FDEPS Kyoto: Bibliography for the lecture notes

Planetary interiors: Magnetic fields, Convection and Dynamo Theory

Chris Jones, University of Leeds, UK

November 2017

1. Observational background to planetary structure

The 2nd edition of the ‘Treatise on Geophysics’ 2015, edited by G. Schubert, published by Elsevier, is an excellent source for many of the topics in Lecture 1. Referred to below as TOG2.

1.1 Interior of the Earth

Internal structure of the Earth from seismology:

Article by Brian Kennett 'Earth structure: major divisions' in the Encyclopaedia of Geomagnetism and Paleomagnetism, eds D. Gubbins and E. Herrero-Bervera, Springer, 2007.

Dziewonski, A.M. and Anderson, D.L., 1981. Preliminary reference Earth model (PREM). *Phys. Earth Planet. Inter*. **25,** 297-356.

Length of Day long term:

Article by L.V Morrison and F.R. Stephenson, 'Length of day variations: long term' in Encyclopaedia of Geomagnetism and Paleomagnetism, eds D. Gubbins and E. Herrero-Bervera, Springer, 2007.

Length of Day decadal variations:

Jault, D., Gire, C. and LeMouel, J.L. 1988. *Nature*, **333**, 353-356.
Holme, R. and DeViron, O. 2013. *Nature,* **499,** 202-204.

Precession and Nutation signals:

Dehant, V. and Matthews P.M. 2015. TOG2 volume 3, chapter 3.10, p 263-305.

Thermal convection in the core:

Jones, C.A. 2015. TOG2 volume 8, chapter 8.05, p 115-159.

Nimmo, F. 2015. TOG2 volume 8, chapter 8.02, p 27-55.

Mantle convection and the Core-Mantle Boundary heat flux:

Hernlund, J.W. and McNamara, A.K. 2015 TOG2 volume 7, chapter 7.11, p 461-519.

1.2 Interiors of other planets

Plate tectonics on other planets: Structure of terrestrial planets and their history:

Gregg, T.K.P., 2015 TOG2 volume 10, chapter 10.09, p307-325.

Internal structure of the giant planets.

Guillot, T., and Gautier, D., 2015 TOG2 volume 10, chapter 10.16, p 529-557.

1.3 Earth's magnetic field

Radial field at the surface: Extrapolating the field to the Core-Mantle Boundary:
Secular variation.

Jackson, A. 2003, Intense equatorial flux spots on the surface of the Earth's core
Nature, **424**, p 760-763
Jackson, A. Jonkers, A.R.T. and Walker, M. 2000. Four centuries of geomagnetic secular variation from historical records. *Phil. Trans. R. Soc. Lond. A*, **358**, p 957–990.

Induction equation and magnetic Reynolds number:

An Introduction to Magnetohydrodynamics. P.A. Davidson, 2001,
Cambridge University Press.

Core-flow inversion techniques:

Holme, R. 2015 TOG2 volume 8, chapter 8.04, p 91-113.

Energy source for the geodynamo: *convection*

Article by Stephane Labrosse 'Geodynamo: energy sources' in Encyclopaedia of Geomagnetism and Paleomagnetism, eds D. Gubbins and E. Herrero-Bervera, Springer, 2007.

Energy source for the geodynamo: *precession*

Tilgner, A. 2015 TOG2 volume 8, chapter 8.07, p 183-212

Reversals and Excursions:

Glatzmaier, G.A., and Coe, R.S. 2015 TOG2 volume 8, chapter 8.11, p 279-295.

1.4 Magnetic fields of other planets:

Connerney, J.E.P. 2015 TOG2 volume 10, chapter 10.06, p 195-237.

1.5 Zonal winds on the giant planets.

Jupiter, edited by Fran Bagenal, Timothy Dowling and William McKinnon. 2004. Chapter 6. 'Dynamics of Jupiter's atmosphere'. Cambridge University Press.

Jones, C.A. and Kuzanyan, K.M., 2009. Compressible convection in the deep atmospheres of giant planets. *Icarus*, **204, p** 227-238.

Zhang K, Kong D, Schubert G. (2017) Shape, Internal Structure, Zonal Winds, and Gravitational Field of Rapidly Rotating Jupiter-Like Planets, *Annual Review of Earth and Planetary Sciences*, volume 45, pages 419-446.

