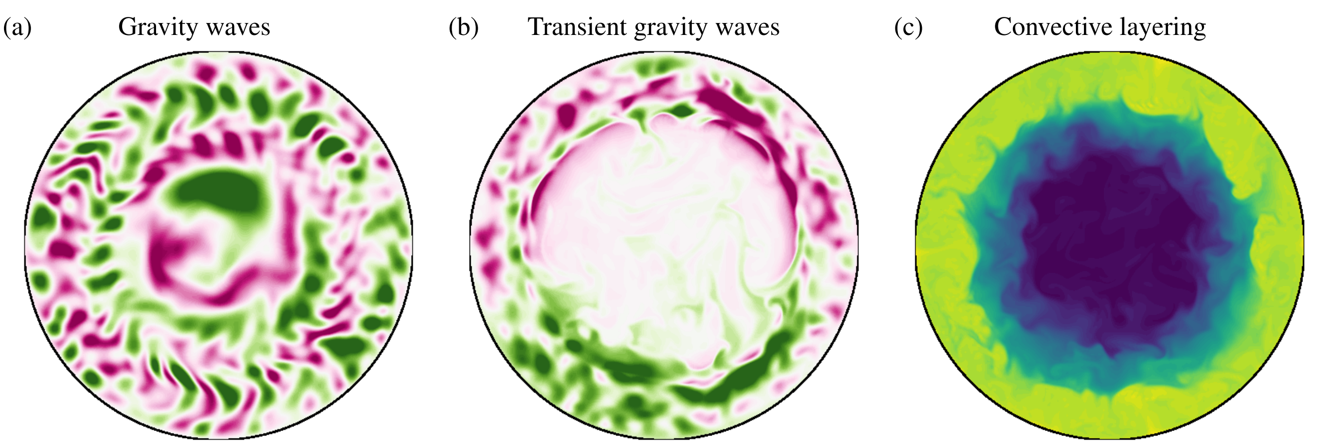

Figure 1: Snapshots of 3 simulations yielding: (a) gravity waves, (b) transient gravity waves, (c) layered convection. Equatorial views (looking down from the North pole) of the fluctuation of composition for Figures 1a and 1b. The fluctuation is defined as the difference between the field and its horizontal average, at any given radius. To better visualise the convective layering, the total composition field is represented in place of its fluctuation in Figure 1c.

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Transitions of thermal convection structures with temperature-dependent viscosity driven by internal heating

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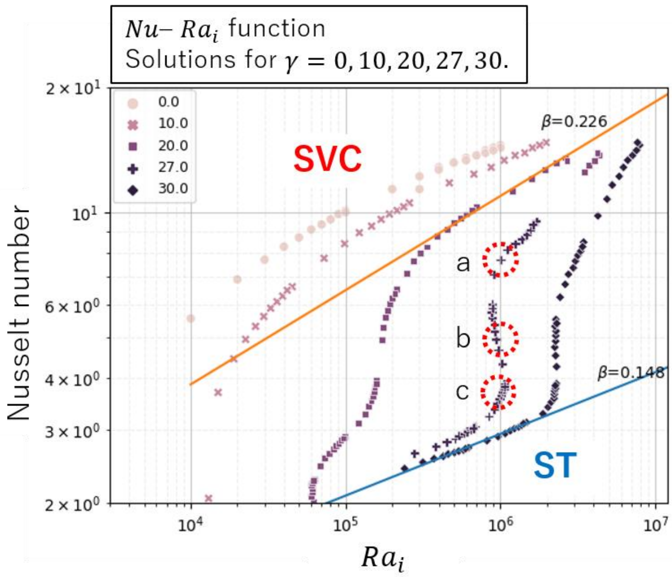
Thermal convection of temperature-dependent viscous fluids has long been investigated to reveal the fundamental characteristics of mantle dynamics in the terrestrial planets. The problem of thermal convection driven by heating from the bottom of the fluid layer is a typical setup to be studied (e.g., Solomatov, 1995; Okuda and Takehiro, 2023). It is also important to study thermal convection driven by internal heating, since, for example, the Earth has a significant heat source within its mantle (Jaupart et al., 2015). Although the cases of almost iso-viscous convection and stagnant-lid convection are well studied (e.g., Davaille and Jaupart, 1993; Grasset and Parmentier, 1998), the intermediate regime between those cases has not been investigated in detail.

