Planetary interiors: Magnetic fields, Convection and Dynamo Theory 1. Observational background to planetary structure

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FDEPS Lecture 1, Kyoto, 28th November 2017

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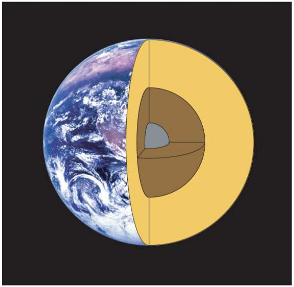
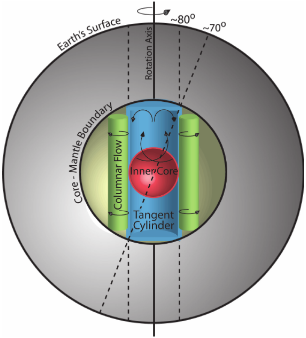
Section 1.

Observational background to planetary structure

1.1 Interior of the Earth

Internal structure of the Earth





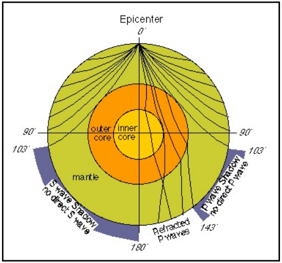
Interior structure of Earth 　　 Columnar flow and Tangent cylinder

Earth's radius is 6371 km. Earth's fluid outer core radius 3480 km, solid inner core radius 1220 km.

Radius ratio of solid inner core to outer core is 0.35.

Mantle convects on a timescale of millions of years. Fluid velocity in the core is $\sim 5 \times 10^{-4}\,\mathrm{m\,s^{-1}}$, so turn-over time is ~ 100 years.

Internal structure deduced from seismology



No shear waves (S-waves) can travel through liquid outer core: sound waves (P-waves) are refracted at core-mantle boundary (CMB) because they travel slower in the core. creating P-wave shadow zone.

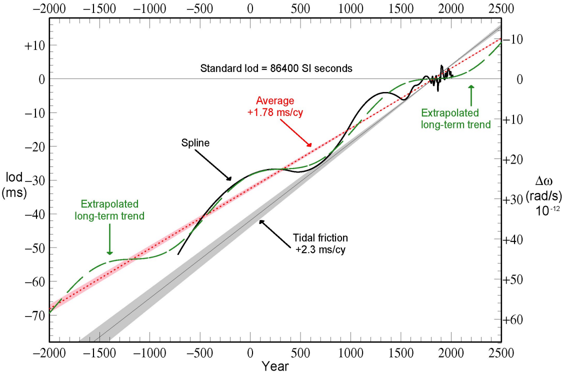
P-wave velocity also changes in the inner core.

Seismology enables us to work out the inner core and outer core radii. Also gives the density of the core as a function of radius r, the Preliminary Reference Earth model (PREM).

Density of outer core just below that of liquid iron at high pressure, suggesting outer core is a mixture of liquid iron with lighter elements (Oxygen, Sulphur?)

Inner core is nearly pure liquid iron.

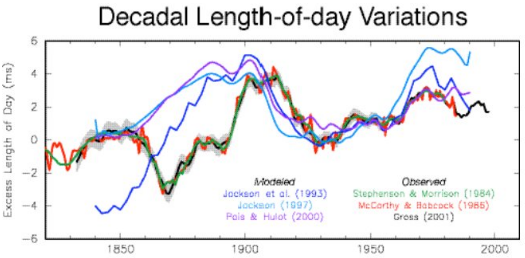
Length of day long term



The length of the day back to 1000 B.C. can be worked out from eclipse records.

The day is gradually getting longer, mainly due to the friction of the ocean tides raised by the Moon. The day is now about about 70 ms longer than it was 4000 years ago.

Decadal variations of the length of the day

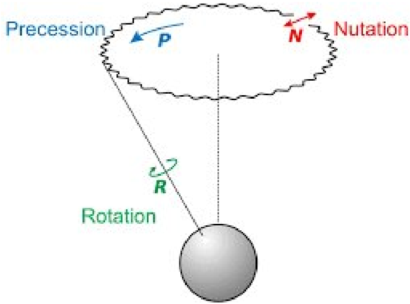


There are also variations on a decadal timescale (Green and Red curves). These are due to fluid motion in the Earth's core.

The total angular momentum of the Earth is constant on these timescales, so if core fluid rotates faster, the mantle must rotate slower to compensate. The length of the day measurses the rotation rate of the mantle.

By looking at how the Earth's magnetic field moves, we can estimate how fast the core is rotating, and work out how fast the mantle rotates. Blue curves give predicted length-of-day signal.

Precession and Nutation

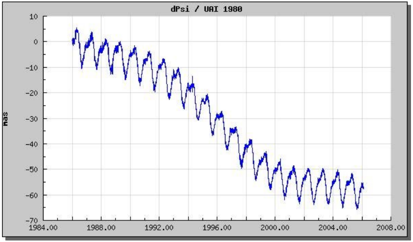


The Earth is an oblate spheroid (shaped like an orange). The gravitational pull of the Moon and the Sun makes the Earth precess about the ecliptic pole once every 26,000 years.

There are also small wobbles about the precessing track with a period of about a year.

It is now possible to measure these wobbles very accurately, using very long baseline interferometry (VLBI).

Nutation signals



Nutation is measured as a small displacement of the latitude and longitude of the rotation axis of the Earth. Figure is a 20 year record of the longitude variation: latitude variation looks similar.

Nutation is roughly periodic, but different frequencies can be extracted by Fourier analysis.

Some of these frequencies depend on conditions in the liquid core of the Earth, so it may be possible to use nutation to get information about conditions inside the core.

Thermal convection in the core

Outer core is believed to be convecting. This is the main reason why the Earth's core moves relative to the mantle.

