Planetary Magnetism
1. Observational Background

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What are planets?

Planetary Science perspective: All bodies with radius > 1000 km, that are smaller than brown dwarfs.

Still hot in the core, but not hot enough for nuclear reactions. Include the larger moons as well as the conventional planets.

Terrestrial planets: rocky mantle and (usually) an iron core. Mercury, Venus, Earth, Mars, Moon, 4 Galilean satellites of Jupiter, Titan and Triton.

Gas Giants: Mostly hydrogen and helium, probably with a small solid core. Jupiter, Saturn and most of the exoplanets, since large exoplanets easier to observe.

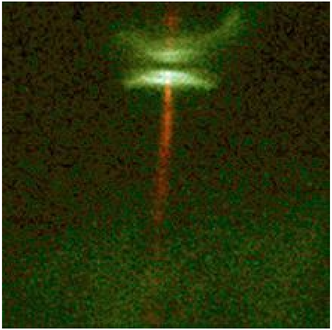
Ice Giants: Uranus and Neptune, mostly water and ammonia. Pluto and Charon. Fluid inside some planetary cores is stirred by convection.

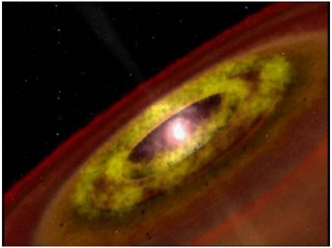
How did the planets form?

Current view is that planets formed from an accretion disk at the same time as the Sun. Star and planet formation all part of the same process. This idea goes back to Kant and Laplace.

Star forming region in the Magellanic cloud.

Star forming regions





Most information about solar system formation comes from observations of T Tauri disks.

Left: a real T-Tauri disk with an axial jet. Right: artists impression of a T-Tauri protoplanetary disk.

Planet building

How do planetary systems form from the protoplanetary nebula?

Very active area of research, but still highly controversial. Many unresolved problems.

Gravitational accretion or collisions of planetesimals?

Diversity of planets suggests collisions are important: e.g. Mercury has a large core and small mantle: lost its mantle in a collision?

Moon has only very small iron core: result of impact between proto-Earth and proto-Moon?

Theories in which near circular orbits are formed (as in solar system) have to come to terms with very eccentric orbits of many exoplanets.

Three stages of Planet formation

Grain condensation and growth

The molecular low temperature (¡1000K) clouds contain dust and grains. As the disk collapses, the density goes up, and grains collide and stick together to form larger objects.

This process is not well understood, but there is observational evidence it occurs. Possibly larger bodies rapidly scoop up more material, so leading to planetesimals of order 1km in size.

Planetesimal dynamics

These planetesimals are now in orbit around the star, but many have intersecting orbits, leading to low velocity impacts which result in fewer, larger objects.

This process can be modelled using N-body integrations.

Late stage collisions

As this process continues, all planetesimals on crossing orbits get merged, leaving much larger bodies on non-crossing orbits.

However, self-gravitation perturbs the orbits over a 10Myr timescale, leading to late stage large impacts.

The evidence of such large impacts can still be seen.

There is also evidence for planetary migration during formation. Difficult to get gas giants to grow in their current location before the gas is lost: T-Tauri stars lose their gas quickly.

Particularly difficult to explain exoplanet formation without migration.

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).

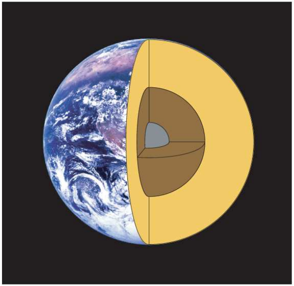
Did the differentiating iron take any radioactive materials with it down to the core, like Uranium or radioactive Potassium K^{40}? Potassium is depleted in the mantle, but did it evaporate into space at formation or end up in planetary cores?

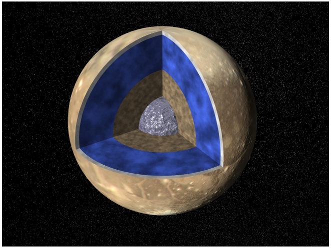
If it didn't, then the core is gradually cooling down, at a current rate of around 1K every 10Myr, which is possible.

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.

Internal structure of planets





Interior structure of Earth Interior structure of Ganymede

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

Earth's solid inner core is deduced from seismology: don't yet know whether other planets have solid inner cores.

Why is there a solid core where the temperature is largest?

Increasing pressure raises melting point.

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.

