Iron Snow in Planetary Cores

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Planetary magnetic fields exhibit remarkable variability in their intensity and spatio-temporal properties. These fields are generated in metallic cores and thus provide a unique probe into the dynamics and evolution of planetary interiors. Earth's liquid core is currently freezing from the bottom upwards as the planet cools, releasing the heat and light material that power the geomagnetic field. In contrast, recent mineralogical studies suggest that the cores of the smaller terrestrial bodies Mercury, Mars and Ganymede freeze from the top down with solid iron particles "snowing" into the deeper core. It has even been suggested that the top of Earth's core may have once entered a crystallizing regime. The evolution and dynamics of bodies in this "iron snow" regime will be profoundly different to those of present-day Earth; however, the ramifications are presently unknown. Since the iron snow regime is a recent discovery, fundamental questions remain: can iron snow generate a global magnetic field? If so, is the generated field compatible with available observations? Will planets in the iron snow regime ever grow a solid inner core like Earth? We have recently developed the first self-consistent thermodynamic model for studying iron snow, including its role in magnetic field generation, and applied it in reduced form to Mars' core. In this project you will relax existing model assumptions so that it can be applied to the cores of Mercury, Mars and Ganymede to evaluate, for the first time, whether iron snow can generate the magnetism observed on these bodies. The analysis will make new predictions regarding the interior structure and evolution of these bodies, constrained by and informing existing and forthcoming observational data. Results may also bear on top-down crystallization in Earth's core.

Planetary Magnetic Field and Iron Snow

All planets in our solar system sustain large-scale magnetic fields except Venus, which is not thought to have ever generated a field, and Mars, which probably generated one long ago (Soderlund and Schubert, 2011). Earth possesses a strong dipole-dominated magnetic field tilted by $\approx 10^{\circ}$ from the rotation axis, a configuration that helps to protect humans and low-orbiting satellites from potentially harmful incoming solar radiation. By contrast, Mercury's surface field is an order of magnitude weaker than Earth's, Saturn's field is strong but displays almost no tilt, while the fields of the ice giants display large tilts and strong non-dipole components (Figure 1; Soderlund and Schubert, 2011). These fields are all generated in metallic cores by a dynamo process that converts kinetic energy from motion of the iron alloy into magnetic energy. Terrestrial dynamos are mainly powered by planetary cooling and so the variations in observed magnetic field properties reflect different thermal, chemical and dynamical conditions as well as evolutionary pathways. The observed magnetic fields therefore provide a unique probe into unobservable interiors of planetary bodies.

Earth's liquid iron core is currently freezing from the bottom upwards as the planet cools because the melting curve of the iron alloy is steeper than the temperature gradient of the core fluid (e.g. Nimmo, 2015). Freezing releases latent heat and causes light elements (e.g. sulfur, silicon and oxygen) to partition into the liquid phase; these effects are crucial, providing the main power sources for generating the geomagnetic field (Nimmo, 2015). The inner core is a young feature of the planet, less than a billion years old (Davies et al, 2015;

Nimmo, 2015) and the conditions that generated the geomagnetic field prior to its nucleation are still the subject of vigorous debate (Davies et al, 2015); indeed, some studies have suggested that crystallization near the top of the core was required to maintain the ancient geodynamo (O'Rourke and Stevenson, 2016; Hirose, et al, 2017). The presence of the inner core may also determine the strength and morphology of the geomagnetic field (Driscoll, 2016; Landeau et al, 2016). It is clear that the onset and termination of core crystallization are among the most significant events in the history of a planetary body.

