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Specialist Discussion Report: Solid-Liquid Interactions in Deep Planetary Interiors

On 14 October 2022 the RAS Specialist Discussion *Solid-Liquid Interactions in Deep Planetary Interiors* took place as the first in person meeting of its kind at Burlington house following the pandemic. The meeting aimed to bring together experimental, theoretical, and observational studies of the deep mantles and cores of terrestrial bodies, with a particular emphasis on their mutual interactions. Solid-liquid interactions deep in the interiors of terrestrial planets shape their evolution and dynamics, the exchanges of mass and energy between cores and mantles, defines the crystallisation sequence of primordial magma oceans, and the power supplies that might sustain magnetic fields. Recent work has suggested that deep solid-liquid regions may be widespread (e.g. Davies and Greenwood 2023), arising at the top and bottom of Earth's core and in the cores of Mars, Mercury, the Moon, and Ganymede. Non-equilibrium thermodynamic processes have also been identified as important despite often being ignored in models of core-mantle evolution. The meeting was divided into two halves, first focusing on the metallic cores of terrestrial bodies and the second explored processes in silicate mantles and magma oceans.

Our morning session began with an invited talk from Tina Rückriemen (DLR) entitled *Freezing metallic cores: Where do all the solids go?* which gave an excellent introductory walkthrough of the various processes by which planetary cores freeze and the ongoing research in the area. While Earth's liquid core is slowly freezing heavy (compared to the liquid) material from the bottom upwards, core freezing in small planetary bodies such as Mars, Mercury, Ganymede, the Moon, and planetesimals might proceed very differently. The direction of freezing depends on the relative gradients of temperature profile and melting temperature in a planets core. Because of a significant pressure dependence of both quantities, larger planets such as Earth freeze from the inside out whilst the metal cores of small bodies likely solidify from the top to the bottom. Different top-down freezing scenarios can be envisioned depending on the type of solid material and its density compared to that of the liquid. If the solid forming is heavier than the surrounding liquid, it may evolve as free crystals and "snows" which fall into the deeper, entirely liquid core (Rückriemen et al. 2015). If the solid is lighter it may create a compact, floating solid layer directly below the core mantle boundary. For example, at low pressure, sulphur partitions strongly to the liquid iron meaning that solid iron is relatively pure when it freezes. This means that as these dense solids sink into the core, they heat up and remelt, creating a dense iron-rich liquid which can drive compositional convection. Ganymede, Mars, the Moon, and Mercury all offer unique geodynamo outputs which can each be explained by a snow zone, showing that these processes are powerful and potentially widespread features in planetary evolution.

Ludo Huguet (CNRS) then presented *A laboratory model for iron snow in planetary cores*, our first experimental talk, where a chilled tank of salt-water forms ice crystals as an inverted analogue for iron snow in planetary cores. Whilst we can learn a great deal from the 1D thermal evolution of planets, this does not allow us to glean details of the dynamics of the processes which are providing convective power. Particularly, we do not yet understand how iron snows come about in planetary cores, much less how they generate flow on the small scale. To answer these questions we can turn to analogous experiments (e.g. Bergman et al. 2005), in this case the freezing of salt water. For iron the solid is always dense compared to the liquid, however, for water ice the opposite is true. For this reason, Ludo's experiments are inverted, with a chilled interface at the base of a tank, producing crystals which detach and float up into the liquid and remelt. The experiments take several days to run and require a fine control of temperature to balance the supercooling (12 C below freezing point) needed to overcome the nucleation barrier (Huguet et al. 2018) and form crystals against freezing the entire system. Perhaps most surprising, and important for planetary processes, is the episodic nature of freezing events where a period of intense nucleation and high solid fraction near the base of the tank is followed by relatively low activity. This is due to crystals forming and releasing latent heat on one part of the experiment before floating up and remelting in a different area.

Andrew Walker (University of Oxford) followed next with *A non-equilibrium model of slurries in planetary cores*. This talk addresses iron slurries close to the growing inner core of Earth and how we can learn from a theoretical model outside of thermodynamic equilibrium. Slurry zones are domains in planetary cores with modest fractions of solids crystalising from stably stratified liquid. In the Earth, the F-layer (a region at the lowermost outer core, characterised by a reduction in compressional wave velocity) has been suggested to be a slurry layer (Wong et al. 2021). Here, the growth of a particles in the F-layer is examined, without the requirement that they are in equilibrium. An Fe-FeO system is considered, with a thermodynamic model defining melting temperature, solid fraction and growth of particles, classical nucleation theory defines the formation of new solids and fluid dynamics informs the sinking of particles and the boundary layer with which they interact. Falling time and particle size are calculated, revealing that the dynamics of the system are most strongly controlled by the viscosity of the liquid and the diffusion rate of O (which slows particle growth with increasing composition). Using the solution from individual particles in a multi-particle case, falling velocity and nucleation rate define the vertical separation of particles. Continued development of this model will provide a description of conditions which can support slurry layers and the thermo-chemical effects that they might have on the evolving core.