Convection in the core

Outer core is probably convecting. Driven by thermal convection and 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, which rises and stirs the fluid.

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

If no radioactivity in the core, the rate of cooling is fast enough that the inner core formed only 1Gyr ago. Much younger than Earth, and much younger than geomagnetic field. Dynamo not always driven by compositional convection.

Temperature of core: CMB about 4000K, inner core 5,500K.

Mantle Convection

Large density jump at the Core-Mantle Boundary (CMB). Earth appears to be the only planet currently have 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 44TW of heat generated in the interior to the surface. Heat flux at the CMB probably around 10TW.

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

Thermal convection

Thermal convection only occurs if the heat flux produced is greater than the amount that can be carried by conduction.

The adiabatic temperature gradient is

$$T_{ad}^{-1}\left(\frac{dT}{dr}\right)_{ad} = -g\alpha/c_p,$$

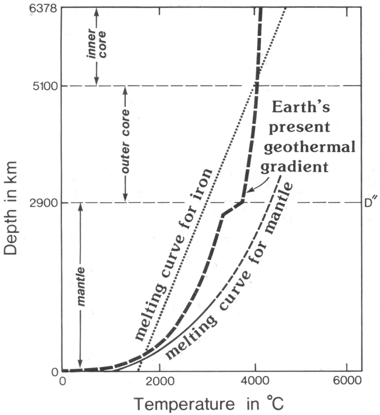
Here α is the coefficient of thermal expansion and c_p the specific heat.

The heat flux carried down this gradient by conduction is

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

For convection need the actual heat flux $F > F_{ad}$

The geotherm



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 ~ 0.5TW at the ICB, rising to ~ 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.

Wiedemann-Franz law

In a metallic core, thermal and electrical conductivities are proportional:

Wiedemann-Franz law $\kappa \rho c_p = 0.02 T/\eta$

High electrical conductivity (low η) implies high thermal conductivity, making F_{ad} large.

Stevenson's paradox: high electrical conductivity is bad for dynamos, because it makes F_{ad} larger than F. Since the heat is conducted rather than convected, nothing to stir the core!

Plate tectonics on other planets? Venus

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

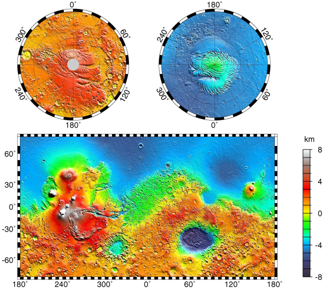
Venus surface does look quite recent, around 500Myr old however, with a lack of cratering compare to the Moon.

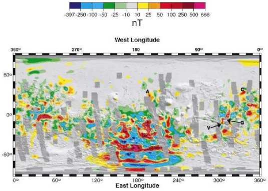
Possibly Venus undergoes periodic resurfacing: heat from radioactivity builds up in the interior because it can't escape by mantle convection.

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?

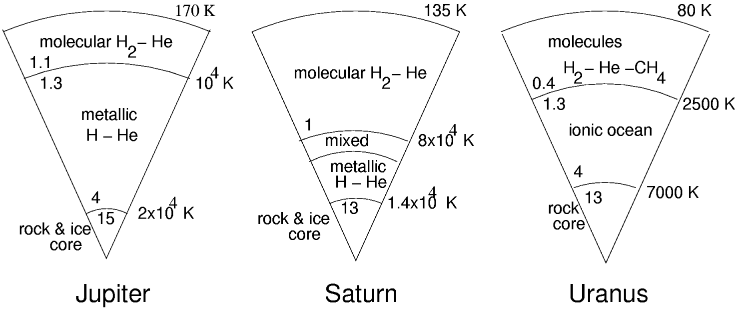
It has been suggested that a dipolar $m = 1$ (spherical harmonics P_l^m) mantle convection may have occurred in the past, giving rise to this structure.

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?

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.