This study focuses on the transition from the small viscosity contrast to the stagnant lid convection in internally heated convection. We numerically obtain convective solutions for various values of the Rayleigh number defined by the viscosity at the upper boundary Ra_0 and the strength of temperature-dependence of viscosity γ. We then examine the dependence of the Nusselt number Nu on the Rayleigh number defined by the interior viscosity Ra_i (left figure). The intermediate regime is found as a phase in which the thickness of thermal conductive lid increases with almost constant Ra_i and γ, in spite of decreasing Ra_0 (right figures).



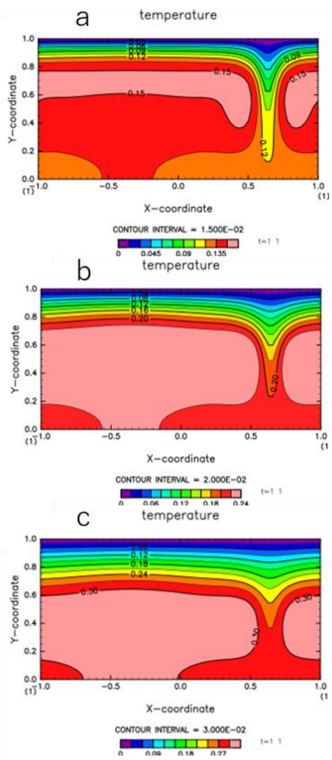


Figure: Nu–Ra_i functions for various values of Ra_0 and γ (left), and convective solutions at red-circled points along an intermediate regime (right).

Geodynamo simulations of internal dynamics and magnetic fields of ice giants

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Uranus and Neptune are the most underexplored planetary bodies of our Solar System , with in-situ observations limited to the Voyagers' fly-bys over three decades ago. This is to be contrasted with the existence of past and present dedicated orbital missions around Jupiter and Saturn.

In contrast with this paucity of observations, a number of studies have attempted at placing constraints on the internal composition, structure and long-term evolution of Uranus and Neptune. In particular, various internal structure models have been proposed to explain the difference in luminosity between the two ice giants and their markedly non-dipolar magnetic fields. Interior structures and compositions vary significantly among these models.

The internal state of a planet shapes its convective dynamics, including the dynamo processes that generate planetary magnetic fields. For example, some scenarios proposed to explain Uranus low luminosity, invoke stable stratification that would hinder convective dynamics in some regions of the planet's interior. It is therefore of great interest to explore how the choice of internal structure and composition, influences the internal dynamics of the ice giants. One way of achieving this is by making use of numerical dynamo simulations, which are widely used to characterise the internal dynamics, magnetic fields and surface winds of Jupiter and Saturn. However, a limited number of studies is dedicated to the study of the convective dynamics and dynamo mechanism of ice giants. Therefore, very few internal structure models have been tested in a dynamical framework.

In this study we present first results from a numerical study targeted at exploring the effect that different internal structure models have on the generation of magnetic fields, on the surface winds and on the luminosity of Uranus and Neptune. We performed highly turbulent numerical simulations with the MagIC numerical code. Preliminary results indicate that the dynamo processes and radial variations in the electrical conductivity have a limited effect on the dynamical state determined by the internal convective processes. Ongoing and future work involves estimating the effect of density, composition and entropy background profiles, including the effect of internal stratification. Based on previous studies, these are expected to have an important impact on the resulting dynamical state, but the exact influence on the highly turbulent regimes we are focussed on, is currently unclear.

The suite of numerical simulations computed in the course of our investigation will be helpful in establishing a reference for the interpretation of the result of future satellite missions to the ice giants.