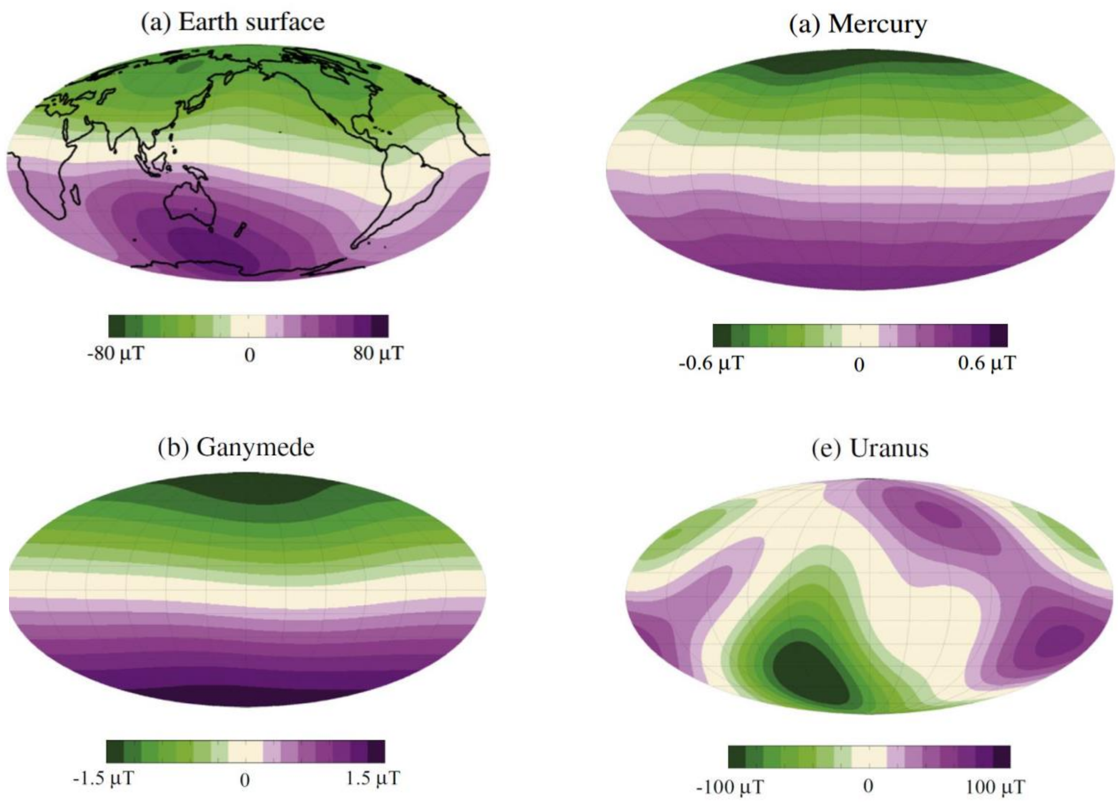

Figure 1: Radial magnetic field at the surface of Earth, Mercury, Ganymede and Uranus. Note the weak field of Mercury and the non-dipolar field of Uranus. Figure from Schubert and Soderlund (2011).

At the pressure-temperature-composition conditions of small terrestrial bodies, recent mineralogical studies suggest that the melting curve is shallower than the core temperature gradient (e.g. Stewart et al, 2007). Therefore, in stark contrast to present-day Earth, the cores of these bodies will freeze from the top downwards. If the solid is heavier than the residual liquid it will fall, snowing onto the deeper core where it may remelt. This "iron snow" regime has been proposed to exist in Mercury (Dumberry and Rivoldini, 2015), Mars (Davies and Pommier, 2018) and Ganymede (Hauck et al, 2006; Ruckriemen et al, 2015). Since the melting and freezing of solid together with movement of solid and liquid constituents involves latent heat and gravitational energy release (see Figure 1), analogy with present-day Earth suggests that nucleation of an iron snow layer will profoundly affect the dynamics and evolution of a planetary core. Simple models of iron snow suggest this is the case (Ruckriemen et al, 2015; Davies and Pommier, 2018) while also predicting that the iron snow regime is very different to the bottom-up crystallization of present Earth. However, owing to the relative simplicity of the models, the ramifications are presently unknown.