Centrally Condensed Polytropic Basic State

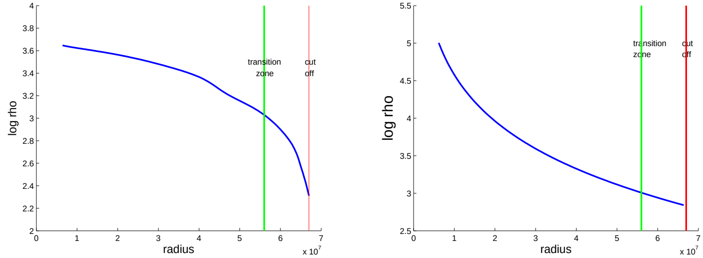
Simpler models were used for the anelastic benchmark exercise.

$$p = p_0 \zeta^{n+1}, \quad \rho = \rho_0 \zeta^n, \quad T = T_0 \zeta, \qquad \zeta = \frac{c_1}{r} + c_0$$

where c_1 and c_0 are constants. These simple formulae originate from assuming gravity comes from a point source at the origin.

$$N_\rho = \ln\left(\frac{\rho_i}{\rho_o}\right), \qquad n: \text{ polytropic index}, \qquad \text{radius ratio} = \frac{r_i}{r_o}$$

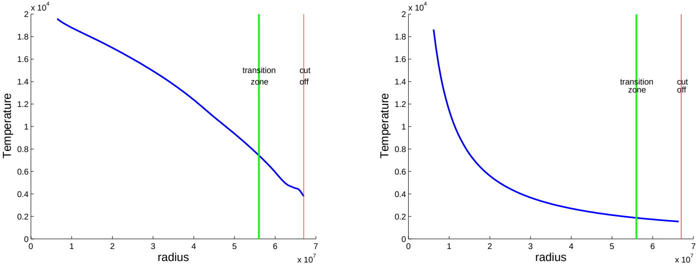
$N_\rho = 3$ has factor 20 density drop across shell, $N_\rho = 5$ factor 150.
An $n = 1$ polytrope that is not centrally condensed, $p = K\rho^2$, has also been used as a model for giant planets



Left: density of Jupiter from the French et al. 2012 model, using ab initio quantum calculations.

Inner core radius 6,450 km, mass 1% Jupiter's. Jupiter radius 69,890 km.

Right: a centrally condensed polytrope model.



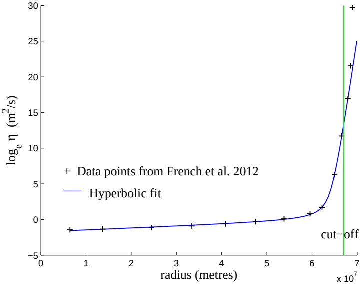
Left: temperature from the French et al. model.

Right: temperature from the condensed polytrope moodel.

The temperature structure is very non-polytropic. In the interior, pressure is provided by electron degeneracy pressure not thermal pressure.

The temperature gradient is much steeper near the surface for the Jupiter model compared to the polytrope.

Jupiter electrical diffusivity profile



Diffusivity $\eta = 1/\mu\sigma$, σ being the electrical conductivity.

$+$ signs are the French et al. 2012 model, the curve is a smoothed hyperbolic fit. The French et al. conductivity drops off super-exponentially, whereas this model drops off exponentially: difference only significant beyond the cut-off.

Stably stratified layers?

An important question: are giant planets convecting everywhere in their interiors?

Uranus has low heat flux from its interior: possibly heat flux blocked by a stable layer?

Saturn may also have a stable layer in its interior, which may be connected with it having a very axisymmetric magnetic field.

Stable layers could be due to helium rain, or to presence of heavy elements. Active area of research.

Gravity field

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

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

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

Juno (arrives July 2016) will measure the gravity field accurately.

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

Zonal winds on the giant planets

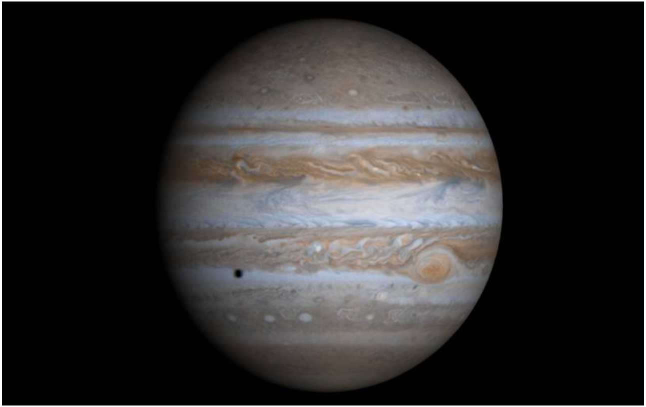
• Jupiter and Saturn have belts and zones associated with east-west zonal flows: east-west flows independent of longitude

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

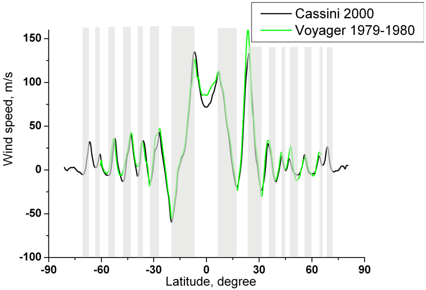
• What drives these winds? Why are they so different from winds on Earth?