Lava Planet Interior Dynamic

Governs the Composition of its Magma Ocean and Atmosphere

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Lava planets are rocky exoplanets that orbit so close to their host star that their day-side is hot enough to melt silicate rock. Their short orbital periods ensure that lava planets are tidally locked into synchronous rotation, with permanent day and night hemispheres. Such asymmetric magma oceans have no analogs in the Solar System and will exhibit novel fluid dynamics. Here we report numerical simulations of lava planet interiors showing that solid-liquid fractionation in the planetary interior has a major impact on the compositional structure and evolution of the planet.

We explored two styles of dynamics that depend primarily on the interior thermal state : 1) a hot fully molten interior, and 2) a mostly solid interior with a shallow day-side magma ocean. In the hot interior scenario, the atmosphere reflects the planet's bulk silicate composition and the night-side crust is gravitationally unstable and constantly replenished. In the cool interior scenario, the distilled atmosphere will lack Na, K and FeO, and the night-side mantle is entirely solid, with a cold surface.

These two end-member cases can be distinguished with observations from the James Webb Space Telescope, offering an avenue to probe the diversity of terrestrial exoplanet evolutions

Secular Variation on Jupiter and Stochastic Modelling of its Magnetosphere

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From the earliest interplanetary missions investigating magnetism, comparisons with features of Earth's magnetic field have been of the utmost interest. In particular, the ability of a planetary field to change with time has only ever been conclusively observed on Earth and its detection on other bodies would be vital for the understanding of planetary dynamos. With the Juno spacecraft in orbit about Jupiter since 2016, a continuous time series of magnetic measurements now exists over an extended period. This provides a suitable foundation by which to study any potential secular variation and determine its validity.

Some of the first indications of secular variation have been attributed to the advection of Jupiter's magnetic field by flow in the form of zonal winds [1]. This was first postulated with respect to variations between the measurements of Juno and earlier satellites such as Pioneers 10 and 11 and Voyager 2 [2]. Subsequent work has been carried out using select data from the Juno spacecraft, that has proposed these observations can account for differential rotation in the planet's deep interior and a time varying zonal flow (the latter suggesting the detection of Alfvén waves as a means of describing the behaviour) [3, 4].

Although such deductions lend credence to the detection of secular variation, they must be subject to continued analysis. This is tackled through the investigation of the null hypothesis, in which Jupiter's field is taken to be static and subsequently analysed to see if its behaviour can be adequately described. Such models are constructed through regularised inversion and then subject to residual analysis. Through these means, we find conclusions relating to earlier spacecraft difficult to unambiguously determine.

In addition to this, the effect of the magnetosphere of Jupiter on satellite measurements is not concretely understood. A problem with this lies in the potential for unmodelled phenomena to influence subsequent internal field models. The majority of models take the external field to be uniform with its source in the magnetodisc − this describes a ring current, tilted with respect to Jupiter's equatorial plane. The effect of this is the production of a uniform field adequately described by an order $l = 1$ spherical harmonic expansion [5, 6]. To supplement this uniform field, a stochastic treatment is considered in which averaging over randomly oriented currents contributes to large scale correlations. The resulting model describes a uniform magnetodisc as well as the remaining non-uniform currents distributed about Jupiter. Such a treatment is yet to be applied to the case of a planetary magnetosphere but has shown its power in the treatment of seamounts and crustal magnetisation on Earth [7–9].

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Dissipation in rapidly rotating spheres caused by weak libration

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Planetary bodies are subject to gravitational torques from their orbital companions. These torques can cause variations of the rotation rate of the planet, which is known as forced longitudinal libration. Several studies have examined the flow driven in an internal planetary fluid layer coupled topographically or viscously to a librating outer shell. However, little attention has been paid directly to the viscous dissipation of energy in these flows. Here we consider laminar flows driven by weak libration where the influence of topographical coupling due to the equatorial ellipticity of the container is negligible. When the frequency of the libration is within the range $(0, 2\Omega_0)$, where Ω_0 is the average planetary angular velocity, the viscous coupling can resonate with the inviscid inertial modes of the fluid layer even at small, planetary scale viscosity. We examine the special case of a full sphere fluid layer with no inner core, constructing numerical and analytical solutions for the oscillating linear response of an incompressible rotating fluid sphere forced by weak longitudinal libration at its surface. We use an asymptotic expansion exploiting the small Ekman number, E that quantifies the strength of viscous forces relative to the Coriolis acceleration. In the planetary regime dissipation is dominated by the contribution of the thin Ekman layer that forms near the surface of the sphere. We show that when the libration forcing resonates with an inertial mode the structure of the boundary layer is modified such that dissipation is reduced by as much as 10% compared to a computation that neglects the interior inertial mode flow. The percentage reduction in dissipation is independent of viscosity and therefore this effect does not modify the leading order asymptotic scaling of the dissipation with E. The frequency width of the reduction window around a given inertial mode eigen-frequency scales as $E^{1/2}$.