Application of the iron snow regime to planetary cores has only recently begun (Hauck et al, 2006) and so fundamental questions remain: can iron snow generate a global magnetic field? If so, is the generated field compatible with available observations? Will planets in the iron snow regime ever grow a solid inner core like Earth? We have recently developed a new parameterised model for studying the evolution of snow zones based on the theory of slurries, i.e. liquid mixtures that contain a suspension of solid particles. There are two key advantages of this slurry evolution model (SEM) over previous studies (Ruckriemen et al, 2015; Scheinberg et al, 2015): 1) the viability of dynamo action is calculated in a thermodynamically self-consistent manner, rather than empirically using scaling laws; 2) the equations are derived directly from the general theory for a two-phase two-component liquid mixture (Loper and Roberts, 1977).

The project

In this project you will relax existing assumptions so that the slurry evolution model (SEM) can be applied to the cores of Mercury, Mars and Ganymede to evaluate, for the first time, whether iron snow can generate the magnetism observed on these bodies. The cores of these bodies exist at much lower pressure and temperature than Earth's core, making them much more amenable to experimental and computational investigation. The analysis will make new predictions regarding the interior structure and evolution of these bodies, constrained by and informing existing and forthcoming observational data. Moreover, exploring the complex dynamics of slurry systems in the small terrestrial bodies will likely improve our understanding of the possibility and nature of top-down crystallization in Earth.

The present SEM describes the long-term evolution (i.e. the past 4.5 billion years) of an iron-sulphur snow zone and utilizes standard procedures to reduce the problem to two dimensions: radius and time. The SEM is a `parameterised model' in the sense (e.g. Nimmo, 2015) that the fluid dynamical behaviour of the snow zone is described by a small number of parameters rather than obtained by a forward solution of the fluid dynamical (e.g. Navier-Stokes) equations. The physical effects included in the SEM and an example calculation are shown in Figure 1. This approach has the significant benefits that it is fast and efficient, allowing many solutions to be obtained that span uncertainties in the input parameters. However, the parameterisation is only as good as our understanding of the underlying physics, which comes from laboratory experiments and numerical simulations of the forward problem. This project will utilise both parameterised and forward modelling approaches.

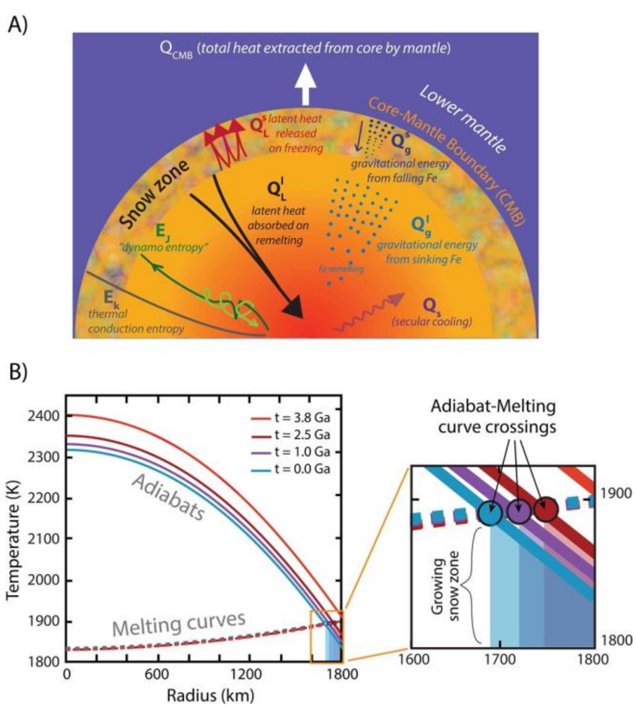

Figure 2: Cartoon of the iron snow regime. (A) Heat sources used to calculate the evolution of the Martian core and dynamo. Q_S *is the secular cooling. Crystallization leads to latent heat release as solid iron forms throughout the snow zone,* Q_L^s *, latent heat absorption* Q_L^l *as iron snow remelts at the top of the liquid region and gravitational energy release due to the negative buoyancy of iron sinking in the snow zone (*Q_g^s*) and remelting at the top of the liquid region (*Q_g^l*). The viability of dynamo action is determined by* E_J *through an entropy balance. (B)*

Example model run showing growth of a snow zone. The adiabatic temperature and melting curve (Stewart et al., 2007) both evolve with time and the radius where they intersect defines the instantaneous base of the snow zone.