Driven by thermal convection and compositional convection.

Thermal convection: the Earth was hot when it was formed. Gravitational collisions occurred building the Earth up from smaller pieces. These collisions released a lot of energy.

The Earth, including the core, has been cooling down for 4.5 billion years. A significant fraction of the heat leaving the core is carried by thermal conduction, but not all of it.

The rest is carried by convection, that is hot fluid rising and cooler fluid sinking. This is stirring the core, and this stirring generates the Earth's magnetic field by dynamo action.

The flow is slow, about 5×10^{-4} metres/sec, about the speed of a snail.

The adiabatic temperature gradient

The pressure rises as we go deeper into the core

$$\frac{dp}{dr} = -g\rho, \tag{1.1}$$

As core fluid rises, it expands because the pressure goes down, and so it cools. The adiabatic temperature gradient is

$$\left(\frac{dT}{dr}\right)_{ad} = -g\alpha T_{ad}/c_p, \tag{1.2}$$

Here α is the coefficient of thermal expansion and c_p the specific heat. The heat flux carried down this gradient by conduction is

$$F_{ad} = -\kappa\rho c_p\left(\frac{dT}{dr}\right)_{ad} = -K\left(\frac{dT}{dr}\right)_{ad} \tag{1.3}$$

Here κ is the thermal diffusity, and K is the thermal conductivity. Pozzo et al. (2012) found that the thermal conductivity is larger at high pressure, doubling the previous value of K

Condition for convection

Thermal convection only occurs if the heat flux produced by cooling (and possibly radioactivity) is greater than the amount that can be carried by conduction.

That is the actual heat flux $F > F_{ad}$ for convection.

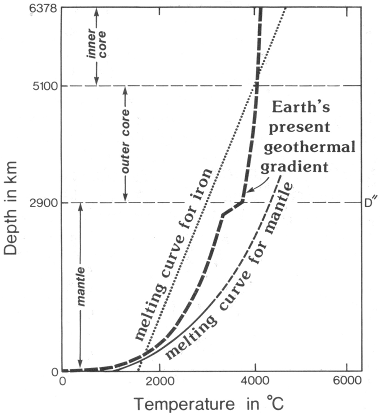
It is believed that the Earth is convecting, but other planets such as Mars and Venus have $F < F_{ad}$, so don't convect and don't have a dynamo.

When convection occurs, it can transport the heat outwards with only a very small superadiabatic temperature gradient, so

$$-\frac{dT}{dr} - \left(-\frac{dT}{dr}\right)_{ad} = \epsilon << 1 \tag{1.4}$$

.

So in the Earth's convecting core, the temperature gradient will be close to adiabatic. Temperature of core: CMB about 4000K, inner core 5,500K.



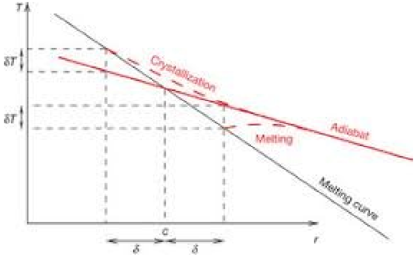
At bottom of mantle there is a thermal boundary layer D''.

In the outer core, geotherm is close to adiabatic.

Heat flux carried by conduction only $\sim$ 0.5TW at the ICB, rising to $\sim$ 10TW at the CMB. Mostly because of larger surface area.

If latent heat is dominant heat source, possible that core is superadiabatic (convecting) near ICB and subadiabatic (stable) near CMB.

The liquidus and the Inner Core



Why does the inner core freeze at the centre where it is hottest?

Melting temperature of outer core material depends on pressure as well as temperature. High pressure in the interior causes the inner core to solidify.

The P-T curve along which the core material melts is called the liquidus. It intersects the temperature curve, which is close to adiabatic, at the inner core.

Compositional convection

Compositional convection: iron in the liquid outer core is a combination of iron and lighter elements (Sulphur, Oxygen). As almost pure iron solidifies onto the inner core, it releases buoyant light material at the inner core boundary (ICB), which rises up and stirs the fluid.

How do we know this? Seismology indicates the outer core is significantly less dense than liquid iron, so there must be a light component. The inner core is quite close to the density of pure solid iron.

The light material released at the may collect at the top below the core-mantle boundary (CMB) (stably stratified 'inverted ocean') or it may just mix.

Thermal history of the Earth

When the Earth formed, it was hot, so the liquidus and the temperature curve didn't intersect, so there was no inner core.

If there is no radioactivity in the core, the rate of cooling is fast enough that the inner core formed less than 1Gyr ago. Much younger than Earth.

Rocks aged 3.5Gyr old which have been magnetised are known, so the geomagnetic field is much older than the inner core.

Dynamo not always driven by compositional convection, which requires an inner core. Could have been driven then by thermal convection alone.

Differentiation of terrestrial planets

The gravitational energy of formation, GM^2/R, must have turned into heat, and this is enough heat to ensure that the Earth and other terrestrial planets started hot enough to melt the rock.

The heaviest element present in large quantities, iron, made its way to the centre of the planet, releasing more gravitational energy. This process is known as differentiation, and can happen in a few Kyrs only.

This forms the structure of terrestrial planets, with iron cores and rocky mantles.

The heat of formation is ultimately the most likely energy source for planetary dynamos. Convection carries the heat flux outward, but there was so much initial heat, the planets havn't yet cooled down.

Radioactivity in the Core?

Radioactive elements are present in the mantle, and contribute a large part of the heat coming out of the Earth's surface (44TW).

Did the differentiating iron take any radioactive materials with it down to the core, like Uranium or radioactive Potassium K^{40}? Potassium is depleted in the mantle, but did it evaporate into space at formation or end up in planetary cores?

If it didn't, then the core is gradually cooling down, at a current rate of around 1K every 10Myr, which is possible.

