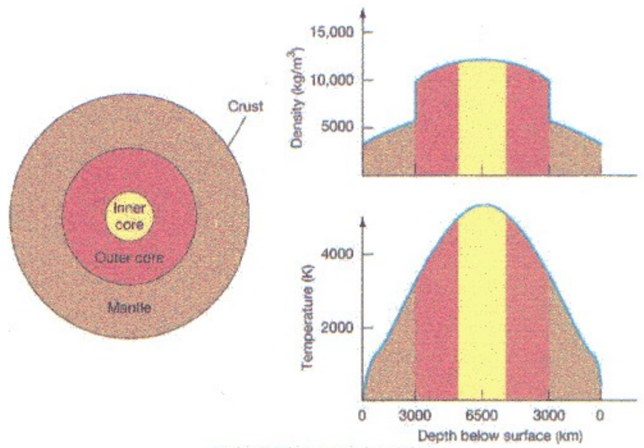
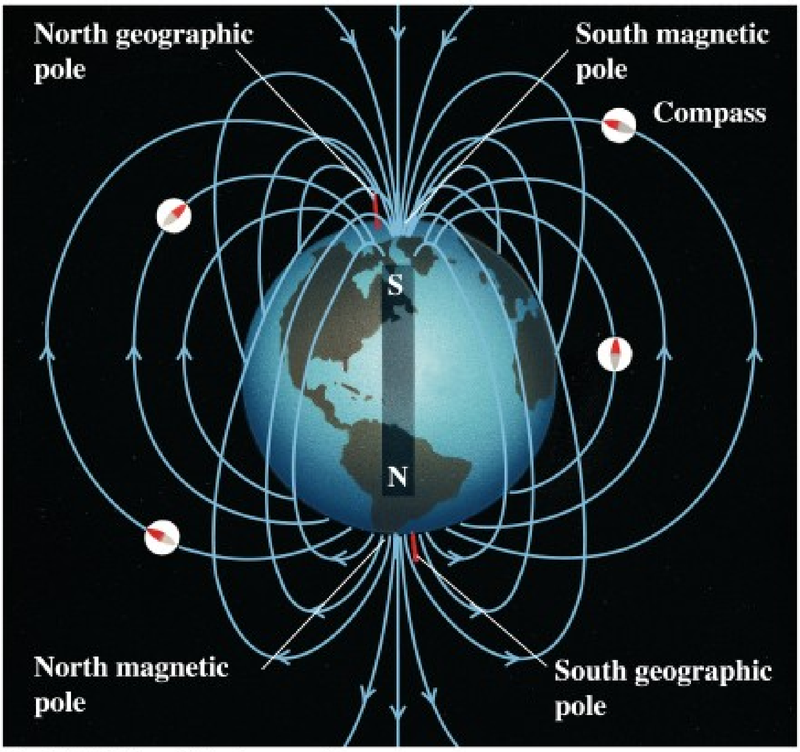
CHAPTER 1

- **Earth magnetic field.**
- **Planet rotation and core at the origin of the magnetic field.**
- **Charged particles motion in the magnetic field of the planets.**
- **Van Allen belts and plasma torus of Jupiter due to Io.**
- **Magnetosphere of a planet.**

Earth magnetic field



Origin: convective currents in the outer fluid core coupled to the planet rotation.



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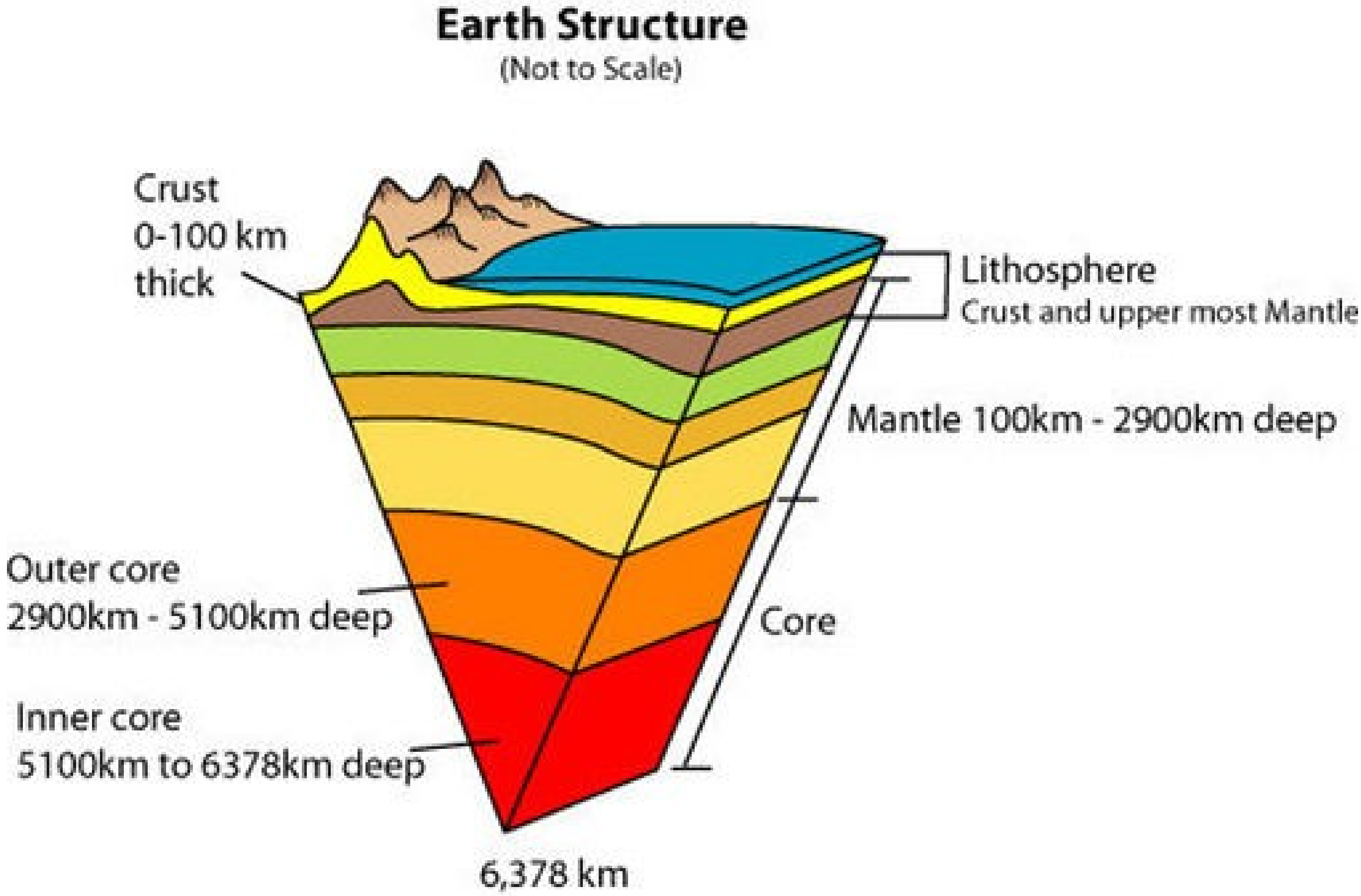
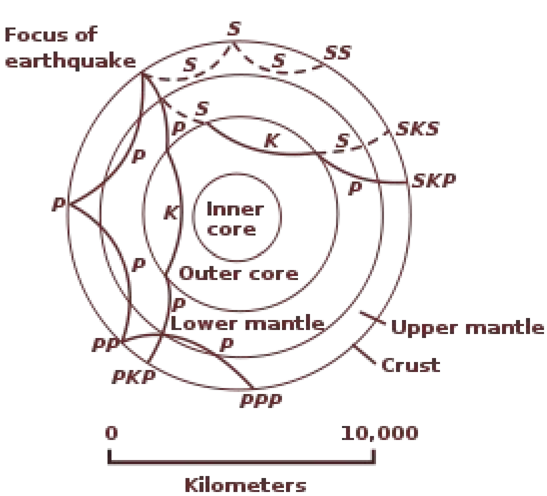
Dipole field: 90% of the total field.