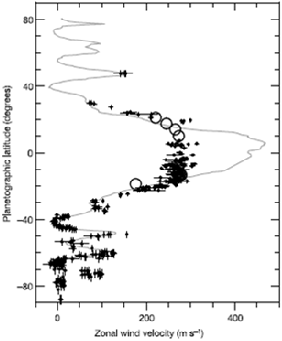
Are the winds just on the surface, or do they reach deep into the planet?

Jupiter from the Cassini Mission



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

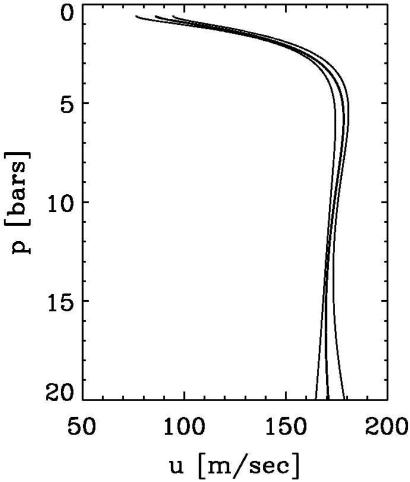




Jupiter zonal flow

Saturn zonal flow

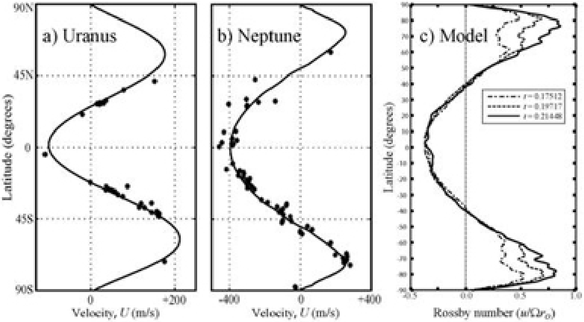
More variability in Saturn's winds than Jupiter's. Eastward (prograde) jets at equatorward side of dark belts, westward (retrograde) jets at poleward side of dark belts.



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.

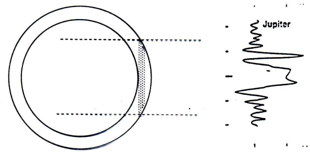
Winds on the Ice Giants



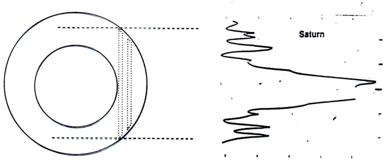
Note that the equatorial belt goes westward on the ice giants, eastward on Jupiter and Saturn

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

Zonal flows in Jupiter and Saturn

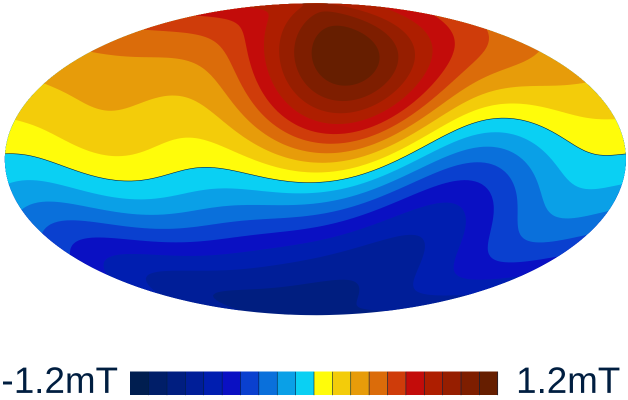


Jupiter: Large radius ratio, narrowly confined bands



Saturn: Smaller radius ratio, less confined bands

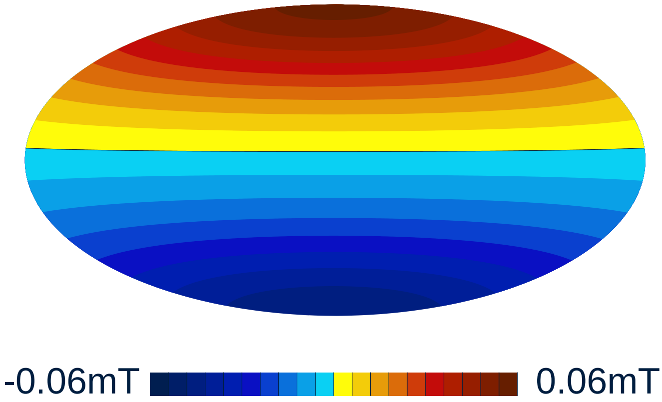
Are zonal flows **deep**, 15,000 km, driven by convection in molecular H/He layer, or **shallow**, confined to stably stratified surface layers? Broader equatorial belt on Saturn suggests that the surface zonal flow is affected by the deep structure



Radial magnetic field at the surface of Jupiter.