Kathryn Dodds (University of Cambridge) presented her talk Inwards core crystallization: *Insights from analogue experiments*, which was the next of our experimental analogue studies focusing on iron snow. Kathryn investigates how fluid flow from sinking crystals might drive convection in small planets. Studies of snow zones in planetary cores have shown how snows can provide power to geodynamo action (Davies and Pommier 2018); however this does not translate efficiently to smaller bodies where pressure gradients are low. In these cases, inward crystallisation is expected, however as crystals fall, they may not re-melt until deep in the liquid core, if at all, greatly reducing potential for compositional convection. This presents a conundrum for asteroids derived from small planetesimals which have palaeomagnetic records suggestion strong magnetic fields (Dodds et al. 2021). So how else can snow zones generate convection in small cores? Kathryn performs experiments of super-eutectic NH_4Cl liquids, cooled (by a chill plate at the top of the experiment tank) to the point where they will spontaneously nucleate ammonium chloride crystals, which then sink into the remaining liquid and form a cumulate at the base of the tank. When a snow regime is entered, crystals form and entrain liquid as they sink, developing downwelling plumes. A test where crystals are not formed, but thermal convection remains, confirms that the crystals are driving greater flow velocities. In an asteroid or small planet, it is therefore reasonable that crystals might form in a layer at the top of the liquid core before detaching as plumes which help drive convection. An evaluation of the magnetic Reynolds number suggests that cores greater than 70 km in radius might be able to generate a magnetic field via this process.

Quentin Kriaa (IRPHE) issued our final experimental talk of the morning; *Compositional convection from iron snow: laboratory modelling with dissolving sugar*. Here, he also studies the overall fluid flow in the presence of dense sinking crystals but does so exclusively with compositional convection. Thus far, we have considered either that falling snow melts and then drives compositional convection through dense liquids, or that sinking crystals can entrain flow and drive convection in doing so without remelting. There is, of course, an important region between these extremes, where some of the crystals have remelted and are now sinking as dense liquids, and others (particularly large ones) continue to sink as solids (Kriaa et al. 2022). This talk uses experiments to explore the influence of this regime and the effect on the dynamics of downwelling plumes. Dyed sugar crystals are dropped through a sieve into a laser illuminated tank of water with neutrally buoyant tracer makers (see figure 1), because they do not dissolve instantaneously, if a constant mass flux into the experiment is maintained, a steady state region is established where solids are sinking through the water column. As the downward flux of sugar begins, Rayleigh-Taylor instabilities organise the flow of particles into a single plume. Despite the difference in geometry and forces for a planetary core, one would expect the development of downward plumes which periodically exhaust the supply of new crystals at the top of the liquid core and are perhaps more efficient at driving convection than the dense liquids typically considered.