- 97-99% Main field due to dynamo effect in the nucleus
- 1-2% Field due to magnetized rocks
- 1-2% External field due to electrical currents around the Earth

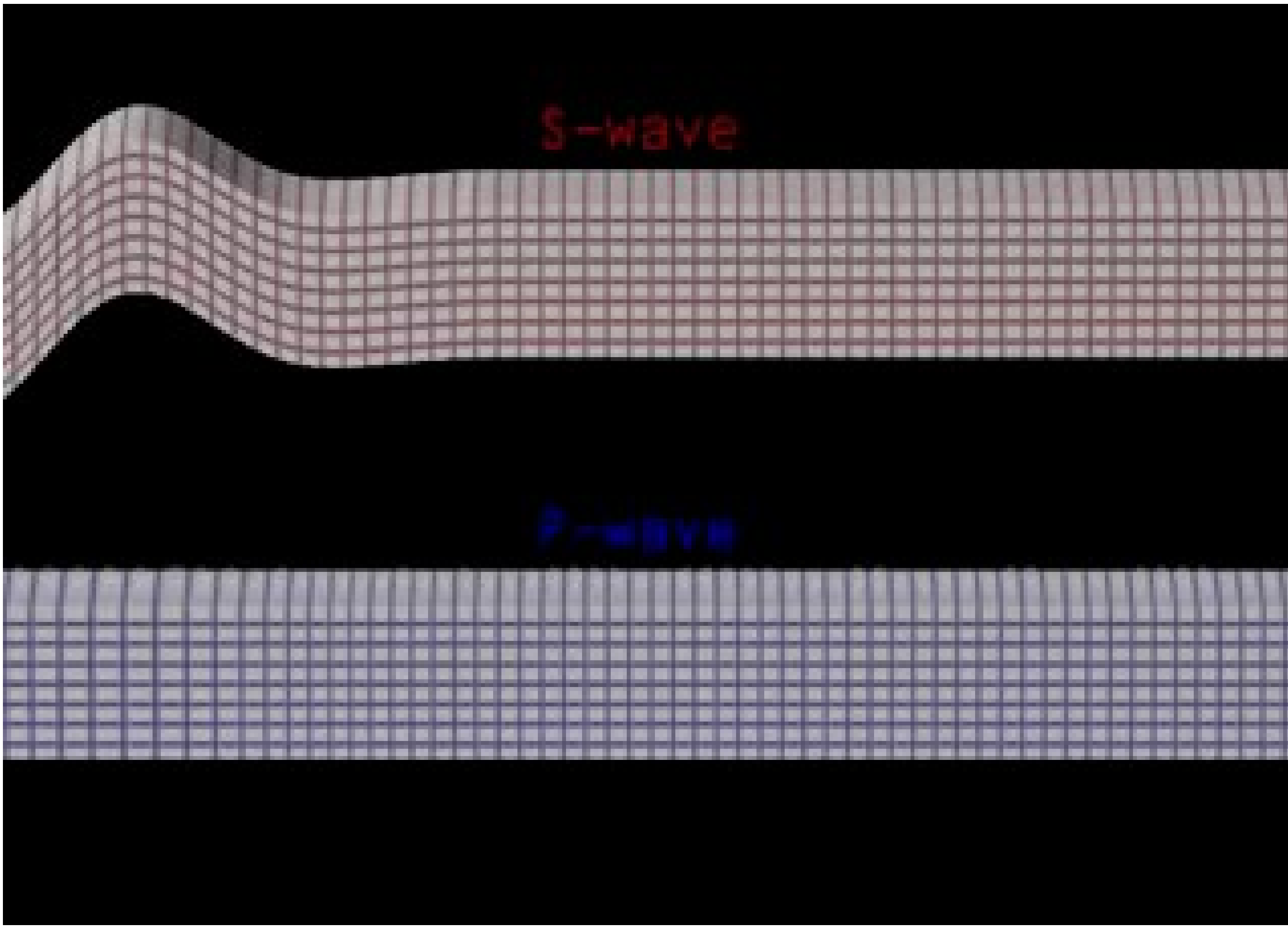


Tomography based on sismic waves

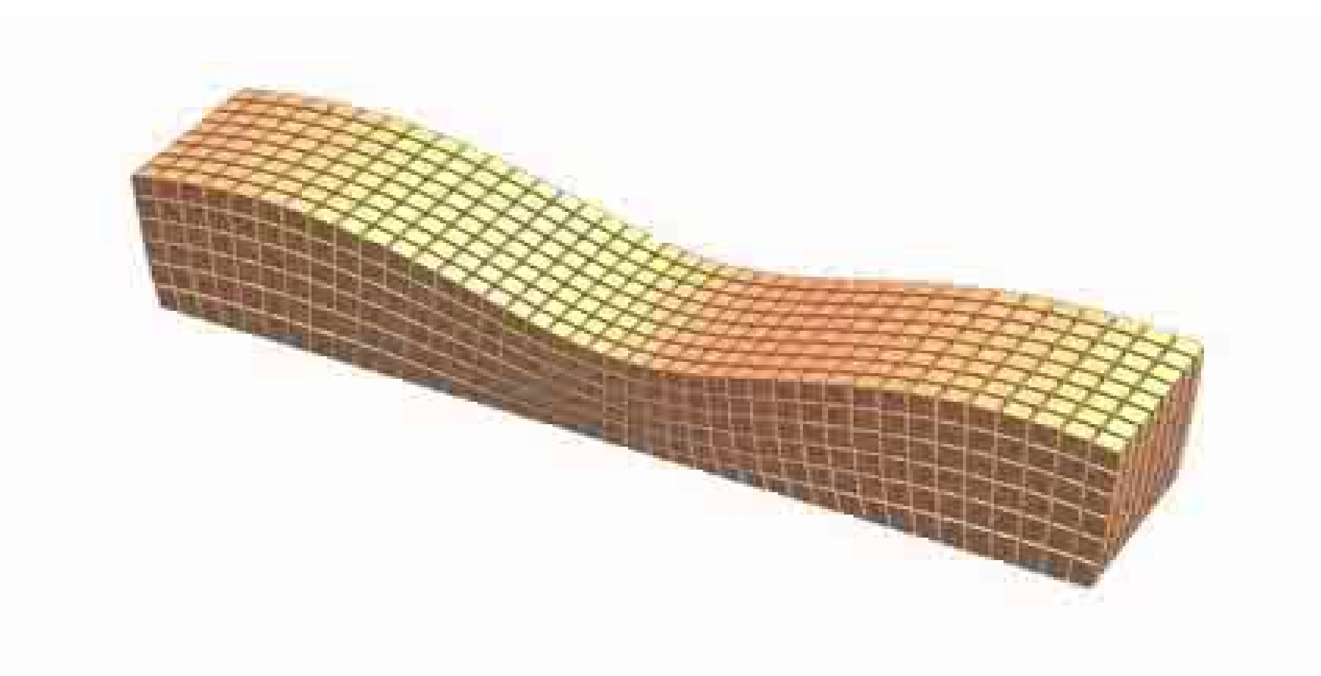


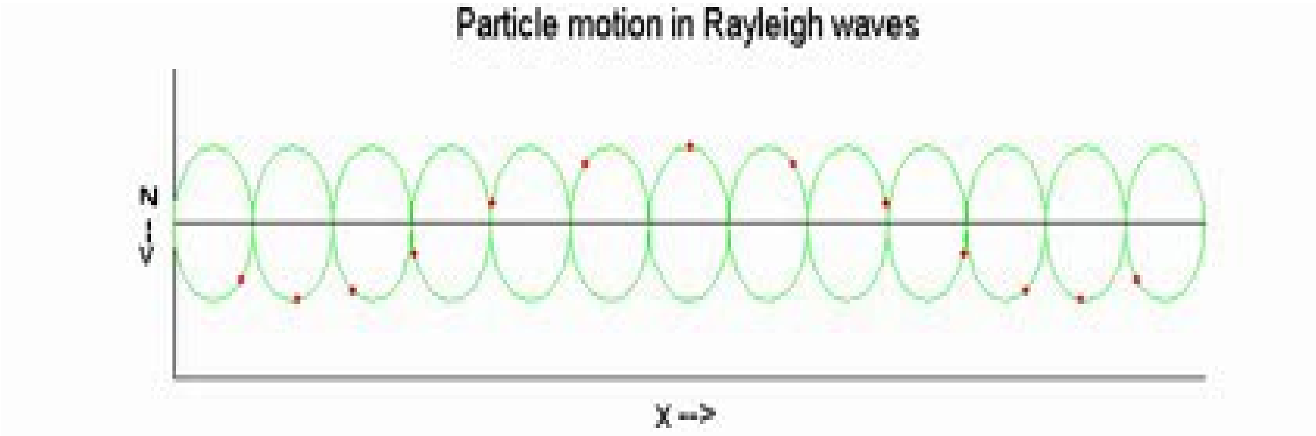
Body waves:
P-wave (primary wave): faster, v~5-13 km/s
S-wave (secondary wave): slower v~1-8 km/s