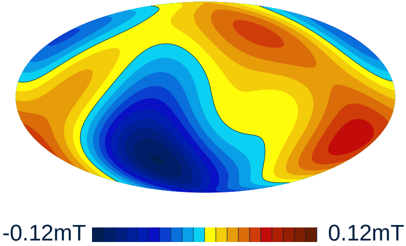
Tilted dipolar field, broadly similar to the geomagnetic field.

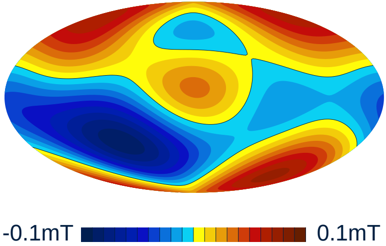
Saturn's magnetic field



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.



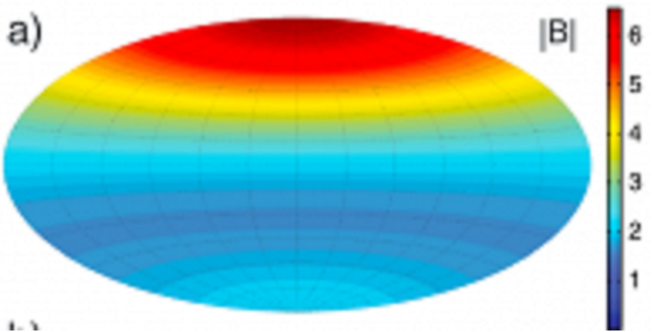


Magnetic field of Uranus

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.



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.

Major Problems in Planetary Dynamo theory

(i) Why is Mercury's field off-centre and 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?

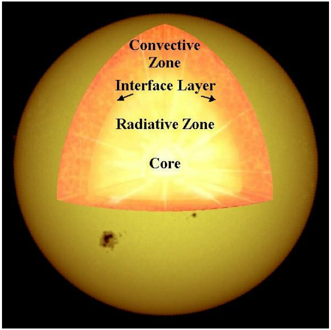
(v) What killed off the Martian dynamo?

(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?

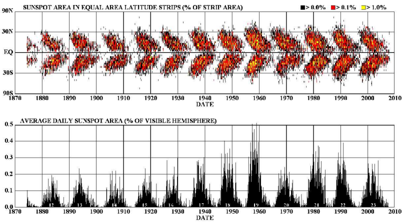
Solar Dynamo



Sun's magnetic field is generated in the convection zone. The surface sunspots are the evidence of magnetic activity.
The interior is stably stratified.
The interface region is the solar tachocline.

Heat is carried by convection. Velocity varies from a few metres per second near the interface region to several km/sec near the surface. It is this motion which is ultimately responsible for the solar dynamo.

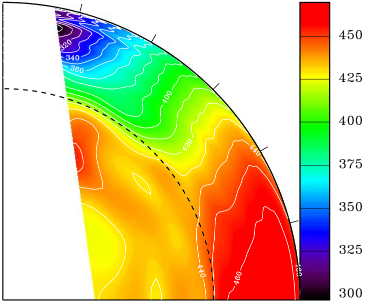
The 22-year cycle



Sunspots have an eleven-year cycle, but the magnetic field reverses sign in alternate cycles. Sunspots first emerge at higher latitudes, then migrate towards the equator. The field has a dynamo wave form.
Leads to the Butterfly diagram

Currently in a very long minimum. There have been long intervals with no solar activity (Maunder minima). Last was from 1650-1720.

The solar differential rotation



Using helioseismology, we can measure the internal rotation rate of the Sun, shown in nHz. The differential rotation is driven by rotating convection. The interface region is called the solar tachocline, because it is a region of strong vertical velocity shear.

Meridional magnetic field may be being stretched out there to give a strong toroidal fields. A small magnetic field in the stably stratified region could account for the near solid body rotation there.