Iron snow in planetary cores: Laboratory and numerical models

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The space mission Galileo revealed that Ganymede has its own intrinsic magnetic field. One of the prevailing theories explaining this intrinsic magnetic field is that the flow within the Ganymede's liquid core is driven by crystallisation occurring in the vicinity of the core-mantle boundary. Since the liquid core is assumed to be composed of iron and some lighter elements like sulphur, when a pure iron flake is formed, it sediments towards the centre of the planet due to its relatively higher density with respect to the ambient fluid. As the temperature within the core increases with depth, the iron crystals melt as they descend deeper. Since molten iron is denser than the surrounding fluid, it generates compositional convection. The coupled effect of the flow driven by the sedimentation process and compositional convection establishes a dynamo within the moon, generating the magnetic field.
Previous numerical studies ([1], [2]) have considered an homogeneous and continuous snow of monodisperse crystals melting at a single depth, consequently creating an homogeneous and stationary source of compositional buoyancy. The physical phenomenons of iron snow such as crystallisation, sedimentation and melting were not modelled directly . In order to produce a more detailed model of the iron snow, we are running an analog experiment of snow in the laboratory. Our work expands beyond the experimental and numerical investigations of the sedimentation conducted by Kriaa *et al.* [3] by focusing on the phase change process of crystallisation, which has heretofore been far less studied. We examine the crystallisation process through an experiment where we investigates the crystallisation of water in a tank heated from the top and cooled from the bottom, which is an upside-down model of what happens in the planet's core. These experiments are leading us towards a more robust and complex parameterization of the physics by allowing us to consider undercooling, polydispersity, intermittence, and non-uniformity (see also [4]).
In parallel, we develop a theoretical snow model based on the salt solidification experiment in which we consider a monodisperse field of particles, inspired from Ezraty *et al.* [5] and Vallis *et al.* [6]. Source and sink terms in the transport equations of the salt concentration (solid and solute) are added to model the crystallisation and the melting. We also consider the influence of the latent heat produced by the phase change on the temperature field and the sedimentation velocity of the solid particles.
Our model, first benchmarked and validated with our experimental results, will then be integrated in planetary dynamo models to investigate the possibility of iron snow dynamo in Ganymede and in other small bodies.

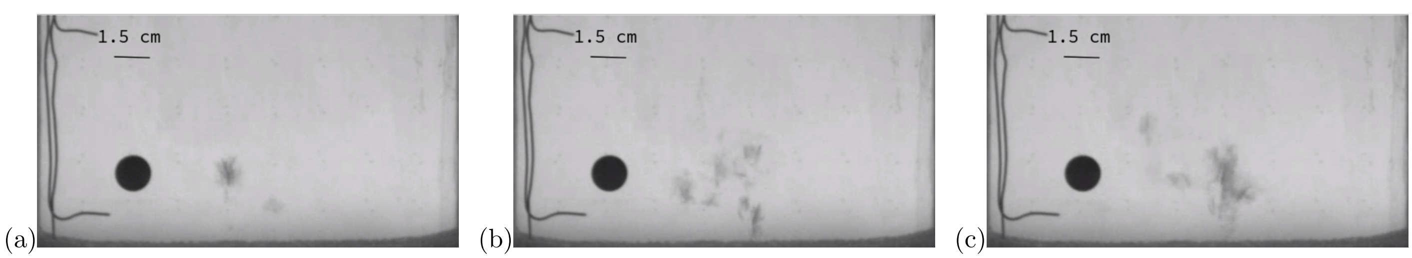

Figure 1: Pictures of the snow experiments, we can observe non homogeneous, intermittent and polydisperse crystals.