Surface waves:
Love and Rayleigh waves: 2-6 km/s the first, 1-5 km/s the second

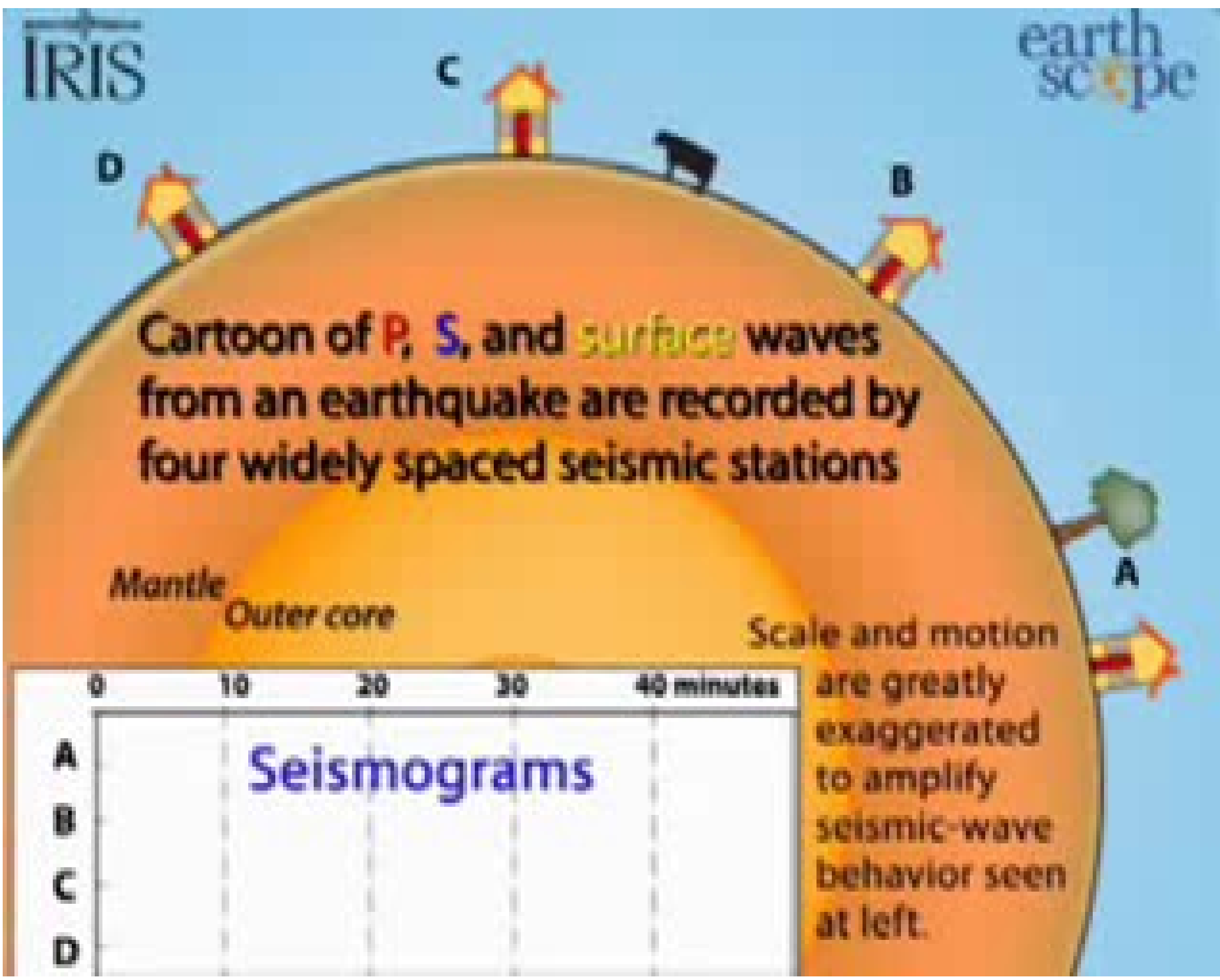


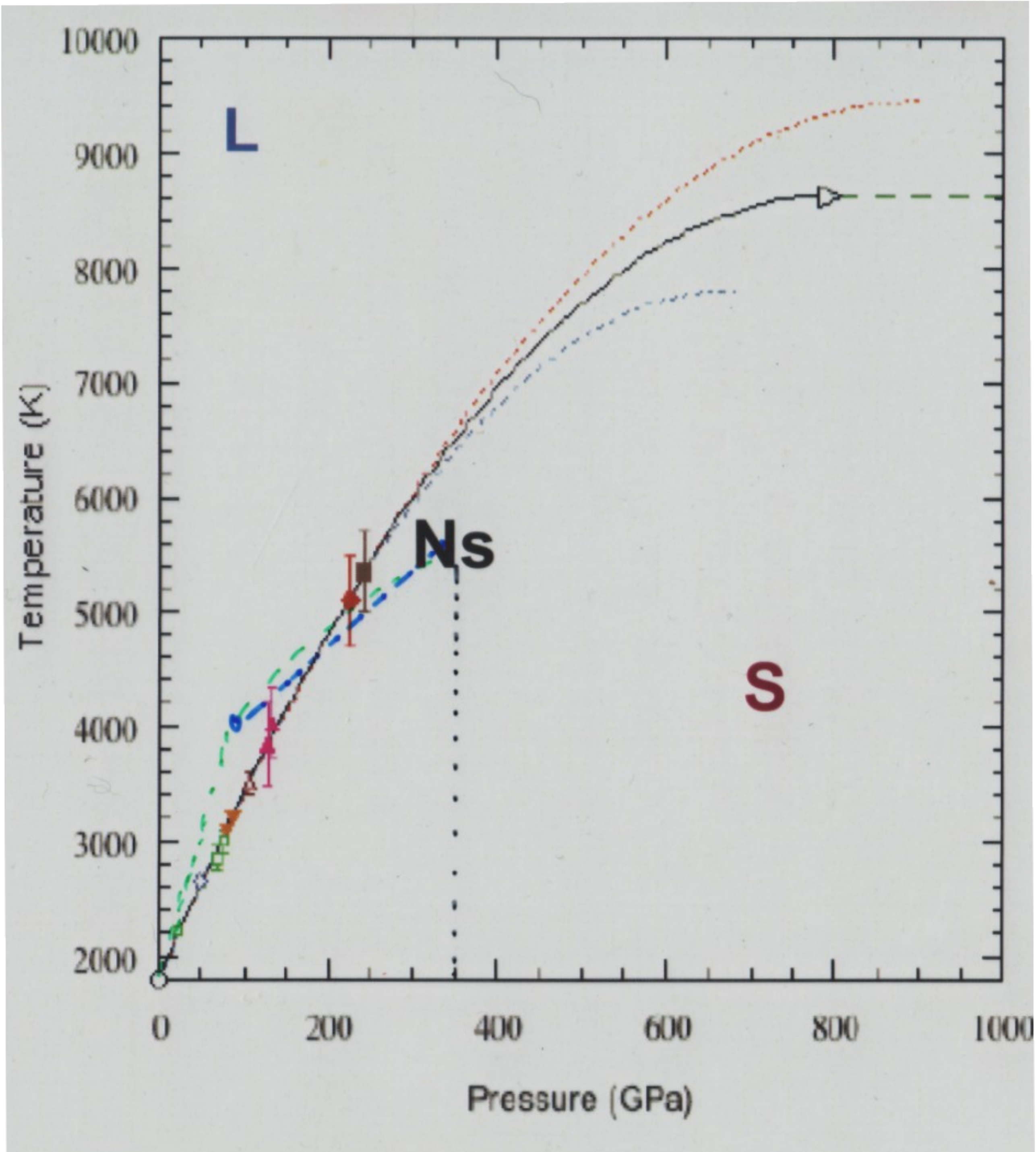
S-waves do not propagate in liquids (or gases) because they lack rigidity (shear stress) and do not have restoring forces.





From seismic waves it is possible to perform a tomography of Earth.

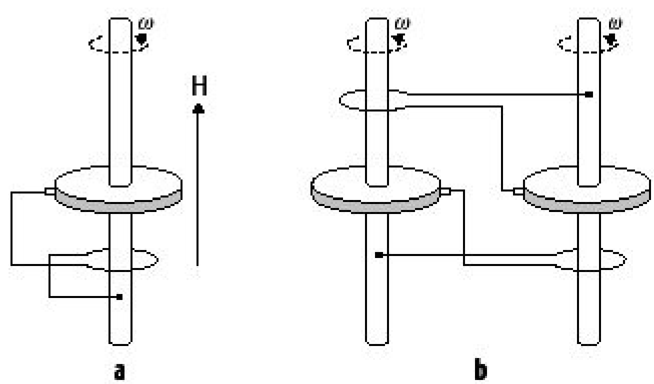




The Earth nucleus is partly liquid (outer core) and partly solid (inner core) because the radial temperature growth with pressure changes slope and the line of the fusion temperature is crossed. In the inner core P~ 350 Gpa and T ~ 5700 K. The core temperature is decreasing and, as a consequence, the liquid core shell is shrinking with time.

Dynamo effect

The dynamo effect is the process by which a moving, electrically conducting fluid generates and sustains a magnetic field. In astrophysical objects (like Earth, the Sun, and other stars), convection and rotation cause liquid metal or plasma to move. These motions induce electric currents via electromagnetic induction since the charges move through an existing (seed) magnetic field, and those currents in turn produce and amplify magnetic fields. If the motion is strong and organized enough, the generated magnetic field reinforces itself, creating a self-sustaining magnetic field without the need for a permanent magnet. The Earth's magnetic field began from a tiny seed magnetic field that was amplified and sustained by the dynamo action in the liquid outer core.



Classical example: the presence of an initial magnetic field B and the rotation motion generates a current which, passing through the bottom coil, generates a new magnetic field. Once the cycle is started, B is self-sustained.

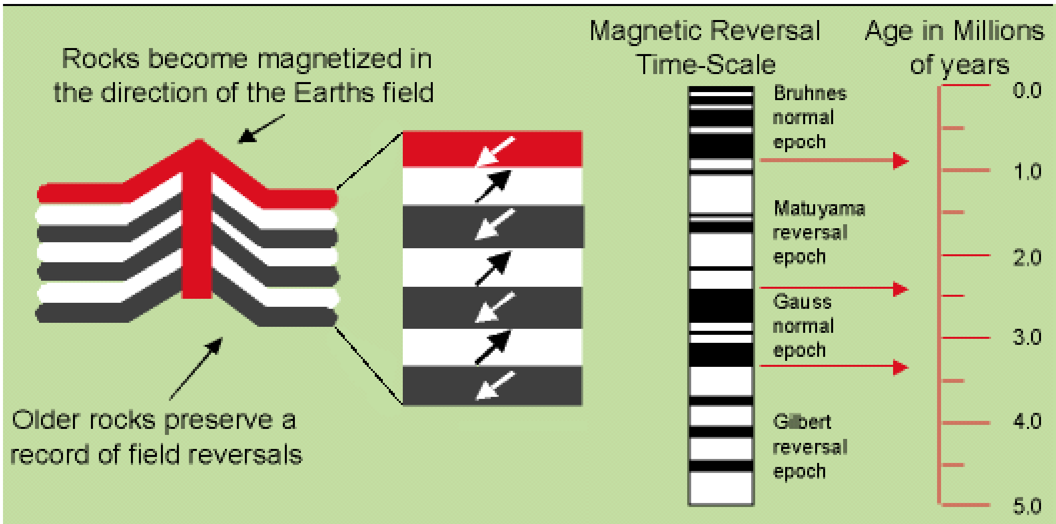
$$\frac{D\mathbf{u}}{Dt} = \frac{1}{\rho}\nabla p + \nu\nabla^2\mathbf{u} + \rho g + 2\mathbf{\Omega}\times\mathbf{u} + \mathbf{\Omega}\times\mathbf{\Omega}\times\mathbf{r} + \frac{1}{\rho}\mathbf{J}\times\mathbf{B}$$