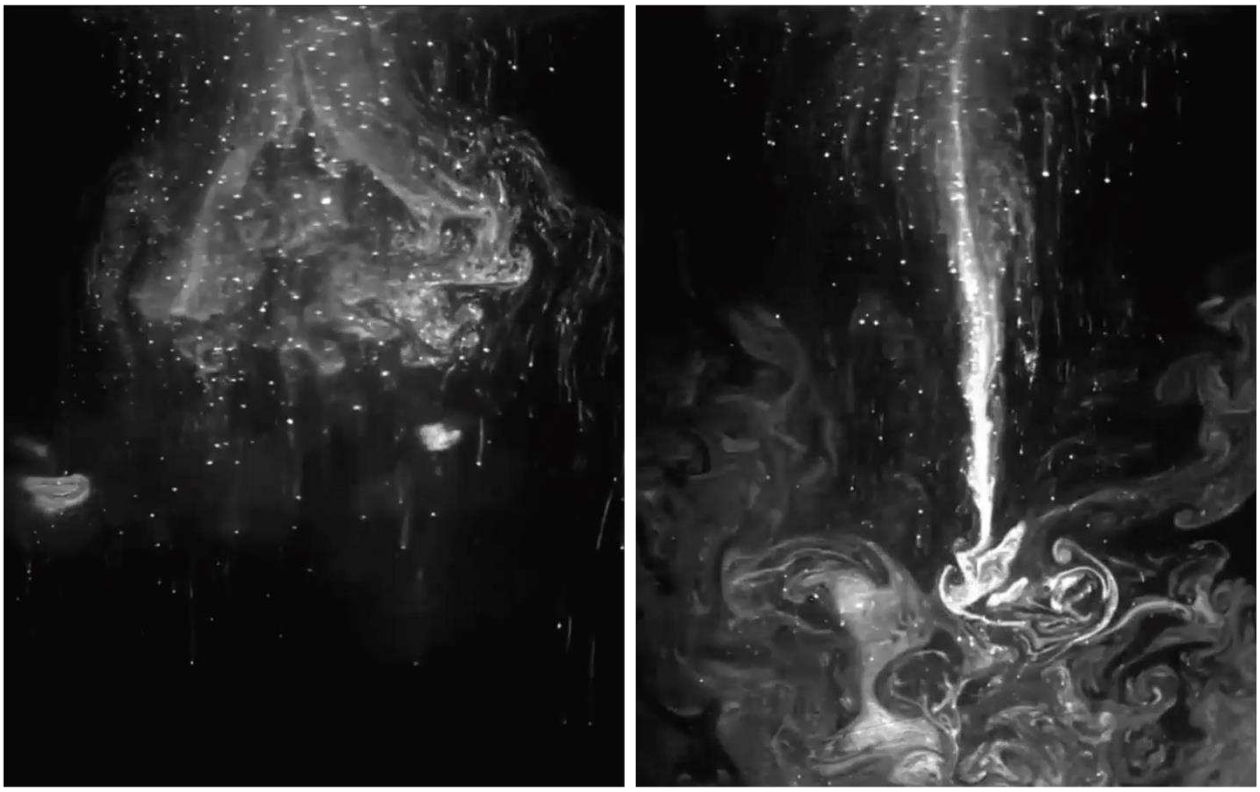

Figure 1:Image credit Quentin Kriaa. Left: Sugar crystals (with rhodamine tracer) are dropped into water and dissolve to create a dense liquid. Right: the dissolving sugar creates a coherent dense plume which exceeds the falling velocity of the remaining crystals in isolation. The particle size of the sugar defines the dynamics of suspension and entrainment in the system.

Our morning core session was concluded by Jac van Driel (UCL), presenting *Composition of the Martian Core*. Jac uses a new class of multi-component equation of state, powered by density functional theory calculations, to decipher recent InSight data of the Martian interior. All talks in the morning session have highlighted the important role that composition plays in defining the dynamic processes which are at play in planetary cores, despite this even for Earth's core, composition is poorly constrained. Data from the now retired NASA InSight mission has found that the Martian core is both larger than previously thought and perhaps entirely molten (Stähler et al. 2021). Furthermore, inversion of the new findings gives estimates of the core density and seismic properties, allowing this study to estimate composition. Mars is smaller than Earth, meaning the pressures of its core are significantly lower and largely below the spin transition of iron. This means that whilst calculation of the Earth's core properties can negate the influence of spin states and magnetic entropy, it is imperative that these are considered for Mars. This study employs density functional theory calculations to calculate the free energy difference between different spin states of the materials being investigated. Once the thermodynamically favoured states are found, properties of individual compositions can be calculated and confirmed against experiment. A gaussian regression approach allows the construction of self-consistent equations of state which can estimate the properties of untested compositions. The model finds that a core with 15 wt% S, 3.6 wt% O and 1 wt% H is most compatible with the inverted data.