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Scaling of internally heated compressible convection

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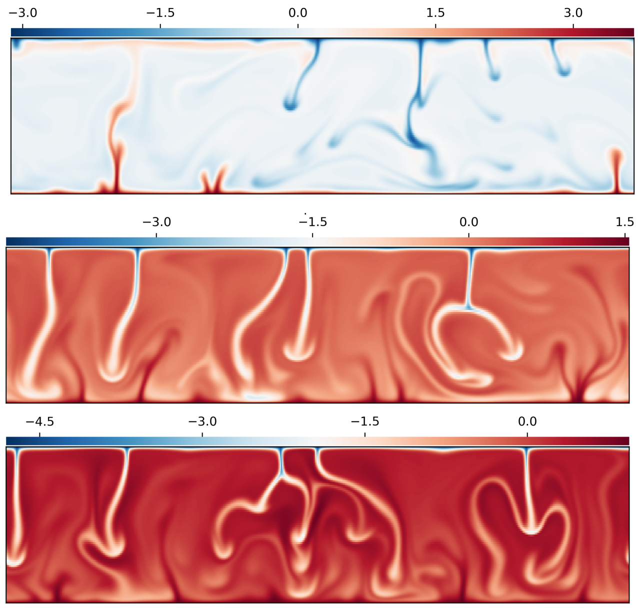
The thermal evolution of terrestrial planets is paced by the efficiency of convective heat transfer in their rocky mantle. Two types of heat source produce buoyancy in such layers, the temperature difference between the surface and the hot core and the radiogenic heating source that is distributed in the bulk. The scaling of such mixed heating convection is rather well established for incompressible fluids in the Boussinesq approximation and we extend this scaling to the case of fully compressible fluids (i.e. without using an anelastic approximation), using the Murnaghan equation of state developed by Ricard et al. (2022). The convection equations are solved in 2D using Dedalus (Burns et al., 2020). The system is controlled by 6 dimensionless numbers but we fix 3 of them to typical planetary values and explore the parameter space formed by $Ra, \mathcal{H}$ and $\mathcal{D}$, the Rayleigh number, dimensionless internal heating rate and dissipation number, respectively. We consider two alternative setups, a nearly purely internally heated situation, with a zero super-isentropic heat flux imposed at the bottom, and a mixed heating situation with an imposed temperature at the bottom. For each choice of input parameters, an isentropic fit is computed for the average profiles in the bulk, which allows us to define super-isentropic quantities, temperature, Nusselt number, Rayleigh number and internal heating rate. Using these quantities, we find that we can obtain scaling laws analogous to those already known in the Boussinesq approximation (Sotin and Labrosse, 1999).



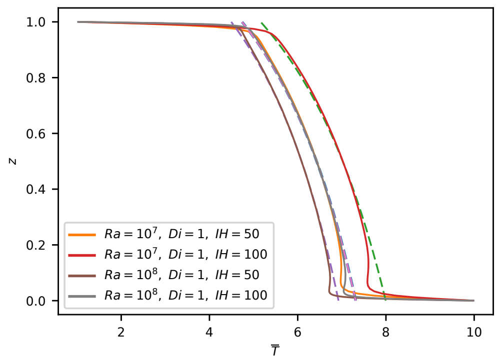


Figure 1: Snapshots of super-isentropic temperature for $Ra_{si} = 10^7$, $\mathcal{D} = 1$ and $\mathcal{H} = 0, 150, 200$ (left) and various mean temperature profiles and isentropic fits (right).