With radioactivity, the core might be in thermal equilibrium, with the heat flux out of the core balancing the radioactive input.

These different scenarios have implications for solid inner core formation and for dynamo theory.

Mantle Convection

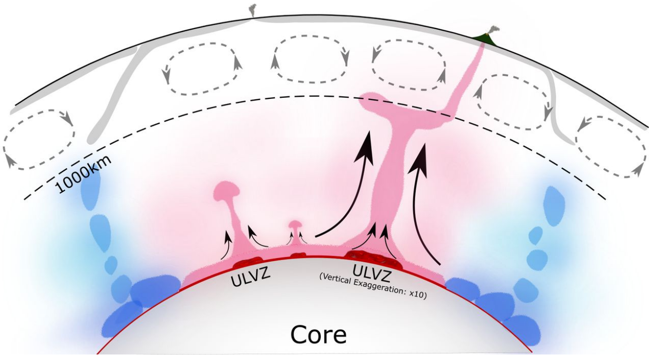
Large density jump at the Core-Mantle Boundary (CMB). Earth appears to be the only planet that currently has plate tectonics (mantle convection).

Although the mantle is a solid on short timescales (seismology) it can flow slowly on long-timescales. Shifts the plates around on 100Myr timescale.

Mantle convection transports the 46TW of heat generated in the interior to the surface. Heat flux at the CMB probably around 10-15TW.

Plumes coming out of the Core-Mantle boundary, may go right through the mantle and emerge at hotspots like Hawaii and Iceland.

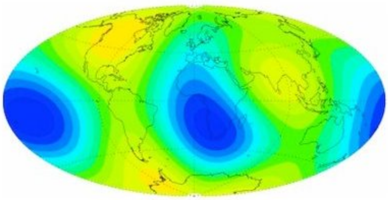
Mantle Convection Plumes



Yuan and Romanowicz, 2017.

ULVZ's are Ultra low velocity zones, where the seismic speed is surprisingly small. Hot buoyant mantle rises up in a plume, eventually emerging as a volcano.

Heat flux at the CMB



CMB Heat Flux from Vs tomography

The heat flux passing through the CMB is controlled by the mantle.

Because mantle convection is inhomogeneous, with a low heat flux under the Atlantic and Pacific, the core heat flux is similarly inhomogeneous.

Possible that the convection pattern and hence the dynamo in the core could reflect this inhomogeneity.

1.2 Interiors of other planets

Plate tectonics on other planets? Venus

Venus might be expected to have plate tectonics, but the surface suggests not.

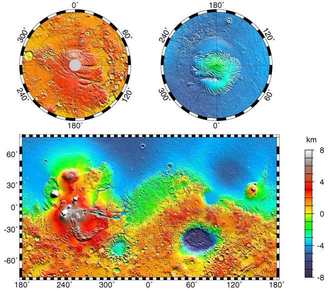
Venus surface does look quite recent, around 500Myr old however, with a lack of cratering compare to the Moon.

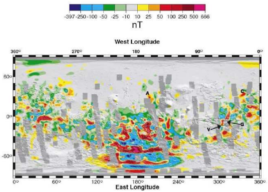
Possibly Venus undergoes periodic resurfacing: heat from radioactivity builds up in the interior because it can't escape by mantle convection.

No mantle convection means low heat flux through the iron core, so heat flux small enough to be conducted down the adiabat. So no core convection.

Mars also doesn't seem to have mantle convection at present. But there was a dynamo in the past, which magnetized the surface layers.

Mars has two very different hemispheres





Left Topographic map with Tharsis region prominent: Right Magnetic field of Mars, indicating the hemispheric structure is deep-seated. (Note longitude plotted differently! Hellas basin (blue) is nonmagnetic.)

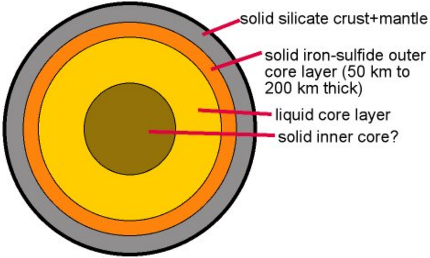
What happened on Mars?

It has been suggested that a dipolar $m = 1$ (spherical harmonics P_l^m) mantle convection may have occurred in the past, giving rise to this structure.

Alternatively, could be due to a giant impact.

Crustal magnetization is strong and global, so Mars must have had a strong magnetic field when the Southern Uplands formed. The Hellas basin formed about 500Myr after Mars formation, and is nonmagnetic.

Mars used to have a dynamo, but it switched off about 350Myr after formation. What caused it to fail?



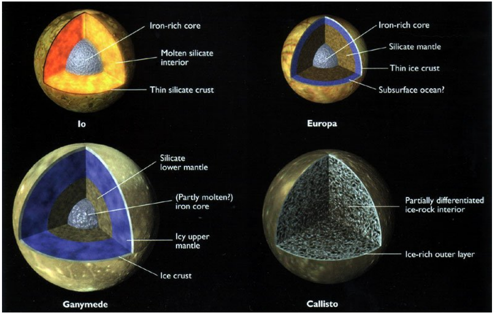
Mercury's new interior revealed by MESSENGER.
Core is larger than previously thought: 85% radius.

Mercury is a small planet, but is has a large iron core, so Mercury's magnetic field is probably due to a dynamo.

It is the high overall density of Mercury that indicates the large core.

Nutation observations suggest the core is at least partially liquid.