The SEM relies on three main assumptions: 1) solid forms instantaneously, leaving the snow zone in phase equilibrium and at the liquidus temperature; 2) all light element (here sulfur) partitions into the liquid on freezing; 3) solid iron falls out of the snow zone while sulphur-rich fluid rises, creating a density stratification across the snow zone (light fluid overlying heavy fluid). The first two assumptions are common to all iron snow evolution models. Departures from phase equilibrium drastically increase the complexity of the equations and rely on macroscopic parameterizations of microscale processes (Loper, 1992) that are poorly understood and observationally unconstrained at planetary core conditions. Assumption (2) is supported by experiments that reported very low sulfur concentrations in the solid phase (Kamada et al, 2011; Li et al, 2001). Assumption (3) will be investigated in this project.

Another way of stating assumption (3) is that the snow zone is not convecting. This assumption is clearly important as convecting and non-convecting systems behave very differently in terms of how they transfer mass, momentum and energy. The assumption of a stable snow zone is at odds with the conventional intuition regarding planetary cores, which are usually thought to be turbulent and vigorously convecting. However, the behaviour of slurry systems can be very different to standard thermal convection systems. Indeed, while increasing the temperature difference across a fluid tends to promote convection, in slurries it can have the opposite effect (Loper and Roberts, 1987)! The stability of snow zones in planetary cores has received little attention and so this investigation is both important and timely given the recent interest in these systems.

The stability of snow zones will depend on a number of factors, including the size, δ, and number, N, of solid particles. We have recently developed a system of Boussinesq equations describing snow zone dynamics (Wong, Davies and Jones, 2018), which are suitable for implementation in a numerical fluid dynamical model. You will be involved in the extension of an existing 2D code describing thermo-chemical convection, developed at Leeds. The main modifications, which utilize existing code, are to implement the liquidus relation and an additional advection-diffusion equation describing evolution of the solid fraction. A 2D model is appropriate for this project since it is fast (individual runs take a few hours), which will allow a wide range of δ and N (and other relevant parameters) to be explored. Extension into 3D can be achieved by modification of existing code. From these simulations the parameters needed by the SEM (e.g. mean temperature, composition and solid profiles) will be obtained.

In the final stage of the project the SEM will be applied to Mercury, Mars and Ganymede. For each planet you will use the latest estimates of structural, thermal and chemical properties as inputs to the snow model; the results will therefore be consistent with these data by default. The model will predict the time-dependent evolution of the snow zone, including its thickness and thermo-chemical properties, which can be tested using present and future observations. The model also predicts the viability of dynamo action, which provides new constraints on the magnetic history of these bodies. From this the present-day dipole moment can be obtained using scaling laws (Aubert et al, 2009) and compared to observations.

Training environment

You will receive training in skills tailored to the project but also useful to help secure a future career as a research scientist in academia or elsewhere. To allow you to complete the project you will learn a range of computational and mathematical methods as well as developing an understanding of the properties of the planetary interior. You will also learn how to develop software for the analysis of results and to use large-scale high performance computing resources, including those at the University of Leeds (Figure 3). Alongside the transferable skills in communication and management this can open a wide range of career pathways. These skills will be developed by a mixture of hands on experience, attending external training courses, and by participating in the Leeds–York NERC doctoral training partnership.

Figure 3: University of Leeds hosted tier 2 high performance computing facility of the N8 HPC consortium (http://n8.hpc.org.uk), one of the supercomputers that can be used in this project.

Student profile

This project offers plenty of flexibility depending on the interests and experience of the candidate. There is ample scope for code development, while those interested in the more fundamental fluid dynamical aspects of the problem may choose to consider the effects of rotation and magnetic fields in the 2D models, which are basically unexplored. Whatever the candidate's background, strong mathematical skills, curiosity and a desire to learn will form an important part of the project.