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Where Did the Martian Ocean Go?
Clues from InSight Seismic Studies

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Abstract

Ancient shorelines and fluvial features argue that Mars possessed an ocean during much of its early history. The two reconstructed stages for this ocean, the Arabia Ocean (~4 Ga) and the Deuteronilus Ocean (~3.6 Ga) suggest a ~70% loss of surface water during an intervening period of Tharsis plume volcanism. We hypothesize that Mars surface water returned to the planetary interior to metasomatize its shallow mantle as a byproduct of Tharsis volcanism, similar to metasomatic underplating of many mid-ocean hotspot islands on Earth. The oceanic Moho beneath many Earth hotspot volcanoes is underlain by a ~10-km "underplated" layer with Vp between gabbroic and peridotite values. These sub-Moho layers exhibit strong anisotropy, consistent with serpentinization from a 1-km column of seawater that infiltrated down thermal cracks to react with olivine-rich mantle rock. For a similar thickness of altered Martian mantle, the estimated volume of the Arabia Ocean could be sequestered in an area roughly 1/3 that of the Martian surface. Less area would be required if the serpentinization is more complete or the layer is thicker. Evidence for this hypothesis includes (1) two or three "crustal" layers inferred from InSight receiver-functions, on a planet that has not likely experienced extensive tectonic reworking, (2) strong anisotropy in the shallow layers of Mars, and (3) the position of Tharsis astride the inferred shoreline of the Arabia Ocean, ensuring that much of its plume volcanism would have erupted at a seafloor.

Keywords: Mars, Deuteronilus Ocean, InSight, receiver function, serpentinization, Tharsis Rise

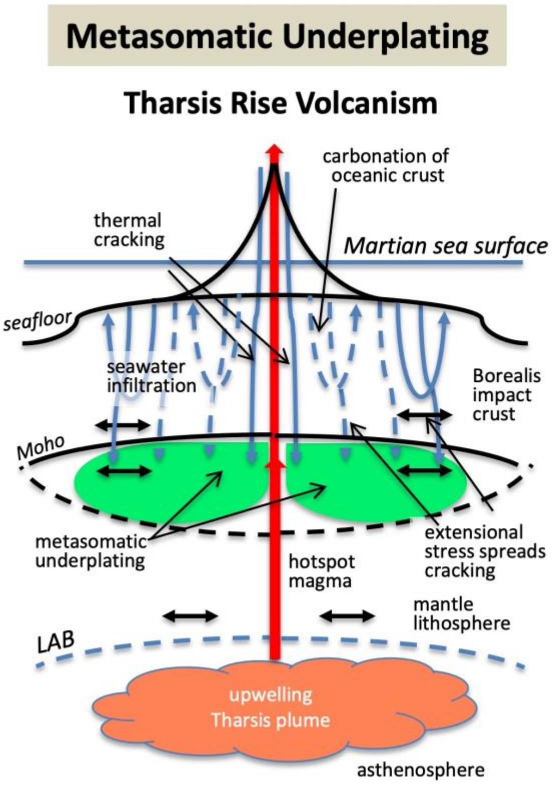

Figure Caption. Cartoon schematic of metasomatic underplating. In the model, once hydrothermal flow is established, the volume expansion associated with olivine-serpentine hydration will fracture a growing volume of peridotite mantle. More olivine lies within mantle rock than crustal rock, so the expansion of the mantle will exert extensional stresses within the crust above it. Together with horizontal extension associated with plume uplift, these stresses induce further cracking of the oceanic crust, allowing seawater access to the sub-Moho mantle away from the plume conduit.

Dynamos of Uranus and Neptune: Roles of density stratification and varied amplitudes of convective driving

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The magnetic fields of Uranus and Neptune are distinctive across the solar system, where the dipole component is comparable to or smaller than the quadrupole and octupole components (even when evaluated at the planetary surface) and is significantly tilted away from the rotation axis. These magnetic fields are thought to result from convective dynamo action in their interiors. Here, we carry out a suite of numerical dynamo models with a background density profile that includes both the deep interior and the atmosphere to self-consistently capture the dynamical coupling between these regions. Three amplitudes of convective driving are also considered, motivated by the large energy balance differences between Uranus (lowest ratio of emitted thermal to absorbed solar energies among the giant planets) and Neptune (which has the highest ratio). All models produce multipolar magnetic fields and are so far challenged to produce the prominent m=1 (equatorial) mode measured during the Voyager 2 flybys. Ongoing work is exploring the additional role of electrical conductivity variations with radius to determine under what conditions ice giant-like magnetic fields can be obtained.