The afternoon session of talks on mantle and magma ocean processes began with an invited talk from Charles-Édouard Boukaré (IPGP) titled *Beyond 1D magma ocean models*. Charles-Édouard studies multiphase flow processes to understand how the Earth's early magma ocean evolved into the present day mantle. The magma ocean is a widely accepted early state of Earth's silicate mantle, thought to arise from a giant impact, perhaps that which formed the moon (Nakajima and Stevenson 2015). At high pressures, a non-linearity in the melting temperature of mantle silicates means that it is possible for the magma ocean to freeze from the middle outwards, potentially separating surface, and basal magma oceans (Labrosse et al. 2007). The dynamics of this process are not well understood as models will typically study only the 1D evolution of the liquid regime, or the 2D evolution of the solid regime, neither capturing this crucial time where both phases are present. Charles-Édouard uses multiphase physics to model 2D systems where convection is driven by thermal and chemical density contrasts as well as allowing crystals can grow and remelt (figure 2). The latter effect also introduces latent heat and chemical fractionation. The main finding is that the melt mobility in these models has a strong effect on the final state of the mantle. When melt mobility is low, the system remains well mixed which crystals and liquids entrained in the same flows. When mobility is high, liquids can be expelled from slurry layers and more strongly fractionate the magma ocean. At an extreme, this produces mantle stratification too strong to be mixed by convection and structures which are incompatible with seismic observation of the deep Earth. In an intermediate case, a basal magma ocean is generated via fractionation, without the need for a mid-depth crystal barrier, and features similar to those observed atop the present day core mantle boundary can be preserved. In the future, constraints from geochemical tracers will be included to elucidate a range of plausible melt mobilities.

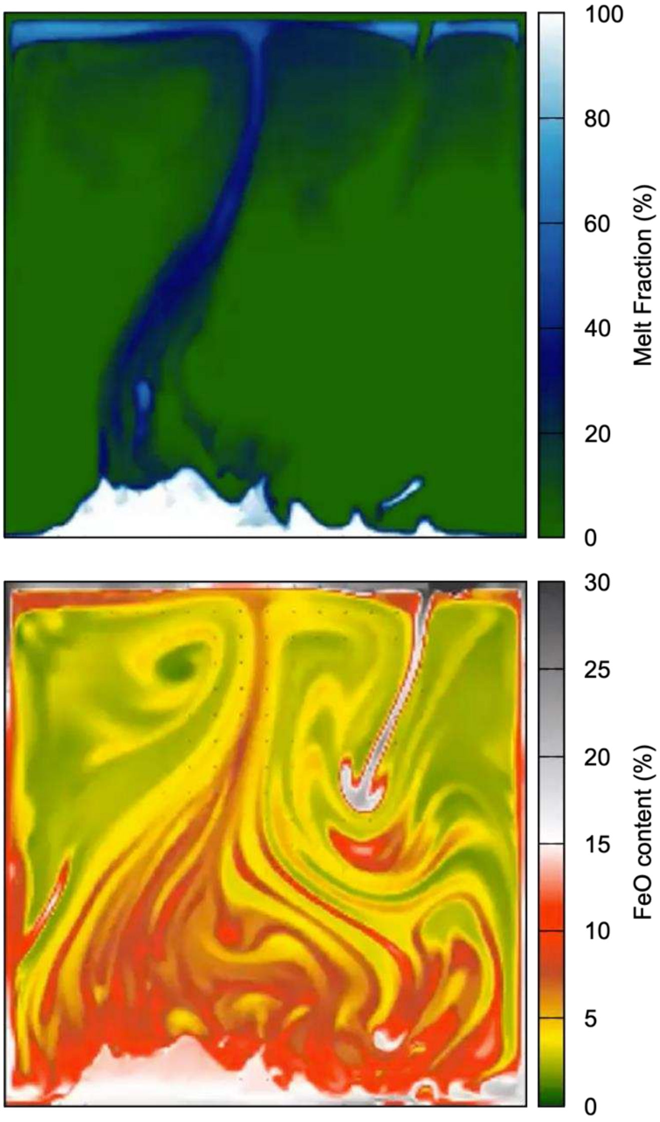

Figure 2: Image credit Charles-Édouard Boukaré. A multiphase 2D convection model of Earth's mantle which includes both thermal and chemical convection alongside phase changes. The long term stability and growth of solid lower-mantle features depends primarily on the melt mobility of the system, which controls how a dense cumulate can expel trapped liquids. Features which share characteristics with seismically observed lower mantle features can be produced and destroyed by tuning this melt mobility.