2. Convection in planetary interiors

2.1 Boussinesq Rayleigh-Benard convection.

***Hydrodynamic and Hydromagnetic Stability*.** S Chandrasekhar**,** S., 1961. Oxford University Press. (available online). This is the fundamental source for the linear theory of convection. Referred to below as HHS.

Laboratory experiments and astrophysical and geophysical applications;

A.V. Getling (1998). *Rayleigh-Bénard Convection: Structures and Dynamics* (World Scientific).

2.2 Stability of the basic state:

HHS.

2.3 Nonlinear Rayleigh-Bénard convection

Heat transport, Nusselt number: Nu - Ra relations: Malkus-Howard theory:

Siggia, E. D. 1994. High Rayleigh number convection. *Ann. Rev. Fluid Mech*. **26**, p137-168.

Dissipation integrals and the Grossmann-Lohse theory:

Grossmann, S. and Lohse, D., 2000. *J. Fluid Mech.*, **407**, p27-56

2.4 Rotating flows.

Taylor-Proudman theorem. Geostrophic flow. Rotating flow experiments.

Greenspan, H.P., *The Theory of Rotating Fluids*. 1968. Cambridge University Press, New York.

2.5 Plane layer rotating convection

Plane convection model: Vorticity equation and inertial waves. Dispersion relation for the Rayleigh number. Steady and oscillatory modes. Small Ekman number limit:

HHS.

2.6 Nonlinear rotating convection

Tall thin columns. Formation of large scale vortices:

Busse, F.H. Thermal instabilities of rapidly rotating systems. *J. Fluid Mech*. **44**, p441-460.

Nusselt number - Rayleigh number relations from experiments.

Formation of large scale vortices:

Guervilly, C., Hughes, D.W. and Jones, C.A. 2014. Large-scale vortices in rapidly rotating Rayleigh-Bénard convection. *Journal of Fluid Mechanics* **758,** 407-435.

2.7 Rotating spherical convection

The Busse annulus:

Busse, F.H. Thermal instabilities of rapidly rotating systems. *J. Fluid Mech*. **44**, p441-460.

Jones, C.A. 2015. TOG2 volume 8, chapter 8.05, p 115-159.

Experiments in rotating convection: columnar flow:

Busse, F.H. and Carrigan, C.R. 1976. Science, 191, p 81-83.

Zonal jet formation in the Busse annulus model:

Rotvig, J. and Jones, C.A., 2006. Multiple jets and bursting in the rapidly rotating convecting two-dimensional annulus model with nearly plane-parallel boundaries. *Journal of Fluid Mechanics* **567,** 117 - 140.

Quasi-geostrophic approximation:

Gillet, N and Jones, C.A., 2006. The quasi-geostrophic model for rapidly rotating spherical convection outside the tangent cylinder. *Journal of Fluid Mechanics* **554,** 343 - 369.

Onset of convection in a rapidly rotating sphere:

Dormy, E., Soward, A.M., Jones, C.A., Jault, D. and Cardin, P., 2004. The onset of thermal convection in rotating spherical shells. *Journal of Fluid Mechanics*, **501**, 43-70.

Jones, C.A., Soward, A.M. and Mussa, A.I., 2000. The onset of convection in a rapidly rotating sphere. *Journal of Fluid Mechanics*, **405**, 157-179.

Scaling laws in convection. Inertial theory of rapidly rotating convection:

Jones, C.A. 2015. TOG2 volume 8, chapter 8.05, p 115-159.

3. How planetary magnetic fields are generated

This lecture is an updated version of my article in Chapter 2. Dynamo Theory, which appeared in *Dynamos: Les Houches Session LXXXVIII*, eds. Ph Cardin and L.F. Cugliando. Elsevier 2008. Chapter 2 is p 45-132. References to the original papers are given there.

3.1 Fundamentals of MHD and Maxwell's equations.

The MHD equations. Ohm's law and the induction equation. Magnetic Reynolds number.

Frozen flux, Alfvén's theorem. Flux expulsion:

An Introduction to Magnetohydrodynamics. P.A. Davidson, 2001,
Cambridge University Press.

3.2 Kinematic dynamo problem

Definition of kinematic dynamos: the four anti-dynamo theorems:

Cowling T.G., The magnetic field of sunspots, *Mon. Not. R. Astr. Soc*. **94**, p 39-48 (1934).

Zeldovich, Ya. B., 1957. *Sov. Phys. JETP*, **4**, p 460-462.