Modelling the magnetic fields of Uranus and Neptune

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The ice giants Uranus and Neptune are the only planets in the solar system with an unusual magnetic field morphology that deviates significantly from a dipole-dominated field observed on all other planets. Uranus and Neptune's magnetic fields were measured only once during the Voyager II flybys in 1986 and 1989. We analyse to which extend these measurements enable accurate determination of the magnetic fields. In particular we analyse to which extend a classical regularized least-square inversion constrains individual Gauss coefficients and other global field properties. In the next step we simulate and analyse various multipolar-dominated magnetic fields using MagIC. We then evaluate how effectively the measurements along the Voyager II track allow to determine the simulated magnetic fields using a statistical analysis. Finally, we quantify the similarity to Uranus and Neptune's field models by comparing the well determined Gauss coefficients. The regularisation already significantly starts to quench the amplitude of coefficients of degree three for Uranus and degree four for Neptune's field models. While the degree one contributions can be determined with high confidence, the error for degree two is already around 30% and for degree three more than 50%. For degree four and higher, the error exceeds 100%. Comparing global measures like the equatorial symmetry of the models to Uranus and Neptune's field models is not promising due to the high time variability of the simulated fields. Using the same inversion for the original data and the simulations, we would expect a similar decrease in the spectrum with spherical degree for a Uranus- or Neptune-like dynamo model. However, the decrease is significantly steeper for the original data inversion. We thus conclude that the dynamo models contain too pronounced small scale contributions. Based on this, none of our simulations are ice giant-like.

"Low-temperature friction experiments on ice–salt mixtures: Implications for the strength of ice plate boundaries on Europa"

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Europa, an icy satellite of Jupiter, exhibits evidence of rapid resurfacing over timescales of only 4-9 Kyr, as inferred from topographic observations (Bierhaus et al., 2009). This suggests the presence of active geological processes, such as the subduction of ice plates (e.g., Kattenhorn and Procter, 2014). However, previous studies calculating the force balance of ice plates using the friction coefficient of pure H_2O ice found that the high frictional forces would preclude subduction (Howell and Pappalardo, 2019). This discrepancy necessitates a reevaluation of the frictional strength at Europa's ice plate boundaries (Fig. 1a).

Near-infrared spectroscopic observations indicate the presence of non-ice materials on Europa's surface, such as NaCl and $MgCl_2$ (Ligier et al., 2016; Fig. 1a). These non-ice materials form eutectic mixtures with ice, thereby depressing its melting point. The frictional strength of ice exhibits a marked decrease with increasing temperature, particularly as it approaches the melting point (McCarthy et al., 2017). Consequently, the presence of these non-ice materials potentially reduces the frictional strength at Europa's ice plate boundaries. However, few experimental studies have investigated the effects of non-ice materials on the frictional behavior of ice.

Here, we conducted friction experiments on gouge mixtures of H_2O and $MgCl_2$ with 0, 17, 29.5, and 47 wt% $MgCl_2$ under low-temperature conditions (−40 to −10 °C), under constant normal stresses (2.5 or 5.0 MPa), and a constant shear velocity (3 μm/s) (Fig. 1b). Our experimental results for the eutectic mixtures showed smaller steady-state friction coefficients compared to those of pure ice. These differences in friction coefficients indicate that non-ice materials can significantly reduce the frictional strength along the plate boundaries on Europa. Additionally, the observed stick-slip behavior at low temperatures (<−35 °C) in our experiments suggests the potential for intermittent slip along the shallower parts of the plate boundaries, whereas steady-state sliding is more likely to occur along the deeper parts.