Moons of Jupiter

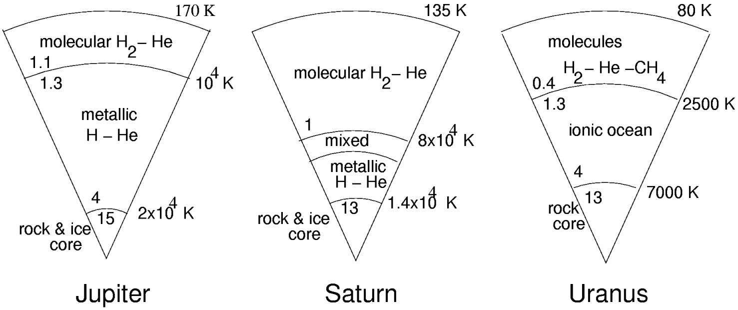


The internal structure of Jupiter's 4 largest moons has been worked out from their gravity fields.

The largest, Ganymede, has an internally generated magnetic field, so it probably has a liquid iron core and a convection driven dynamo.

The other moons apparently do not have internal fields, though Io is difficult as any internal field would be swamped by Jupiter's field.

Structure of the giant planets



The rocky core is actually entirely conjectural. It can't be seen in the gravity field, and consistent models can be produced with no core. Its drawn in because its hard to understand how Jupiter or Saturn formed without a core.

Metallic hydrogen

Metallic hydrogen layer is caused by the high pressure. The matter is squashed into a small space, and so the particle velocity goes up (exclusion principle).

Hydrogen ionizes, and so becomes electrically conducting. This allows currents to flow and hence a dynamo.

Increase in particle velocity due to the exclusion principle increases the pressure, see e.g. Kippenhahn, Weigert and Weiss, 2012.

High pressure physicists have developed sophisticated equations of state, giving pressure in terms of density and temperature, using quantum mechanics methods.

These techniques also give the electrical and thermal conductivities at very high pressure, e.g. French et al. 2012.

Saturn and the ice giants

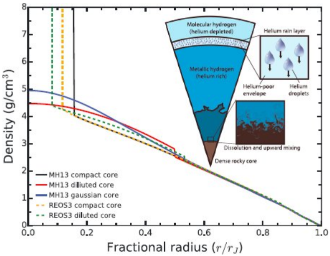
Saturn's lower mass leads to lower pressures and hence a smaller metallic hydrogen region.

Helium rain: the upper parts of gas giants have lower helium content than solar ratio. Suggestion is that there is an inhomogenous region where a helium/hydrogen phase transition occurs leading to helium droplets forming and helium 'rain'.

Ice Giants, Uranus and Neptune. These planets have a mantle believed to be a water-ammonia ocean, which has an ionic electrical conductivity. This is where the dynamo is believed to be.

However, ionic conductivity is much lower than from metallic hydrogen or liquid iron. Further complication is that Uranus has very little heat flux coming from interior.

Dilute core model for Jupiter?



The standard French et al. model used for dynamo simulations fits the new Juno gravity data results rather well.

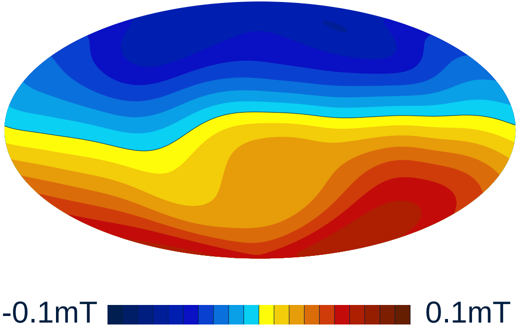
However, different density functional theories give different equations of state. Using one of these would allow a different equilibrium structure model that still satisfied Juno constraints.

Helium rain-out might have led to a dilute core model: also might have given rise to the stable layer suggested by Saturn's axisymmetric field.

1.3 Earth's magnetic field

B_r at Earth's surface

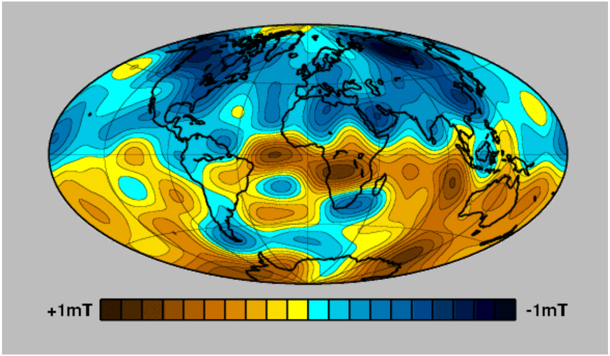
Earth: mainly dipolar magnetic field. Inclination of dipole axis to rotation axis currently 11.5°.



Field at the CMB in year 2000, units 10^{-3} T. Note the non-dipolar behaviour in the South hemisphere: the weak field associated with the South Atlantic anomaly.

Earth's field evaluated at the CMB

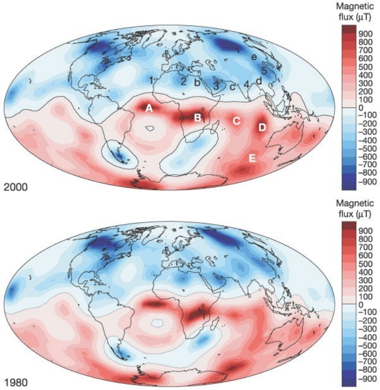
Field at Core-Mantle boundary, CMB, can be reconstructed from satellite and observatory data. Strength $\sim 8 \times 10^{-4}$Tesla $= \sim 8$ Gauss.



Field at the CMB in year 2000, units 10^{-3} T. Note the intense flux patches near Canada and Siberia. Patches under Africa are moving westward. Field at poles surprisingly low.

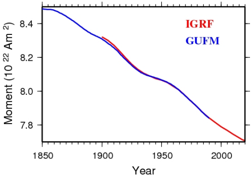
Geomagnetic field is described in terms of the Gauss coefficients of the spherical harmonic expansion outside the core $\mathbf{B} = -\nabla\Psi$, $\nabla \cdot \mathbf{B} = 0$, so $\nabla^2\Psi = 0$, Laplace equation.