3.3 Working kinematic dynamos.

Ponomarenko dynamo and the Riga dynamo experiment:

Ponomarenko Yu. B., On the theory of hydromagnetic dynamo, *J. Appl. Mech. Tech. Phys.* 14, 775 (1973).

Gailitis, A. et al. 2008. History and results of the Riga dynamo experiments. *Comptes Rendus Physique*, **9**, Pages 721-728.

The G.O. Roberts periodic dynamo:

Roberts G.O., Spatially periodic dynamos, *Phil. Trans. R. Soc. Lond., A* **266**, 535-558 (1970).

Spherical dynamo models and the Dudley-James dynamos:

Dudley M.L. \& R.W. James, Time-dependent kinematic dynamos with stationary flows,
Proc. R. Soc. Lond., A **425,** 407-429 (1989)

3.4 Field generation in numerical geodynamo models.

Creation of meridional and azimuthal field:

U. Christensen, P. Olson and G. A. Glatzmaier 1999. *Geophys. J. Int.* (1999**) 138**, p 393-409.

3.5 Fast and slow dynamos.

ABC dynamos and the Galloway-Proctor dynamo:

Galloway D.J. and Proctor M.R.E., Numerical calculations of fast dynamos for smooth velocity fields with realistic diffusion, *Nature*, **356**, 691-693 (1992).

3.6 Mean-field dynamo theory.

Mean and fluctuating parts in the induction equation. Scale separation and derivation of the alpha and beta effects:

Krause F. and Radler K.-H., *Mean field magnetohydrodynamics and dynamo theory*, Pergamon Press (New-York, 1980).

3.7 Mean field α-effect dynamos

Axisymmetric mean field dynamos. The Omega-effect. Dynamo waves. Spherical αω-dynamos:

Parker E.N., *Cosmical Magnetic Fields: Their Origin and Their Activity.* (1979) Oxford University Press.

Parker E.N., Hydromagnetic dynamo models, *Astrophys. J.*, **122**, 293-314 (1955).

Roberts P.H., Kinematic Dynamo Models. *Phil. Trans. R. Soc. Lond., A* **272**, 663-703.

4. Core dynamics: Rotation and Magnetic fields

4.1 Rotating magnetoconvection.

Plane layer models. Non-rotating limit and sunspots. Alfvén waves, magnetic field lines as stretched strings:

HHS.

Elsasser number and the breaking of the Taylor-Proudman constraint.

Jones, C.A. 2015. TOG2 volume 8, chapter 8.05, p 115-159.

4.2 Waves in rotating MHD.

Types of wave found in the core. MC waves and their dispersion relation. Slow magnetic Rossby waves:

D. Jault, C.C. Finlay, 2015 TOG2 Chapter 8.09 - Waves in the Core and Mechanical Core–Mantle Interactions, Pages 225-244.

Malkus model:

,
Malkus, W.V.R., Hydromagnetic planetary waves. *J. Fluid Mech.* (1967), **28**, pp. 793-802.

4.3 Torsional waves in the core.

Dynamics of torsional waves. Observations of torsional waves in secular variation and length of day.

Roberts, P.H. and Aurnou, J., On the theory of core-mantle coupling.
Geophysical & Astrophysical Fluid Dynamics**,** **106**, p 157-230. (2012)

Torsional waves in dynamo models and magnetoconvection models.

Teed, R.J., Jones, C.A. and Tobias, S.M. 2014. The dynamics and excitation of torsional waves in geodynamo simulations. *Geophysical Journal International* **196,** 724-735.

Teed, R.J., Jones, C.A. and Tobias, S.M. 2015. The transition to Earth-like torsional oscillations in magnetoconvection simulations. *Earth and Planetary Science Letters* **419,** 22-31.

4.4 Magnetic Rossby waves in the core.

Secular variation: waves or flow? Magnetic Rossby waves in a thick shell. Magnetic Rossby waves in simulations:

Hori, K., Jones, C.A. and Teed, R.J. 2015. Slow magnetic Rossby waves in the Earth's core *Geophysical Research Letters* **42,** Art No. 10.1002/2015GL064733

4.5 Shallow water MHD model

Gilman shallow water MHD equations:

Gilman, P. A., 2000. Magnetohydrodynamic “Shallow Water” equations for the solar tachocline. *Astrophys. J. Lett.,* **544***, l79.*

Linearised model, and the types of wave that occur. Magnetic instabilities:

Marquez-Artavia, X., Jones, C.A., and Tobias, S.M. 2017. Rotating magnetic shallow water waves and instabilities in a sphere. *Geophysical & Astrophysical Fluid Dynamics* **111,** 282-322.