Viscosity ($\nu\nabla^2\mathbf{u}$) — Gravity (ρg) — Coriolis ($2\mathbf{\Omega}\times\mathbf{u}$) — Lorentz ($\frac{1}{\rho}\mathbf{J}\times\mathbf{B}$)

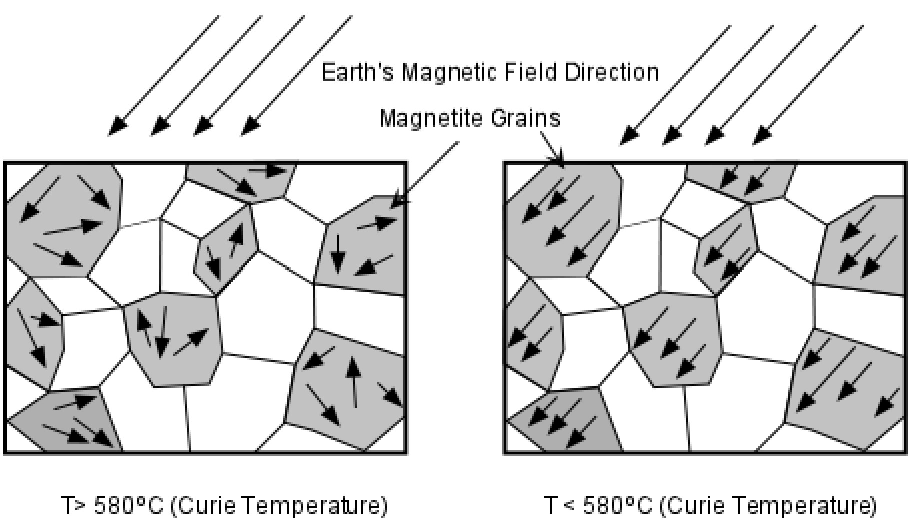
In the melted shell of the Earth core the combination of convective motion and Coriolis force generates spiral motions creating the magnetic field. Rotation of the core (Coriolis force) is then important for the generation of B.

Experimental test of the dynamo mechanism: two rotating spheres separated by thousands of kilograms of liquid sodium (a conducting fluid) aim to mimic Earth's interior (University of Maryland). The Earth's magnetic field will give the initial kick. Question: what was the initial kick for Earth's magnetic field?

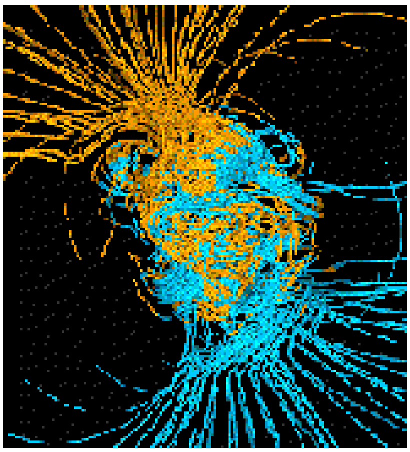
The Earth magnetic field flips about every 250000 years. (On average it is almost random…). How do we know of the flip? Sediments!! Coring to study B vs. time

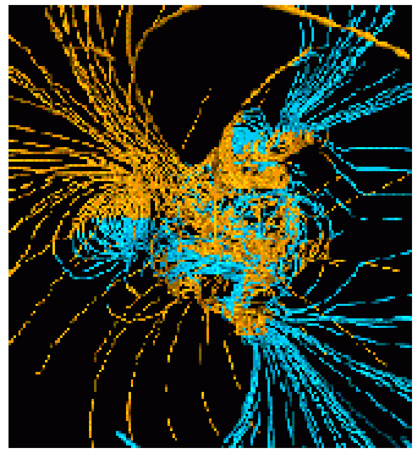


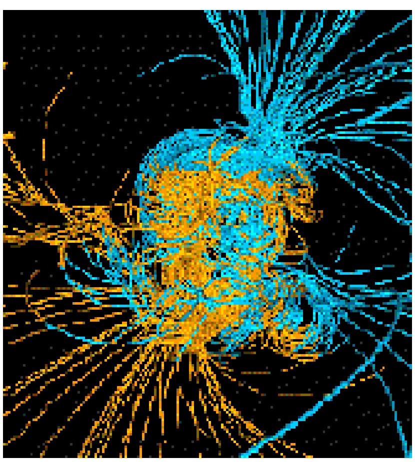
Magma flows out of the crust with T > T of Curie and it is not magnetized. When it cools down, it becomes magnetic and the orientation is that of the Earth B.



Numerical model simulating the evolution of the magnetic field of the Earth. The MHD equations are solved.

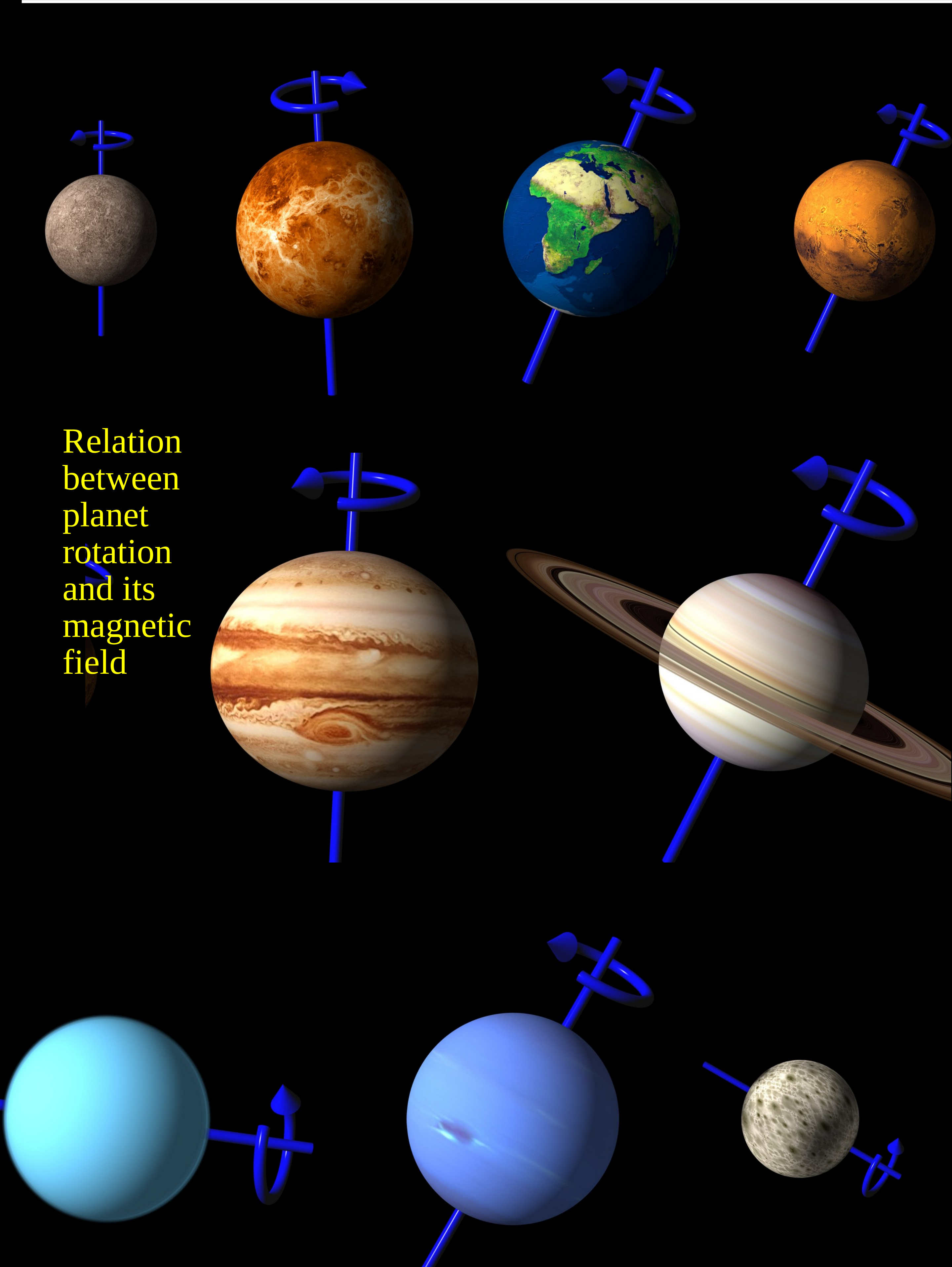




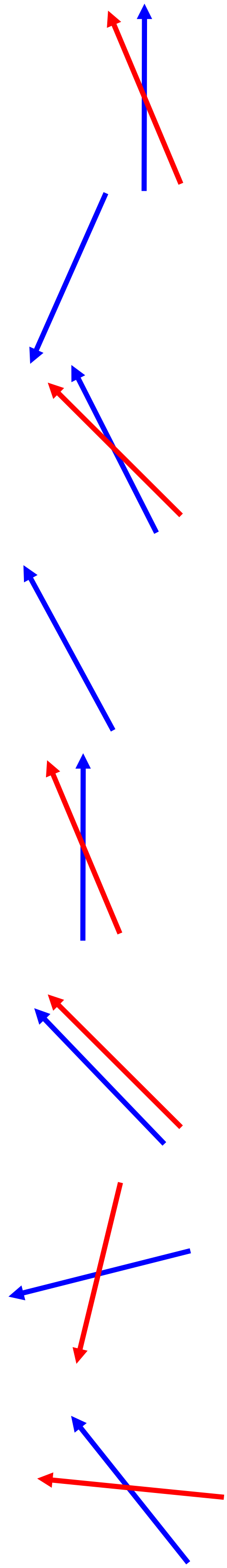


Hydro-simulations of Glatzmaier-Roberts: the convective motions in the outer core are modeled. The reversal of B lasts only a few thousands yrs.