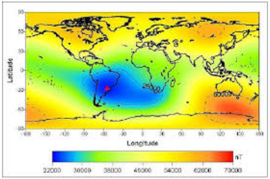
$$\Psi = r_s \sum_{n=1}^{\infty} \sum_{m=0}^{m=n} \left(\frac{r_s}{r}\right)^{n+1} P_n^m(\cos\theta)(g_n^m \cos m\phi + h_n^m \sin m\phi). \quad (1.5)$$



Magnetic field B_r measured at the surface, but mantle insulating, so can extrapolate field B_r to Core-Mantle boundary (CMB).

Radial geomagnetic field at CMB in 1980 and 2000.
Small changes occur in 20 years.
Secular variation is first time-derivative of geomagnetic field.
Some Westward drift is visible.





- Dipole moment, proportional to g_1^0, is declining steadily since 1850. IGRF=International Geomagnetic Reference Field. GUFM is a field model constructed by synthesizing available data since 1590.
- Plot of field intensity $|\mathbf{B}|$ shows the weak patch in the South Atlantic. Corresponds to reversed field when extrapolated down to the core.
- This patch is growing, which is why dipole is declining. Reversal ahead?

Note that extrapolation down to the CMB only works for n and m less than about 15. We cannot see very small scale features at the CMB.

Dynamo theory for planetary magnetism

No permanent magnetism above the Curie point, 800°C for iron. Earth's outer core between 4000K and 5500K.

Fluid motion in the core produces dynamo action (Larmor, 1919)

the magnetic field obeys the induction equation which is

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}, \tag{1.6}$$

if the electrical conductivity is assumed constant. Full derivation in lecture 3.

The induction term must overcome the diffusion term. The magnetic diffusivity $\eta = 1/\mu_0 \sigma$, where σ is the electrical conductivity and $\mu_0 = 4\pi \times 10^{-7}$ is the permeability.

The ratio of induction to diffusion is approximately the Magnetic Reynolds number $R_m = U_* \ell / \eta$. Here U_* is the typical fluid velocity, ℓ the typical length scale, either outer core radius or gap between inner/outer core.

Magnetic Reynolds number

It can be proved that for induction to overcome diffusion in spherical geometry, R_m must be greater than π^2, and in practice in the numerical dynamo simulations R_m of around 50 is needed for dynamo action.

Earth's core velocity $U_* \sim 4 \times 10^{-4}\,\mathrm{ms}^{-1}$, and Earth's core size $\ell \sim \quad 3.5 \times 10^6\,\mathrm{m}$, giving $R_m \sim 700$

U_* from secular variation studies 'Westward Drift'

Ohmic decay time $\ell^2/\pi^2\eta \sim 20,000$ years

How is the velocity at the CMB found from observing the geomagnetic field?

Ignore diffusion, (large R_m) and take radial component of induction equation,

$$\frac{\partial \mathbf{B}}{\partial t} = -(\mathbf{u} \cdot \nabla)\mathbf{B} + (\mathbf{B} \cdot \nabla)\mathbf{u}, \tag{1.7}$$

and since $u_r = 0$ at CMB, get

$$\frac{\partial B_r}{\partial t} = -(\mathbf{u} \cdot \nabla) B_r. \tag{1.8}$$

Since B_r and $\partial B_r / \partial t$ can be observed, we might hope to use this equation to determine $\mathbf{u}$. Unfortunately, there are two unknown components of $\mathbf{u}$ and only one equation. Velocities along contours of constant B_r give no signal.
Assume tangential geostrophy, that is near CMB

$$2\rho\Omega\hat{\mathbf{r}}\cos\theta \times \mathbf{u} = -\nabla p, \tag{1.9}$$

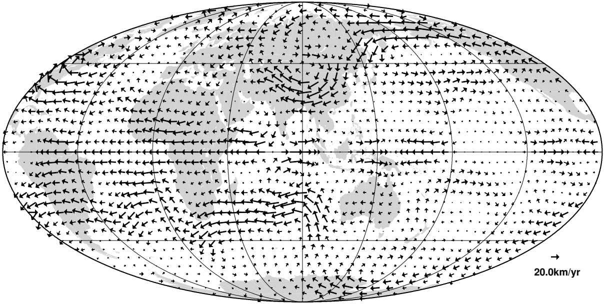
Reasonable, as buoyancy and Lorentz forces small close to CMB.

Core flow inversion (2)

Taking the radial component of the curl of this force balance gives

$$\nabla \cdot \cos\theta \mathbf{u} = 0, \qquad (1.10)$$

and (1.8) and (1.10) are enough to reconstruct $\mathbf{u}$.



20 km per year is 6×10^{-4} metres/sec. Slower than a snail! Note westward drift in S. Atlantic, Indian Ocean. Pacific has low secular variation. Waves or flow?

Energy Sources for Planetary Dynamos

• Dynamo energy source: Precession, Tidal interactions, Thermal Convection, Compositional Convection

Tides and precession derive their energy from the Earth's rotation. Tides distort the CMB, precession is caused by the torques on the Earth's equatorial bulge. Earth's axis of rotation precesses once every 26,000 years.

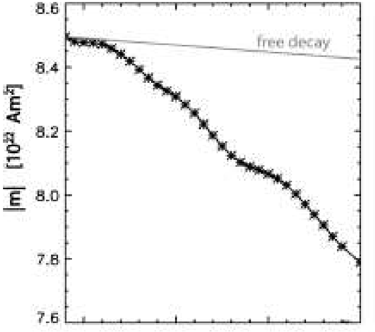
Precessing systems lead to a core flow which is unstable, and these instabilities can drive motion, just as buoyancy instabilities can.

Successful simulations have been done, but only with Precession/rotation ratios of 10^{-3}. Stabilised even by very small viscosity, so not clear it works in Earth's core.