Lecture 5 Thursday 30th November 2pm - 5pm

How numerical dynamo models are constructed and what they produce

5.1 Spherical geodynamo models

Boussinesq spherical dynamo models. Basic state and boundary conditions. Dimensionless parameters:

U.R. Christensen, J. Wicht., 2015. TOG2 Volume 8, Chapter 8.10 - Numerical Dynamo Simulations, Pages 245-277.

5.2 Pseudo-spectral method for Boussinesq dynamo models

Poloidal-Toroidal decomposition. Expansion in spherical harmonics. Deriving the scalar equations. Solution using the influence matrix method. Radial dependence and time-stepping: Magnetic boundary conditions:

Gubbins, D., Willis, A.P. and Sreenivasan B., 2007. Phys. Earth Planet Inter. 162, 256-260.

5.*3 Results from Boussinesq dynamo codes. Dipolar, non-dipolar solutions. Variation with Ekman and Magnetic Prandtl number. Earth-like geodynamo models, subcriticality and helicity. Scaling laws for geodynamo models:*

Jones, C.A., 2011. Planetary magnetic fields and fluid dynamos. *Annual Review of Fluid Mechanics,* **43,** 583-614.

Christensen, U.R., Aubert, J. and Hulot, G., 2010. Conditions for Earth-like geodynamo models. *Earth and Planetary Science Letters*, **296**, p 487-496.

Sreenivasan, B. and Jones, C.A., 2011. Helicity generation and subcritical behaviour in rapidly rotating dynamos. *Journal of Fluid Mechanics* **688,** 5-30.

Davidson, P.A. 2013. Scaling laws for planetary dynamos. *Geophys. J. Int.* **195**, p 67-74.

5.4 Compressible convection equations.

Fluid mechanics, Landau, L.D. and Lifshitz, E.M., 1959. Pergamon Press.

5.5 Anelastic convection equations. Anelastic approximation. Entropy diffusion. Lantz-Braginsky Roberts approximation.

Jones, C.A., Boronski, P., Brun, A.S., Glatzmaier, G.A., Gastine, T., Miesch, M.S. and Wicht, J. Anelastic convection-driven dynamo benchmarks. *Icarus* **216,** 120-135.

Jones, C.A., 2014. A dynamo model of Jupiter's magnetic field. *Icarus* **241,** 148-159.

5.6 Pseudo-spectral method for anelastic convection. Poloidal-Toroidal decomposition. Deriving the scalar equations in the entropy-diffusion model.

5.7 Anelastic dynamo benchmark.

Need for benchmarks. Hydrodynamic benchmark. The steady dynamo benchmark:

Jones, C.A., Boronski, P., Brun, A.S., Glatzmaier, G.A., Gastine, T., Miesch, M.S. and Wicht, J. Anelastic convection-driven dynamo benchmarks. *Icarus* **216,** 120-135.

Research Seminar Friday 1st December 9am-11am

Anelastic spherical dynamos with variable conductivity

A series of numerical simulations of the dynamos of gas giant planets has been performed. We use an anelastic, fully nonlinear, three-dimensional, benchmarked MHD code to evolve the flow, entropy and magnetic field. Our models take into account the varying electrical conductivity, high in the ionised metallic hydrogen region, low in the molecular outer region. Our suite of electrical conductivity models ranges from Jupiter-like, where the outer hydrodynamic region is quite thin, to Saturn-like, where there is a thick non-conducting shell. The rapid rotation leads to two distinct dynamical regimes forming which are separated by a magnetic tangent cylinder - mTC. Outside the mTC there are strong zonal flows, where Reynolds stress balances turbulent viscosity, but inside the mTC Lorentz force reduces the zonal flow. We find a rich diversity of magnetic field morphologies. There are Jupiter-like steady dipolar fields, and a belt of quadrupolar dominated dynamos spanning the range of models between Jupiter-like and Saturn-like conductivity profiles. This diversity may be linked to the appearance of reversed sign helicity in the metallic regions of our dynamos. With Saturn-like conductivity profiles we find models with dipolar magnetic fields, whose axisymmetric components resemble those of Saturn, and which oscillate on a very long time-scale. However, the nonaxisymmetric field components of our models are at least ten times larger than those of Saturn, possibly due to the absence of any stably stratified layer.