Animation showing the evolution of Earth’s B from the Hydro-simulations of Glatzmaier-Roberts


Relation between planet rotation and its magnetic field

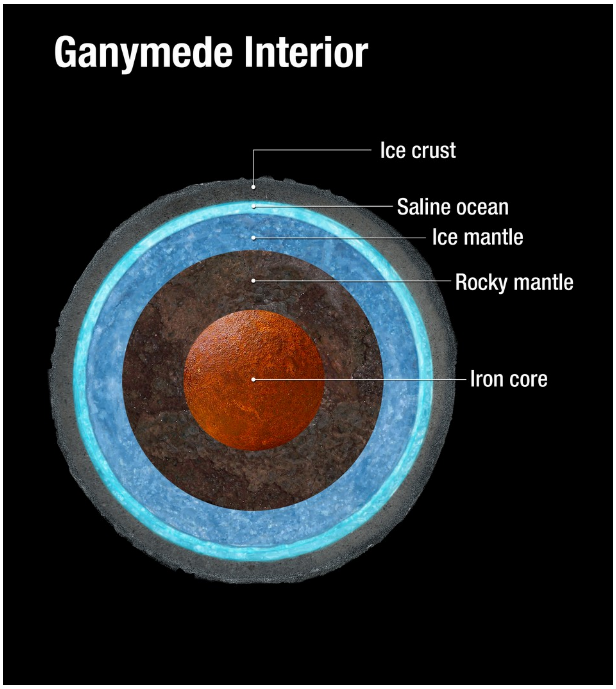
ε = obliquity α = angle between B and rot axes Ω



Planet	α	ε	M_B	P
Mercury	$\alpha=10^\circ$	$\varepsilon=0^\circ$	$M_B = 4\ 10^{-4}$	P ~ 58.6 d
Venus	$\alpha=0^\circ$	$\varepsilon=177^\circ$	$M_B = 0$	P ~ -243 d
Earth	$\alpha=10.8^\circ$	$\varepsilon=23.5^\circ$	$M_B = 1$	P ~ 1 d
Mars	$\alpha=0^\circ$	$\varepsilon=25.9^\circ$	$M_B = 0$	P ~ 1 d
Jupiter	$\alpha=9.6^\circ$	$\varepsilon=3.12^\circ$	$M_B = 20000$	P ~ 9.9 h
Saturn	$\alpha <1^\circ$	$\varepsilon=26.75^\circ$	$M_B = 600$	P ~ 10.7 h
Uranus	$\alpha =60^\circ$	$\varepsilon=97.86^\circ$	$M_B = 50$	P ~ -17.2 h
Neptune	$\alpha =47^\circ$	$\varepsilon=29.56^\circ$	$M_B = 25$	P ~ 16.1 h

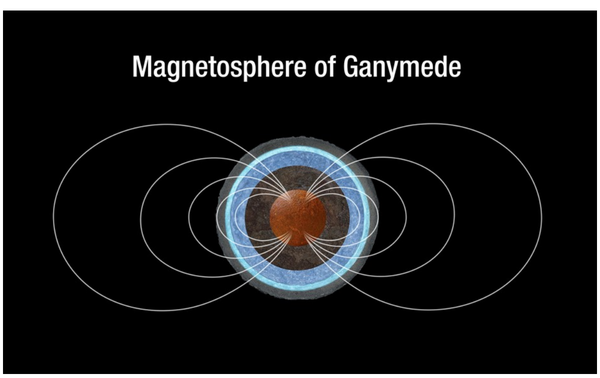
$M_B = 7.906\ 10^{25}$ Gauss cm^{-3} Earth magnetic moment

Also **Ganymede**, satellite of Jupiter, has a magnetic field. It is the only one among the 4 Galilean satellites (Io, Europa, Ganymede and Callisto) to have an intrinsic magnetic field (the fields of the others are induced). It has an iron core and it has a synchronous rotation rate = 7.155 days.



Magnetic fields on **Europa** and **Callisto** are produced by electromagnetic induction as the moons move through Jupiter's time-varying magnetospheric field.

1) Jupiter's magnetosphere approximately co-rotates with the planet. The plasma in the magnetodisk (centrifugally confined near the magnetic equator) is tied to the magnetic field and also nearly co-rotates.



2) Because the moons orbit more slowly than the rigid corotation speed of the magnetospheric plasma at their radial distance, the plasma flows past the satellites from behind (i.e., in the corotational direction).

3) Jupiter's magnetic dipole axis is tilted (~10°) relative to its rotation axis. As Jupiter rotates, the magnetic field at the orbital location of the moons varies periodically in direction and magnitude.

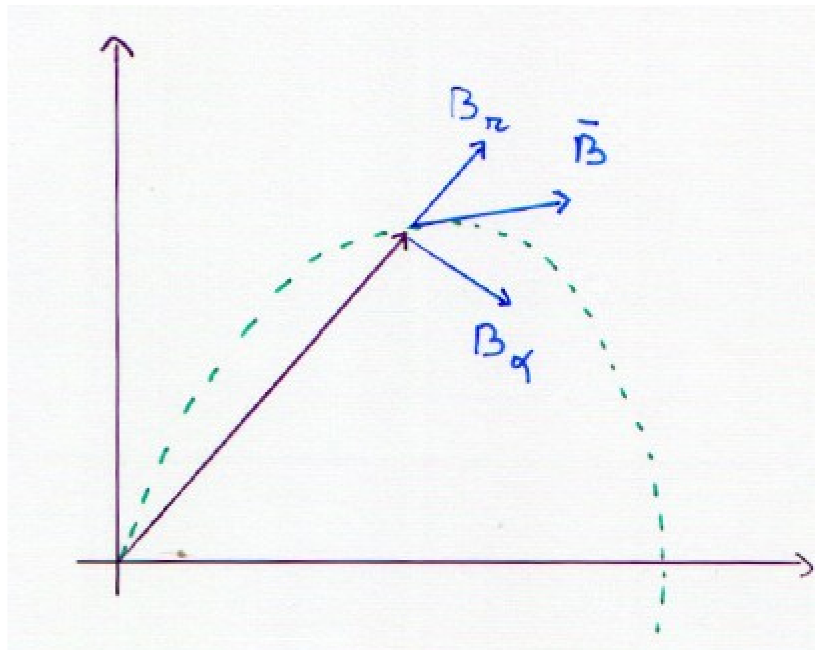
4) In the reference frame of the satellites, this time-varying magnetic field induces electric currents (eddy currents) in any electrically conducting layer inside the moon.

This is the mechanism described in Khurana et al., Nature 395, 777 (1998), which provided strong evidence for subsurface salty oceans in Europa and Callisto.

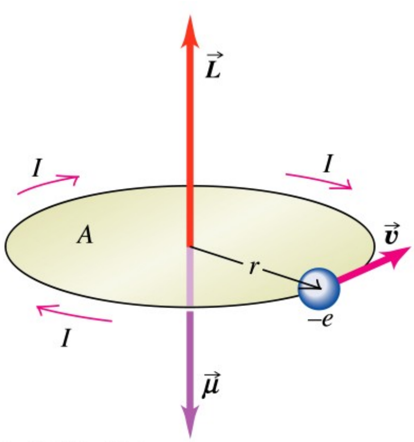
Classical dipolar field:

$$B_r = \frac{2\mu_0 m}{4\pi r^3}\cos\alpha$$
$$B_\theta = \frac{\mu_0 m}{4\pi r^3}\sin\alpha$$
$$B_\phi = 0$$

m= magnetic moment

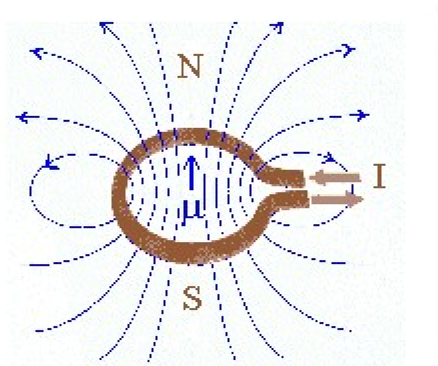


Magnetic moment of a coil:



Units: Tesla   1 T = 1 N s/ (C m)
1 T = 10000 Gauss

$$\vec{m} = As \cdot I\,\hat{z}$$

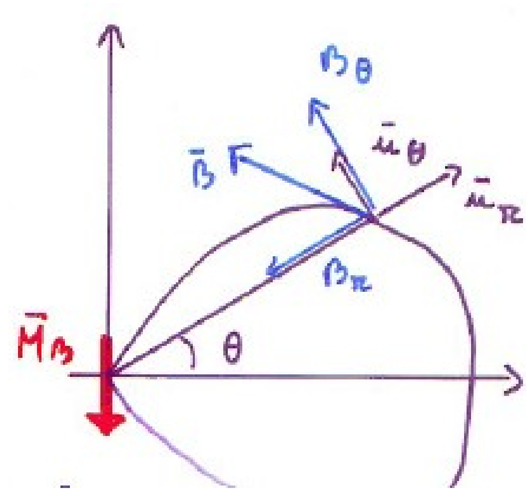


Earth magnetic field: dipolar approximation

$$B_r = -\frac{2M_B}{r^3}\sin\theta$$

$$B_\theta = \frac{M_b}{r^3}\cos\theta$$

$$B_\phi = 0$$



$$M_B = 7.906\times 10^{15}\ T\,m^3 = \frac{\mu_0 m}{4\pi}$$

$$r(\theta) = r_e\cos^2(\theta)$$

Field line

$$\vec{v} = \dot{r}\,\vec{u}_r + r\,\dot{\theta}\,\vec{u}_\theta + r\sin\theta\,\dot{\phi}\,\vec{u}_\phi$$

$$\vec{v}_c = -2r_e\cos\theta\sin\theta\,\dot{\theta}\,\vec{u}_r + r_e\cos^2\theta\,\dot{\theta}\,\vec{u}_\theta$$

$$\vec{v}_c = r_e\cos\theta\,\dot{\theta}\left(-2\sin\theta\,\vec{u}_r + \cos\theta\,\vec{u}_\theta\right)$$

Field line tangent vector

$$\vec{v}_c \parallel \vec{B}$$

Magnetic field along field lines.

$$|\vec{B}| = \frac{M_b}{r_e^3\cos^6\theta}\left[4\sin^2\theta + \cos^2\theta\right]^{1/2} = \frac{M_b}{r_e^3}\frac{\left[4-3\cos^2\theta\right]^{1/2}}{\cos^6\theta} =$$

$$= B_e\frac{\sqrt{4-3\cos^2\theta}}{\cos^6\theta}$$

At the equator

$$B_e = \frac{M_B}{r_e^3}$$

Formal way to compute field lines from a vector field

Given a vector field

$$\boldsymbol{V}(x, y) = (v_1(x, y), v_2(x, y))$$

The field lines can be computed as follows:

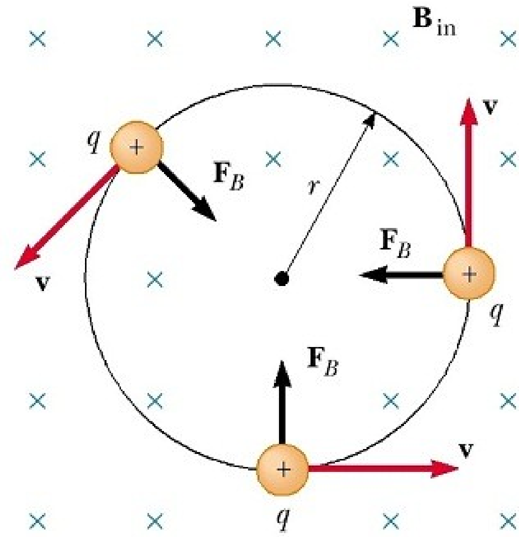
$$\frac{dy}{dx} = \frac{v_2(x, y)}{v_1(x, y)}$$

Integration by parts lead to

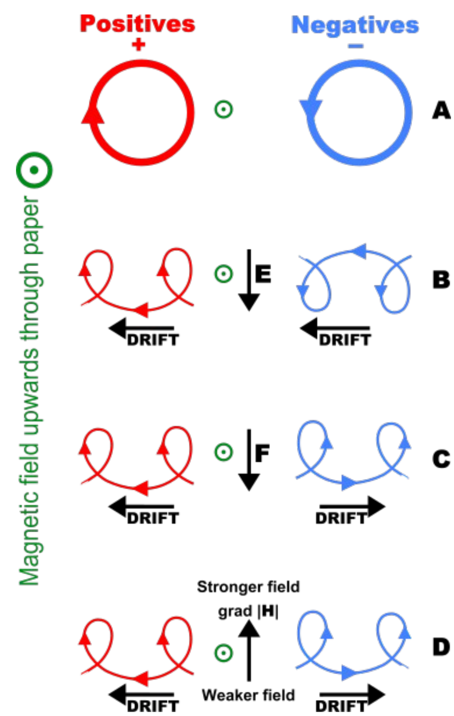
$$\int v_1(x, y)\, dy = \int v_2(x, y)\, dx$$

This gives a function y(x) which is the field line since in any point it is tangent to the field

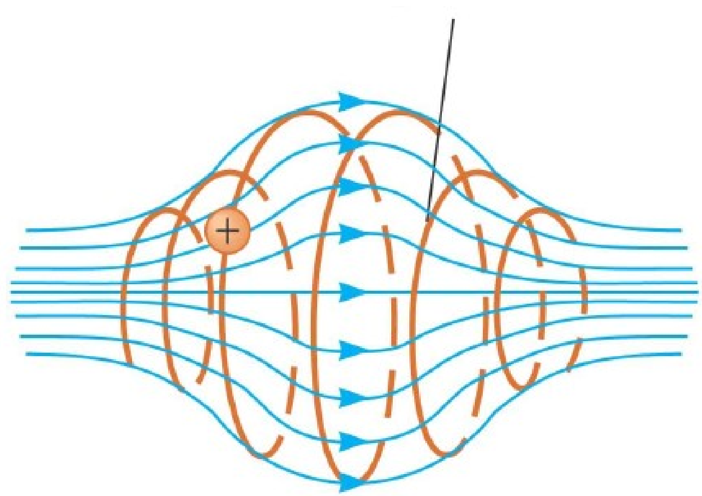
Dominant motion: gyromagnetic
(locally constant B-field)



Drift motion: B-field gradient and curvature + external forces.



Mirror motion.



Charged particle motion in the Earth magnetic field

1) Unperturbed motion: gyromagnetic (constant and uniform magnetic field)

$$\boldsymbol{B}=(0,0,B) \quad \boldsymbol{v}=(v_x, v_y, 0)$$

$$m\dot{v}_x = q v_y B \qquad \ddot{x}=\frac{qB}{m}\dot{y}=-\left(\frac{qB}{m}\right)^2\dot{x}$$

$$m\dot{v}_y = -q v_x B \qquad \ddot{y}=\frac{qB}{m}\dot{x}=-\left(\frac{qB}{m}\right)^2\dot{y}$$

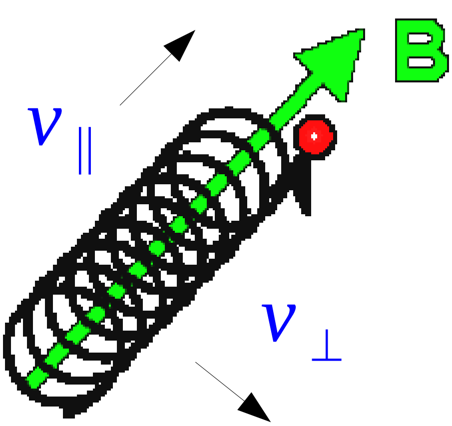
$$\ddot{x}=-\Omega_c^2 x \qquad \ddot{y}=-\Omega_c^2 y$$

Circular uniform motion: $\boldsymbol{a}=-\Omega_c^2\boldsymbol{r}$

$$\Omega_c=\frac{qB}{m}$$ **Cyclotron frequency**

$$|a|=\Omega_c^2|r|=\frac{v^2}{r} \qquad r=\frac{v}{\Omega}=\frac{v_\perp m}{qB}$$

Cyclotron radius (or Larmor)



For Earth at a distance of about 2 R_E and at the equator:

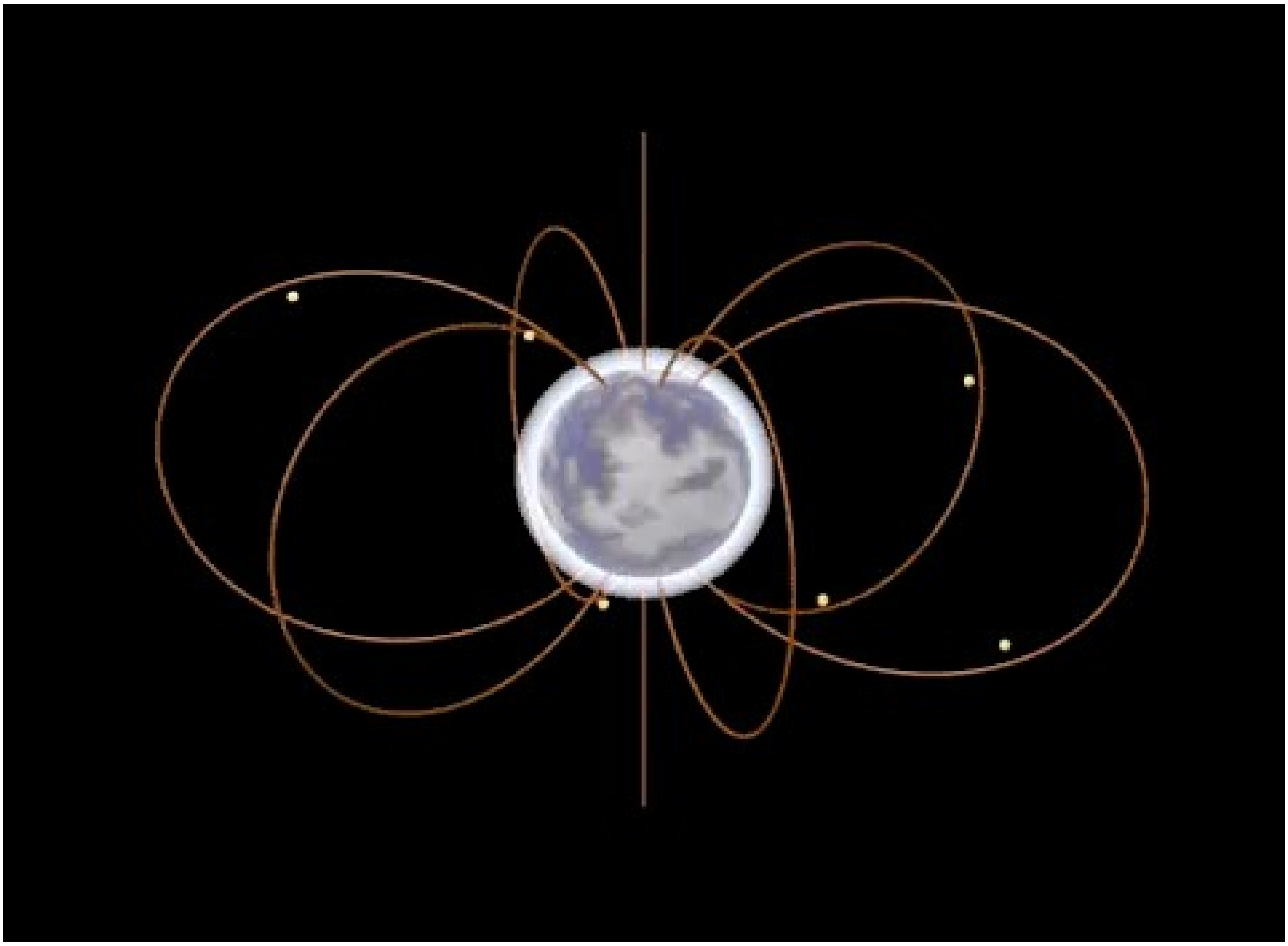
$$e^- \Rightarrow \quad E\sim 100 \; KeV \quad m_0c^2\sim 511 \; KeV$$

$$E_{tot}=\gamma m_0 c^2 \sim m_0c^2+T \quad \gamma=\frac{E_{tot}}{m_0c^2}$$

$$\frac{v}{c}=\beta=\sqrt{1-\left(\frac{1}{\gamma}\right)^2}\sim 0.5$$

$$v\sim 0.5\cdot c\sim 1.5\times 10^5 \; km/s \quad r\sim 100 \; m \quad P\sim 4 \; \mu s$$

Complete motion of particles around field lines: gyro+drift+mirror



2) Drift motion:

a) Due to the dipolar curvature of field lines

$$v_D^{\|} = m v_{\|}^2 \frac{\boldsymbol{B} \times \boldsymbol{n}}{R_c\, q\, B^2} \qquad R_c = curvature\ \ radius = \frac{B}{\nabla_{\perp} \boldsymbol{B}}$$

b) Due to the gradient of the field

$$v_D^{\perp} = \frac{1}{2} m v_{\perp}^2 \frac{\boldsymbol{B} \times \nabla \cdot \boldsymbol{B}}{q\, B^2}$$

$$v_D^{\perp} > v_D^{\|} \quad because \quad v_{\perp} > v_{\|}$$

Due to the presence of the charge q at denominator, protons and electrons drift in opposite directions

c) Due to the presence of E and G fields

$$v_D^E = \frac{\boldsymbol{E} \times \boldsymbol{B}}{B^2} \qquad v_D^G = m \frac{\boldsymbol{G} \times \boldsymbol{B}}{q\, B^2}$$

Curvature drift: how to compute it.

We start from the drift due to a constant and uniform electric field **E**. The reference frame has **B** oriented along the z-axis.

$$\boldsymbol{B} = B\hat{z}$$

In an inertial reference frame, the motion of the particle is due to the Lorentz force:

$$m\dot{\boldsymbol{v}} = q\left(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}\right)$$

We **ASSUME** that the drift velocity is

$$\boldsymbol{v}_{drift} = \frac{\boldsymbol{E} \times \boldsymbol{B}}{B^2}$$

and we change to a reference frame moving with this velocity. It will be on a plane perpendicular to the z-axis since it is perpendicular to **B**. In this new frame the velocity **u** of the particle will be:

$$\boldsymbol{u} = \boldsymbol{v} - \frac{\boldsymbol{E} \times \boldsymbol{B}}{B^2}$$

If it is the true drift velocity, then in this reference frame the motion will be ONLY gyromagnetic! In the next we will show this.

Since both **E** and **B** are constant and uniform,

$$\dot{\boldsymbol{u}} = \dot{\boldsymbol{v}}$$

$$m\dot{\boldsymbol{u}}=q\left(\boldsymbol{E}+\boldsymbol{v}\times\boldsymbol{B}\right)=q\left(\boldsymbol{E}+\boldsymbol{u}\times\boldsymbol{B}+\frac{\left(\boldsymbol{E}\times\boldsymbol{B}\right)}{B^2}\times\boldsymbol{B}\right)=$$

$$q\left(\boldsymbol{E}+\boldsymbol{u}\times\boldsymbol{B}+\frac{\left(\boldsymbol{E}\cdot\boldsymbol{B}\right)}{B^2}\boldsymbol{B}-\boldsymbol{E}\right)=$$

$$q\left(\hat{\boldsymbol{b}}\left(\boldsymbol{E}\cdot\hat{\boldsymbol{b}}\right)+\boldsymbol{u}\times\boldsymbol{B}\right)$$

..remembering that $\left(\boldsymbol{A}\times\boldsymbol{B}\right)\times\boldsymbol{C}=\left(\boldsymbol{A}\cdot C\right)\boldsymbol{B}-\left(\boldsymbol{B}\cdot\boldsymbol{C}\right)A$

...and defining $\hat{\boldsymbol{b}}=\frac{\boldsymbol{B}}{B}=\boldsymbol{u}_z$

We now split the velocity of the particle in this reference frame in the parallel and perpendicular components respect to the vector $\hat{\boldsymbol{b}}$

$$u_{\|}=\boldsymbol{u}\cdot\hat{\boldsymbol{b}}$$

$$u_{\perp}=\|\boldsymbol{u}-u_{\|}\hat{\boldsymbol{b}}\|$$

$$m\dot{\boldsymbol{u}}\cdot\hat{\boldsymbol{b}}=m\dot{u}_{\|}=q\left(\hat{\boldsymbol{b}}\cdot\hat{\boldsymbol{b}}\left(\boldsymbol{E}\cdot\hat{\boldsymbol{b}}\right)+\left(\boldsymbol{u}\times\boldsymbol{B}\right)\cdot\hat{\boldsymbol{b}}\right)=q\,E_{\|}$$

We now go back to the initial reference frame and we get that $u_{\|}=v_{\|}$ since

$$\boldsymbol{u}\cdot\hat{\boldsymbol{b}}=\boldsymbol{v}\cdot\hat{\boldsymbol{b}}-\frac{\left(\boldsymbol{E}\times\boldsymbol{B}\right)}{B^2}\cdot\hat{\boldsymbol{b}}=\boldsymbol{v}\cdot\hat{\boldsymbol{b}}$$

So finally we solve for the motion along the parallel direction:

$$v_{\|}=\frac{q}{m}E_{\|}t+v_{\|0}$$

For the perpendicular component we get:

$$m\dot{\boldsymbol{u}}_{\perp}=m\dot{\boldsymbol{u}}-m\dot{u}_{\parallel}\hat{\boldsymbol{b}}=q\left(\hat{\boldsymbol{b}}\left(\boldsymbol{E}\cdot\hat{\boldsymbol{b}}\right)+q\left(\boldsymbol{u}\times\boldsymbol{B}\right)-qE_{\parallel}\hat{\boldsymbol{b}}\right)=$$
$$q\left(\boldsymbol{u}\times\boldsymbol{B}\right)=q\left(\boldsymbol{u}_{\perp}\times\boldsymbol{B}\right)$$

$$m\dot{\boldsymbol{u}}_{\perp}=q\left(\boldsymbol{u}_{\perp}\times\boldsymbol{B}\right)$$

In the reference frame moving with the given drift velocity, the motion in the plane perpendicular to B is gyromagnetic around a fixed axis. It means that in the initial reference frame the motion follows a guinding center moving with the drift velocity

$$\boldsymbol{v}_{\boldsymbol{E}}=\frac{\boldsymbol{E}\times\boldsymbol{B}}{B^{2}}$$

This result is generic and it does not depend on the choice of the force (in this case the electric field). In the proof the relation between E and B has never been used. As a consequence, any other force would bring to the same equation. For example, the drift velocity due to gravity is:

$$\boldsymbol{v}_{\boldsymbol{G}}=\frac{m}{q}\frac{\boldsymbol{G}\times\boldsymbol{B}}{B^{2}}$$

This general result helps to compute the drift velocity due to the field curvature. A particle moving along the field line (parallel motion) experiences a local centripetal acceleration since the field lines are curved. In a reference frame fixed with the particle motion along the field line (where it sees the perpendicular magnetic field) it also feels a centrifugal force.

$$\boldsymbol{F_C} = m v_{\parallel}^2 \frac{\hat{\boldsymbol{r}}}{R_c}$$

With $\hat{\boldsymbol{r}}$ oriented outwards perpendicularly to the local tangent while R_c is the curcature radius. The drift velocity due to the centrifugal force is then:

$$\boldsymbol{v_c} = \frac{m}{q} v_{\parallel}^2 \frac{\hat{\boldsymbol{r}} \times \boldsymbol{B}}{R_c B^2} = \frac{m}{q} v_{\parallel}^2 \frac{\boldsymbol{B} \times \boldsymbol{n}}{R_c B^2}$$

Where **n** points towards the Earth.