Dipole moment

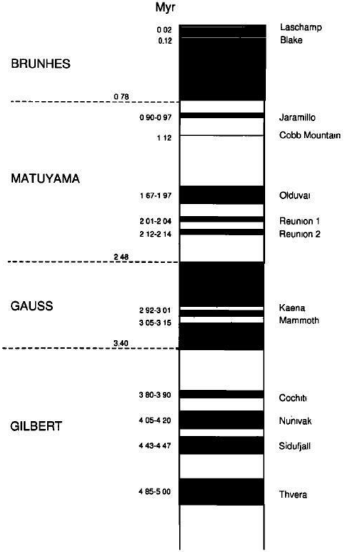
The dipole moment is $M = \dfrac{4\pi r_s^3}{\mu_0} g_1$, where

$$g_1 = \left((g_1^0)^2 + (g_1^1)^2 + (h_1^1)^2\right)^2 .$$



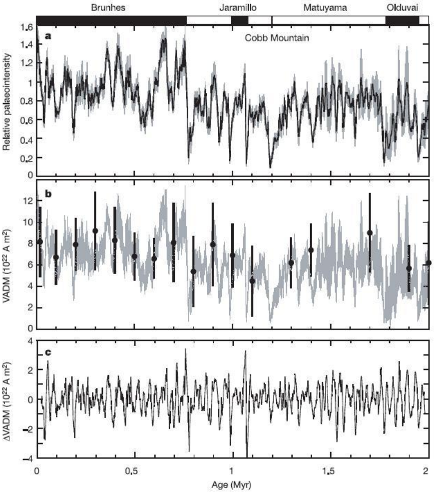
The Earth's dipole moment is currently decreasing faster than free decay rate, i.e. if there were no dynamo! About half its value in Roman times.
Growing reversed flux patches under S. Africa?

Geomagnetic reversal record: last 5 million years



The Earth's field reverses randomly about once every 0.3 million years. There have been periods as long as 60 million years with no reversals (superchrons). Reversals occur relatively quickly $\sim 10,000$ years. During a reversal, the dipole axis traces out a path at the Earth's surface: are there preferred longitudes?

Dipole component varies significantly between reversals, the so-called excursions.



Current decline may be an excursion rather than a reversal.

Other terrestrial planets

Three ideas for Mercury's weak field:

(i) No dynamo, but solar wind field amplified.

(ii) As Mercury cooled, inner core grew. Remaining liquid outer core has progressively higher impurity content, so thin shell of liquid iron. Thin shell dynamos have high harmonic content, low dipole content.

(iii) Most of Mercury's core is liquid, but mostly stably stratified as heat produced mostly carried by conduction. Dynamo only near ICB, only small fraction of field penetrates stably stratified upper core.

1.4 Magnetic fields of other planets

Magnetic fields of other terrestrial planets

Mercury: internal field of dipolar structure. Strength at CMB $\sim 1.4 \times 10^{-6}$T, which is surprisingly small. Rotates only once every 57 days. Liquid iron core, radius 1900 km.

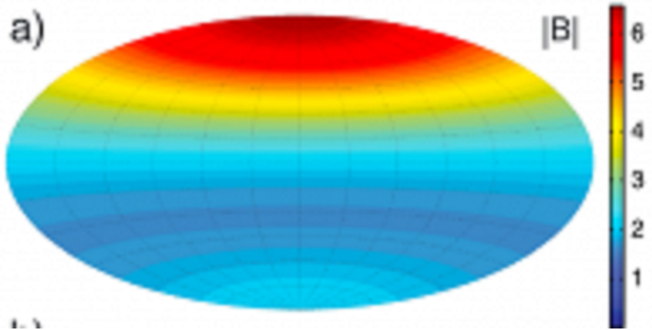
Venus: no magnetic field.

Ganymede: approx dipolar, inclination $\sim 10^{\circ}$. Strength at CMB $\sim 2.5 \times 10^{-4}$T. Rotates once every 7 days. Core radius 480 km

Io: too close to Jupiter's magnetic field to tell whether it has its own magnetic field. Other large moons don't have internal fields at present.

Extinct Martian field is deduced from strong crustal magnetism, which suggests Mars had a dipole field in the past. Lunar rocks also have remanent magnetism

Mercury's magnetic field



Mercury's magnetic field from the Messenger mission.

The field is weak, but fairly axisymmetric. However, the field is much stronger in the northern hemisphere, so there is a quadrupole and a dipole component.

Sometimes called a hemispherical dynamo.

Other terrestrial planets 2

Venus rotates only once every 243 days. But Rossby number $U_*/\ell\Omega$ with Earth-like U_* would still be small.

Venus appears to have no plate tectonics. This could reduce F and hence make Venus's core subadiabatic.

Venus seems to have been resurfaced 300 million years ago. Possibly there was mantle convection then, and possibly a dynamo. High surface temperature unfavourable for remanent magnetism.

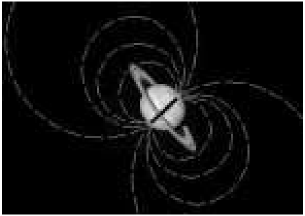
Ganymede has a weak surface field, but a small core, so at CMB field is ~ 2 Gauss, giving an Elsasser number of order unity. Surprising that there is sufficient heating in the core to make it convect.

Collapse of Martian dynamo possibly due to core becoming stably stratified.

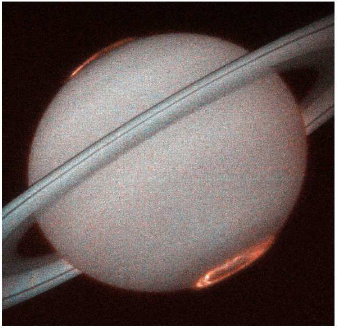
Planetary magnetic fields: Giant planets

Giant planets are all rotating rapidly.
Jupiter: strong magnetic field, basically dipolar (more higher harmonics than Earth), inclined 10° to rotation axis, about 17 gauss at surface.