Maxim Ballmer (UCL) followed with a complimentary talk: *Reactive Crystallization of the Basal Magma Ocean: Consequences for present-day mantle structure*. The previous talk highlighted the importance of the evolving structure of the magma ocean on the subsequent features of the mantle. However, the evolution of the late stages of the magma ocean, where a basal magma ocean is present, can be challenging to reconcile with the present day structure and dynamics of the mantle. It has been suggested that stable features at the base of the mantle are derived from the fractional crystallisation of the basal magma ocean which enriches liquids, and therefore late stage solids, in iron (Labrosse et al. 2007). The issue is that when this is modelled, the effect is too great. Thick layers with extremely high densities are formed and would surely be observed today, which they are not. This work studies the ongoing interactions between the basal magma ocean and overlying young mantle. These interactions both promote freezing, through reactive crystallisation, and also reduce the density of the solids destined to be at the base of the modern mantle. If subducted from the planet's surface early crustal material is also able to interact with the basal magma ocean and a range of mantle features become possible. Lower mantle features become more reasonably dense and neutrally buoyant mid mantle structures (Ballmer et al. 2017) can be generated. If reactive crystallisation is a necessary part of Earth's thermochemical evolution, it could also explain properties of other planets. Venus has had large scale resurfacing events, which might have exhausted its magma ocean, whilst the stagnant lid regime of the Martian crust might suggest a basal magma ocean is extant and very dense.

Helen Williams (University of Cambridge) then offered a logical progression from the previous two talks with *Iron isotopes trace primordial magma ocean material in the Earth's upper mantle*. She asks if the preserved isotopic signatures of the rock record can describe the differentiation of the Earth's mantle.

The possibility of geochemical tracers for tracking differentiation of the magma ocean and mantle is an exciting prospect. Stable isotopes are often fractionated by processes in nature including in the deep Earth. Mantle plumes which reach the Earth's surface as hot spots deliver material from as deep as the core and give a glimpse into the deep interior as well as the past. Unfortunately, modern samples feature many signals which are challenging to untangle and so it is helpful to focus on ancient rocks when studying the differentiation of the Early mantle. The 3.5+ billion year old rocks of Canada and Greenland feature a variety of isotopic anomalies, one of which is elevated \$\mu\$^{182}W and \$\delta\$^{57}Fe (Williams et al. 2021). This signature indicates that the residual melts of a cooling magma ocean equilibrated at moderate pressure with high pressure, oxidised magnesium silicate. This reveals both that the mantle was likely to be oxidised 3.7 billion years ago and that the advection of crystals was active during the freezing of the magma ocean. Whilst these high pressure silicates are not expected to have melted when transported to the upper magma ocean, the lower pressures of smaller planets (e.g. Mars, Vesta, and Mercury) would mean that they would melt, making the process impossible.

Our final presentation of the meeting came from Hannah Rogers (Grenoble): *Investigating regional heterogeneity at the core-mantle boundary and its impact on outer core flow*. Hannah uses satellite data of the Earth's magnetic field strength to understand how mantle structure may alter the field. The Earth's geodynamo is generated by the churning of liquid iron in the outer core. The turbulent convection of the core makes this a process which has significant secular variation, with reversals, polar wander, and anomalous patches (Glatzmaier and Roberts 1995). Models of convection in the core suggest that the magnetic field should be far more complex than the largely dipolar field we observe at the surface. This means that the mantle, and potentially stratified layers at the outermost core, have a filtering effect on the field. Hannah uses the secular variation of the Earth's magnetic field, as recorded by the SWARM network of geomagnetism observing satellites, to understand how large structures in the lowermost mantle might provide lateral variation to this filtering effect. LLSVPs, the origin of which is the focus of both Charles-Édouard and Maxim, are two continent sizes regions extending above the core mantle boundary around 1000 km in height. Because they are thermally, and possibly chemically, distinct from the surrounding mantle, they could present different magnetic filtering qualities. Models which simply hope to capture the observed lateral variation in secular field strength are required to have different magnetic filtering qualities inside and outside of these regions. Additionally, whilst results are still emerging, there seems to be a significant correlation between these regions and periods of rapid magnetic field change.

The meeting offered a most welcome coming together of colleagues who had scarce opportunity to do so in the prior two and a half years. The quality of presentations and surrounding discussion was outstanding, and many remarked on how satisfying it was to discuss our common interests in person. The talks only reinforced how important, diverse, and challenging the interactions of solids and liquids are for the evolution of planets. With more focus than ever on experimental analogues, nuanced simulations of two-phase systems and the observable outcomes from these interactions, the field is advancing at tremendous pace.

Authors:

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Dario Alfè is a professor of theoretical mineral physics at University College London. He focuses on modelling the materials comprising Earth’s core and developing techniques for the efficient calculation of thermodynamic and transport properties .

Chris Davies is a professor of theoretical geophysics at the University of Leeds. His interests lie in understanding the dynamics and evolution of Earth’s deep interior, particularly the generation of the geomagnetic field.

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