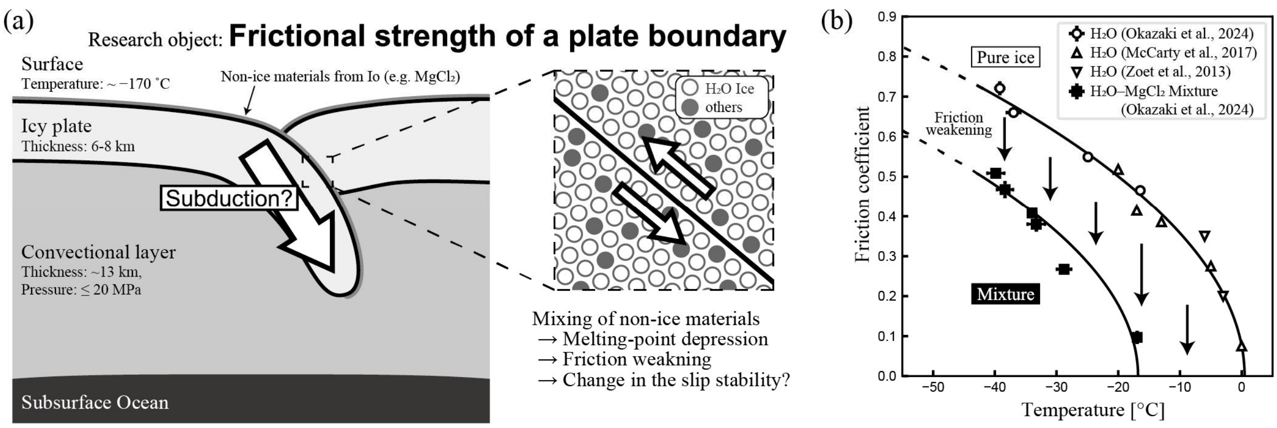

Figure 1: (a) Outer layer of Europa, and (b) decreasing of friction coefficient of ice with mixing $MgCl_2$.

Magnetic Induction in Europa's Ocean

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The Galileo mission discovered a distorted magnetic field around Jupiter's moon Europa that is best explained by induction in a subsurface ocean. NASA's Europa Clipper mission will revisit the moon and measure the field with much higher precision. The data should yield field models with an error of about one nano Tessla (nT). We explore whether this is precise enough for detecting any induction due to zonal flows or the effects of conductivity variations caused by salinity gradients. Our tools comprise analytical solutions, the Matlab code SVzon, and the MHD code MagIC. Unfortunately, we find that both zonal winds and salinity gradients likely have signals well below the expected error level. For example, assuming an electrical conductivity of 10 S/m, flows with peak velocities of about 10 m/s are required to reach the one nT level, which seems excessively fast. We also explore the flows driven by the induction process itself via Lorentz forces. These flows are dominated by geostrophic zonal winds that are reminiscent of the Reynolds-stress driven winds observed in Jupiter's or Saturn's cloud decks. Balancing the Lorentz force with viscous drag indicates that these induction-driven flows in Europa's ocean would remain very slow with velocities below 10^{-5}m/sec. This is orders of magnitude slower than any convective driven flows.

Thermal and magnetic evolution of Mercury with a layered Fe-Si(-S) core

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Abstract

Elucidating the structure and composition of Mercury is important for understanding its interior dynamics and evolution. The planet is characterized by unusual chemical characteristics and a weak magnetic field generated in a large metallic core, and its early evolution was also marked by the presence of a magnetic field, widespread volcanism and global contraction. Here we develop a parameterised model of coupled core-mantle thermal and magnetic evolution considering a layered Fe-Si(-S) core structure with chemical and physical properties of the mantle and the core based on previous laboratory studies. We seek successful solutions that are consistent with observations of Mercury's long-lived dynamo, total global contraction, present-day crustal thickness, and present-day interior structure. Successful solutions have a mantle reference viscosity > 1021 Pa s (corresponding to a present-day bulk mantle viscosity > 2 × 1020 Pa s), a silicon concentration in the core > 13 wt%, a present inner core radius of ~ 1000 − 1200 km and a thermally stable layer ~ 500 − 800 km thick below the core-mantle boundary. Our results show that if present, a molten FeS layer atop the core has minimal effect on Mercury's longterm thermal and magnetic evolution. Predictions from our models can be tested with upcoming Bepi-Colombo observations.