Saturn: very axisymmetric field, about 2.5 gauss at surface.

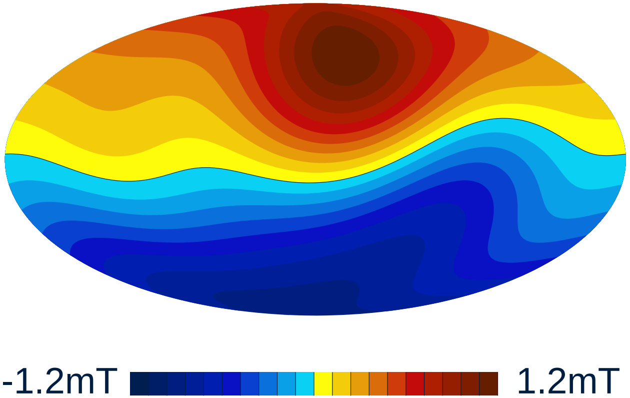


Dipole field of Saturn



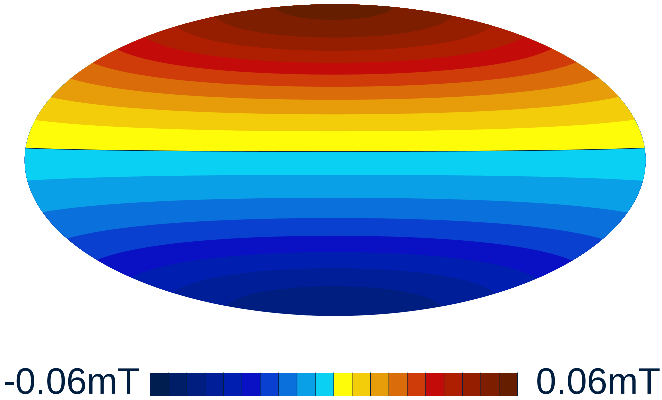
Aurora of Saturn, produced by particles moving along field lines

Jupiter's magnetic field



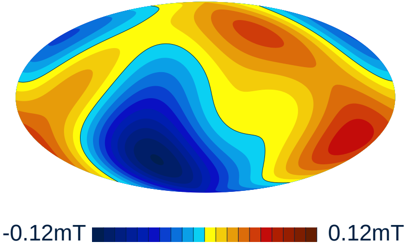
Radial magnetic field at the surface of Jupiter.

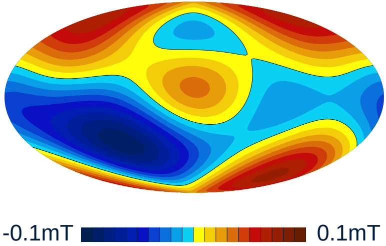
Tilted dipolar field, broadly similar to the geomagnetic field.



Radial magnetic field at the surface of Saturn.

Field is very axisymmetric. Possibly due to a stably stratified layer in Saturn, with a zonal flow wiping out non-axisymmetric components above the dynamo.





Magnetic field of Uranus

Magnetic field of Neptune.

The fields were constructed from Voyager data.

The ice giants have non-dipolar magnetic fields, the quadrupole and dipole components being of similar strength.

Dynamos in the Giant Planets

Electrical conductivity is due to very high pressure ionising electrons (quantum effect).

Earth-like conductivity in the deep interior, gradually falling to low values near the surface.

Giant planets are convecting, so thermal convection most natural energy source.

Some secular variation occurs on Jupiter, suggesting core flow $\sim 10^{-2}$metres/sec. *Rm* large.

Why is Saturn's field so axisymmetric? Stably stratified region with strong differential rotation outside the dynamo region? This could axisymmetrise the observed field

Uranus and Neptune have very unusual fields. Thin shell dynamos suggested. Not much known about internal structure and heat flux. Ionic conductivity is low, so *Rm* cannot be very large.

Major Problems in Planetary Dynamo theory

(i) Why is Mercury's field so weak?

(ii) Why does Venus not have a magnetic field?

(iii) Why are most planets dipole dominated? Why do geomagnetic reversals occur?

(iv) What powered the geodynamo before inner core formation?

(v) What killed off the Martian dynamo?

(vi) How does Ganymede maintain a dynamo when its core is so small?

(vii) Why is Saturn's field so axisymmetric?

(viii) Why are the fields of Uranus and Neptune non-dipolar?

1.5 Zonal flows on giant planets

Zonal winds on the giant planets

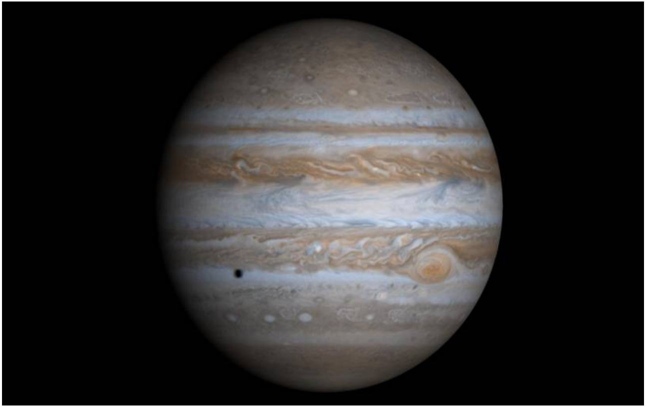
• Jupiter and Saturn have belts and zones associated with east-west zonal flows: east-west flows independent of longitude

• Also, long-lived storms such as the Great Red Spot on Jupiter

• What drives these winds? Why are they so different from winds on Earth?

