FDEPS Kyoto lecture plan

Lecture 1 Tuesday 28th November 9am-12pm

Observational background to planetary structure

(i) Planetary interiors.

Earth: mantle, core and inner core. Seismic observations. Length of day and nutation observations. Thermal history of the Earth: the adiabat, the liquidus and the history of the inner core. Introduction to convection in the core: thermal and compositional convection: thermal conductivity of the core. Possible stably stratified zones in the Earth's core. Inhomogeneous heat flux at the core-mantle boundary and its effect on core convection.

Mars, Venus, Mercury and the moons of Jupiter: what we know about their deep interiors.

Giant planets Jupiter and Saturn. Structure of the planets: equation of state and metallic hydrogen. Electrical conductivity in the metallic hydrogen region. Convection and possible stable layers inside Jupiter and Saturn: the helium depletion problem. Observational data and what it tells us about the deep interior in the light of the Juno and Cassini missions: gravity measurements.

Current ideas on planetary formation in the light of data from exoplanets. Possible structure of hot Jupiters, and effects of tidal dissipation.

(**ii) Planetary magnetic fields**

Data recording the geomagnetic field: long term history, reversals, secular variation, recent satellite data. Spherical harmonic expansions, limitations on accuracy due to crustal field. Determining core flow using the frozen flux hypothesis. Outline of the dynamo theory of magnetic field generation. Possible energy sources for stirring planetary cores: convection, tidal forcing and precession. Theories of geomagnetic reversals.
Observed secular variation on decadal timescales. Introduction to the types of MHD waves already seen and that may be found in the future in planetary magnetic fields.
What is known about the magnetic fields of the terrestrial planets in the light of missions to these planets.
Giant planet magnetic fields: the observed fields of Jupiter, Saturn, Uranus and Neptune gathered from mission data.

(iii) Zonal flows on giant planets

Observational background. The deep/shallow controversy. Connection with Juno's gravity measurements. Introduction to 2D turbulence and the inverse energy cascade. Overview of results from Boussinesq/Anelastic simulations. The Rhines scale and the zonal flow jet width.

Lecture 2 Tuesday 28th November 2pm - 5pm

Convection in planetary interiors

(i) Rayleigh-Benard convection.

Boussinesq convection. Onset of instability, pattern formation, nonlinear convection. Heat transport, Nusselt number - Rayleigh number relations, dissipation integrals and the Grossmann-Lohse theory.

Compressible and anelastic convection. Derivation of the anelastic approximation and the work of Lantz, Braginsky and Roberts. Flow structure and heat transport in compressible convection. Entropy diffusion and the effects of using kinematic or dynamic diffusion laws.

Rotating convection. Why rotation is important in planetary interiors. Rossby number. Taylor-Proudman theorem. Onset of rotating convection, and how rotation changes the pattern of convection. Plane layer model, Busse annulus model and onset of convection in a rotating sphere. Subcritical instability. Recent work on heat transport in rotating convection, and the various regimes of rotating convection. Introduction to anelastic rotating convection.

Formation of large scale vortices and zonal flows. Recent results on large scale vortices in rotaing plane layer convection. Mechanisms of zonal flow generation, and the bursting phenomenon. Zonal flows in the Busse annulus. Simulations of convection in Boussinesq and anelastic rotating shells, and what they tell us about the formation of deep zonal flows.

Lecture 3 Wednesday 29th November 9am - 12pm

How planetary magnetic fields are generated

(i) Fundamentals of MHD and Maxwell's equations. The induction equation. Frozen flux and Alfven waves. Duct flow and flux expulsion. Stretch-twist-fold dynamos. The kinematic dynamo problem.

Classical dynamos and their connection to experimental dynamos: the G.O Roberts dynamo and the Karlsruhe dynamo experiment, the Ponomarenko flow and the Riga dynamo.

Fast and slow dynamos: the ABC and the Galloway-Proctor dynamos.

Mean field dynamo theory and Parker dynamo waves. Observational background of the solar magnetic field, and the 22 year cycle.

Relationship of numerical dynamo models to the classical dynamo models.

Lecture 4 Thursday 30th November 9am - 12pm

Magnetoconvection and MHD waves

(i) Magnetoconvection. Onset of convection with magnetic fields: steady and oscillatory convection. Relationship to sunspots. Rotating magnetoconvection.

(ii) Waves in rotating MHD. MAC waves. Torsional oscillations. Observations of torsional waves in the Earth's core and their relation to length of day observations. Torsional oscillations in dynamo models, and their excitation by convection.

(iii) Nonaxisymmetric waves in the Earth's core. Rossby waves and magnetic Rossby waves. Hide's work on magnetic Rossby waves in the core. Dispersion relation for magnetic Rossby waves in a sphere. The Malkus model of MHD waves in a full sphere. Westward drift and waves in the secular variation.

(iv) Shallow water MHD: the Gilman model. MHD waves in stable layers using shallow water MHD theory. Types of waves and asymptotic solutions. Instabilities.

(v) Magneto-rotational instabilities: theory, laboratory experiments, and astrophysical applications.

Lecture 5 Thursday 30th November 2pm - 5pm

How numerical dynamo models are constructed and what they produce

(i) Underlying equations to be solved. Boussinesq and Anelastic models.

(ii) Toroidal-poloidal decomposition, spherical harmonic expansions. Pseudo-spectral, finite element and finite difference methods. Implementation of boundary conditions.

(iii) Energy balance integrals and dynamo benchmarks.

(iv) Earth-like geodynamo models. Range of possible parameter values, and behaviour at the most extreme parameter values attainable.

(v) Giant planet dynamo models. How they are constructed and outputs from the Jupiter dynamo models.

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.