1. Observational background to planetary structure


1.1 Interior of the Earth

Internal structure of the Earth from seismology:


Length of Day long term:


Length of Day decadal variations:


Precession and Nutation signals:


Thermal convection in the core:

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


Mantle convection and the Core-Mantle Boundary heat flux:

1.2 Interiors of other planets

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

Internal structure of the giant planets.


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

Induction equation and magnetic Reynolds number:


Core-flow inversion techniques:


Energy source for the geodynamo: convection


Energy source for the geodynamo: precession

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

Reversals and Excursions:


1.4 Magnetic fields of other planets:


1.5 Zonal winds on the giant planets.


2. Convection in planetary interiors

2.1 Boussinesq Rayleigh-Bénard 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;


2.2 Stability of the basic state:

HHS.

2.3 Nonlinear Rayleigh-Bénard convection

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


Dissipation integrals and the Grossmann-Lohse theory:


2.4 Rotating flows.


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:

Nusselt number - Rayleigh number relations from experiments.

*Formation of large scale vortices:*


2.7 Rotating spherical convection

*The Busse annulus:*


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

*Experiments in rotating convection: columnar flow:*


*Zonal jet formation in the Busse annulus model:*


*Quasi-geostrophic approximation:*


*Onset of convection in a rapidly rotating sphere:*


*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:


3.2 Kinematic dynamo problem

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


3.3 Working kinematic dynamos.

Ponomarenko dynamo and the Riga dynamo experiment:


The G.O. Roberts periodic dynamo:


Spherical dynamo models and the Dudley-James dynamos:


3.4 Field generation in numerical geodynamo models.

Creation of meridional and azimuthal field:


3.5 Fast and slow dynamos.

ABC dynamos and the Galloway-Proctor dynamo:


3.6 Mean-field dynamo theory.

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

3.7 Mean field α-effect dynamos

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


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:*


4.3 Torsional waves in the core.

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


*Torsional waves in dynamo models and magnetoconvection models.*


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:*


4.5 Shallow water MHD model

*Gilman shallow water MHD equations:*


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


**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:*


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:*


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:


5.4 Compressible convection equations.


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


5.7 Anelastic dynamo benchmark.

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


**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.