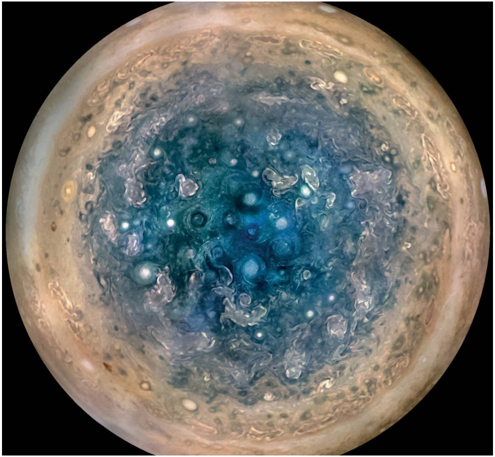
Are the winds just on the surface, or do they reach deep into the planet?

Jupiter from the Cassini Mission



Giant planets have banded structure. Also huge vortices such as the Great Red Spot, and smaller white ovals.

South pole of Jupiter from the Juno Mission



Zonal flow bands don't reach up to the poles.
Instead there are very large scale vortices.

Storms on Outer Planets

As well as the persistent zonal flows, also get giant storms on all the outer planets.

Great Red Spot of Jupiter is only one we know has lasted hundreds of years. Noted by Hooke end of 17th century.

Great White spots on Saturn last typically a few years. There are also vortices at Saturn's poles.

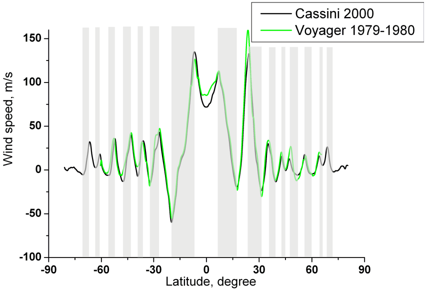
Dark spot of Neptune lasted twenty years, but then disappeared.

The Great Red Spot

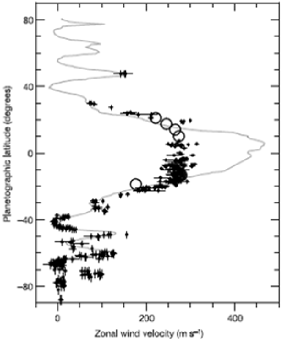
Giant storm, larger than entire Earth. Anticyclonic vortex that has lasted over 300 years

Maintained by absorbing small vortices.

Why doesn't it break up?

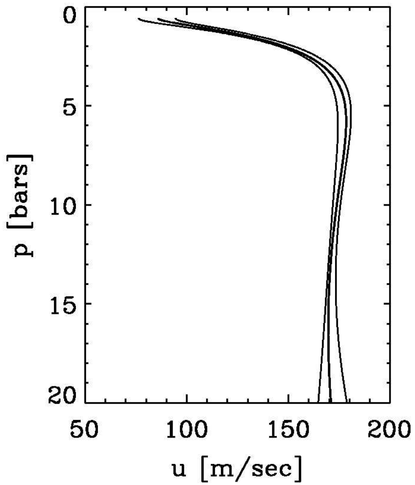


Jupiter zonal flow



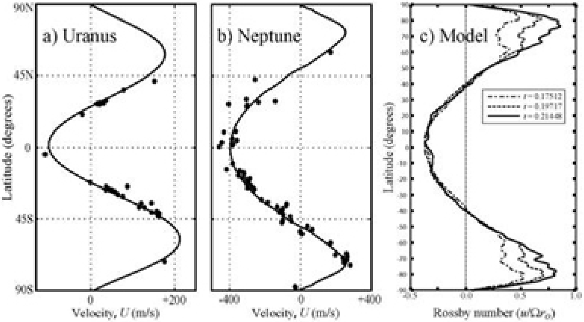
Saturn zonal flow

More variability in Saturn's winds than Jupiter's. Eastward (prograde) jets at equatorward side of dark belts, westward (retrograde) jets at poleward side of dark belts.



Probe entered 7° N, in eastward equatorial jet. Found velocity increases inward, supporting deep convection model.

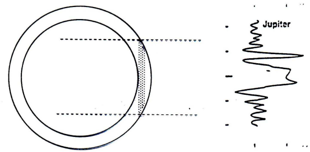
Figure 4. Jupiter's zonal winds at 7.4°N latitude obtained by Doppler tracking of the Galileo Probe signal (Atkinson *et al* 1997). The thick curve is the nominal wind profile and the thin curves bound the uncertainty envelope.



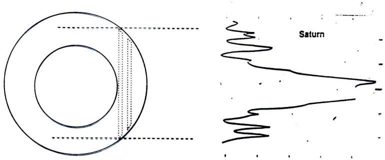
Note that the equatorial belt goes westward on the ice giants, eastward on Jupiter and Saturn

Quite different from the Solar differential rotation, which has a rapidly rotating equator and slowly rotating poles

Zonal flows in Jupiter and Saturn



Jupiter: Large radius ratio, narrowly confined bands



Saturn: Smaller radius ratio, less confined bands

Are zonal flows **deep**, 15,000 km, driven by convection in molecular H/He layer, or **shallow**, confined to stably stratified surface layers? Broader equatorial belt on Saturn suggests that the surface zonal flow is affected by the deep structure

Gravity field

The gravity field around giant planets can be expanded in spherical harmonics

$$V = \frac{GM}{r}(1 + \sum_{n=2} \left(\frac{a}{r}\right)^n \sum_{m=0}^{m=n} P_n^m(\cos\theta)(C_{nm}\cos m\phi + S_{nm}\sin m\phi)$$

The gravity field is measured by satellites and gives information about the distribution of mass inside the planet.

Juno (arrived July 2016) is measuring the gravity field accurately.

Centrifugal force affects mass distribution, so internal rotation rate can in principle be determined.