References and further reading

1. Aubert, J., Labrosse, S. and Poitou, C., 2009. Modelling the palaeo-evolution of the geodynamo. *Geophysical Journal International*, *179*(3), pp.1414-1428.
2. Davies, C., Pozzo, M., Gubbins, D. and Alfè, D., 2015. Constraints from material properties on the dynamics and evolution of Earth's core. *Nature Geoscience*, *8*(9), pp.678-685.
3. Davies, C.J. and Pommier, A., 2018. Iron snow in the Martian core?. *Earth and Planetary Science Letters*, *481*, pp.189-200.
4. Driscoll, P.E., 2016. Simulating 2 Ga of geodynamo history. *Geophysical Research Letters*, *43*(11), pp.5680-5687.
5. Dumberry, M., Rivoldini, A., 2015. Mercury's inner core size and core-crystallization regime. Icarus 248, 254–268.
6. Hauck, S.A., Aurnou, J.M. and Dombard, A.J., 2006. Sulfur's impact on core evolution and magnetic field generation on Ganymede. *Journal of Geophysical Research: Planets*, *111*(E9).

7. Hirose, K., Morard, G., Sinmyo, R., Umemoto, K., Hernlund, J., Helffrich, G. and Labrosse, S., 2017. Crystallization of silicon dioxide and compositional evolution of the Earth's core. *Nature*, *543*(7643), pp.99-102.

8. Kamada, S., Ohtani, E., Terasaki, H., Sakai, T., Miyahara, M., Ohishi, Y. and Hirao, N., 2012. Melting relationships in the Fe–Fe 3 S system up to the outer core conditions. *Earth and Planetary Science Letters*, *359*, pp.26-33.

9. Landeau, M., Aubert, J. and Olson, P., 2017. The signature of inner-core nucleation on the geodynamo. *Earth and Planetary Science Letters*, *465*, pp.193-204.

10. Li, J., Fei, Y., Mao, H.K., Hirose, K. and Shieh, S.R., 2001. Sulfur in the Earth's inner core. *Earth and Planetary Science Letters*, *193*(3), pp.509-514.

11. Loper, D.E. and Roberts, P.H., 1977. On the motion of an iron-alloy core containing a slurry: I. General theory. *Geophysical & Astrophysical Fluid Dynamics*, *9*(1), pp.289-321.

12. Loper, D.E. and Roberts, P.H., 1987. A Boussinesq model of a slurry. In *Structure and Dynamics of Partially Solidified Systems* (pp. 291-323). Springer, Dordrecht.

13. Loper, D.E., 1992. A nonequilibrium theory of a slurry. *Continuum Mechanics and Thermodynamics*, *4*(3), pp.213-245.

14. Nimmo, F., 2015. Energetics of the core. In: Schubert, G. (Ed.), Treatise on Geophysics, vol. 8, 2nd ed. Elsevier, Amsterdam, pp. 27–55.

15. O'Rourke, J.G. and Stevenson, D.J., 2016. Powering Earth's dynamo with magnesium precipitation from the core. *Nature*, *529*(7586), pp.387-389.

16. Rückriemen, T., Breuer, D., Spohn, T., 2015. The Fe snow regime in Ganymede's core: a deep-seated dynamo below a stable snow zone. J. Geophys. Res., Planets 120 (6), 1095–1118.

17. Scheinberg, A., Elkins-Tanton, L.T., Schubert, G. and Bercovici, D., 2016. Core solidification and dynamo evolution in a mantle-stripped planetesimal. *Journal of Geophysical Research: Planets*, *121*(1), pp.2-20.

18. Schubert, G. and Soderlund, K.M., 2011. Planetary magnetic fields: Observations and models. *Physics of the Earth and Planetary Interiors*, *187*(3), pp.92-108.

19. Stewart, A.J., et al., 2007. Mars: a new core-crystallization regime. Science 316, 1323–1325.

20. Wong, J., Davies, C.J. and Jones, C.A., 2018. A Boussinesq slurry model of the F–layer at the base of Earth's outer core. *Geophysical Journal International*. *214, 2236-2249*.