Mirror motion: first adiabatic invariant μ

In dynamical systems that can be treated perturbatively, adiabatic invariants may arise. These are quantities that remain constant provided that a relevant parameter of the system changes **slowly** in time. In the present case, the slowly varying parameter is the **magnetic field**, and the corresponding adiabatic invariant is the magnetic moment. We model a charged particle gyrating around its guiding center as a circular electric current of radius:

$$r_c = \frac{v_\perp}{\Omega_c}$$

The I is then:

$$I = \frac{dq}{dt} = \frac{q\,\Omega_c}{2\,\pi}$$

$$\boldsymbol{\mu} = I\,\pi r_c^2 \cdot \boldsymbol{n} = \frac{e\,\Omega_c}{2\,\pi}\,\pi \frac{v_\perp^2}{\Omega_c^2} = \frac{1}{2} m \frac{v_\perp^2}{B} \boldsymbol{n}$$

μ is an adiabatic invariant if B changes slowly on a gyromagnetic period of the ion/electron.

Proof 1

According to Alfven's theorem, the magnetic flux is constant when moving with the plasma.

$$\frac{\partial \Phi_B}{\partial t} = 0$$

The magnetic field flux enclosed by the gyro-motion of the charge must be constant.

$$\Phi_B = \int B\,dS = const$$

If we assume that the magnetic field does not vary significantly in space over the scale of the gyro-motion and changes only slowly in time, the particle trajectory can be approximated as circular.

$$\Phi_B = \int B\,dS = B\,\pi r_c^2$$

The gyro radius is:

$$r_c = \frac{v_\perp}{\Omega_c} = \frac{m v_\perp}{qB} \quad \Rightarrow \quad \Phi_B = B\,\pi \frac{m^2 v_\perp{}^2}{q^2 B^2}$$

Remembering that

$$\mu = \frac{\frac{1}{2} m v_\perp{}^2}{B}$$

$$\Phi_B = B\,\pi \frac{m^2 v_\perp{}^2}{q^2 B^2} = \frac{2\pi m}{q^2}\mu = const$$

So u, the first adiabatic invariant, is constant.

Proof 2:

In dynamics, the definition of an adiabatic invariant is the following

$$J = \int^{period} p\, dq$$

where *q* is the fast variable. In the case of gyromotion, this corresponds to the rapid rotation of the particle around the magnetic field line. The angle variable is ϕ, which measures the angular position of the charge, and the associated action variable is the angular momentum.

$$L = m v_{\perp} r_g$$

$$J = \int^{period} L\, d\phi = \int_0^{2\pi} m v_{\perp} r_g\, d\phi = m v_{\perp}^2\, 2\pi \frac{m}{qB}$$

J is an adiabatic invariant and this property can be extended to the variable

$$\frac{1}{2} \frac{m v_{\perp}^2}{B} \frac{4\pi m}{q} = \mu \frac{4\pi m}{q}$$

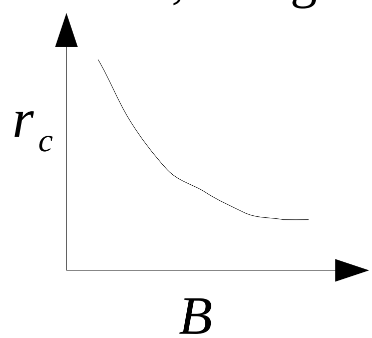
so *μ* is invariant (the other terms are constants).

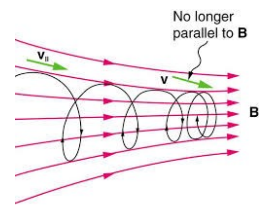
Mirror motion along the field lines and adiabatic invariant and energy conservation

$$\mu=\frac{1}{2}\frac{m v_{\perp}^{2}}{B}$$

This is an invariant if the field B changes slowly in time (low velocity, compared to the gyromotion, along field lines)

$$r_c=\frac{v_{\perp} m}{q B}=\frac{2\mu}{v_{\perp} q}$$



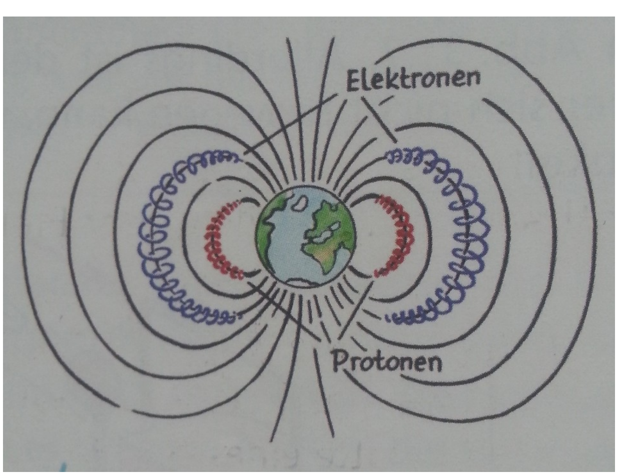


Reduction of the radius of the gyro-motion when the field increases (field lines get denser).

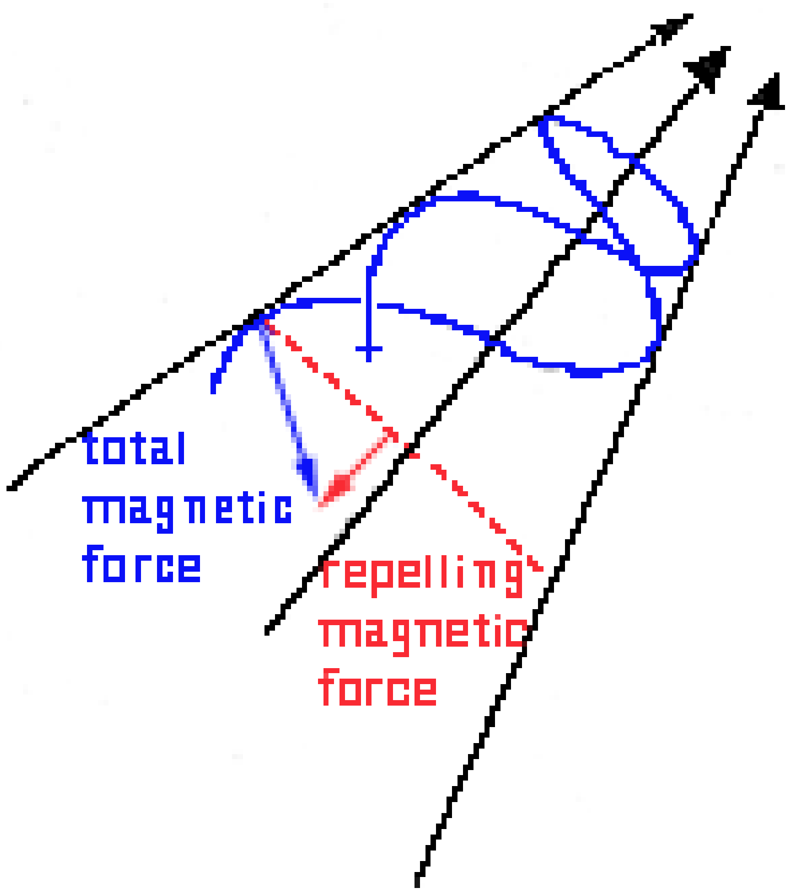
Why does the ion (or electron) come back from poles? Conservation of energy and adiabatic invariant.

$$E=\frac{1}{2}m\left(v_{\perp}^{2}+v_{\parallel}^{2}\right) \qquad constant: \ \mathbf{B} \ does \ not \ make \ work.$$

Closer to the poles B increases, then $v_{\perp}$ grows at the expences of $v_{\parallel}$ which decreases to 0. The motion is reversed and the ion/electron goes back towards the equator.

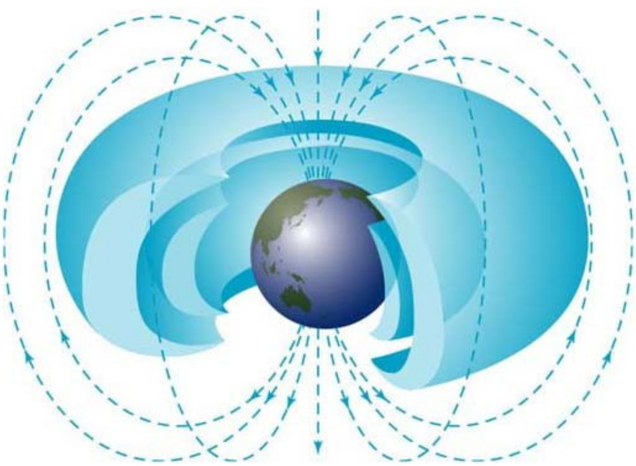


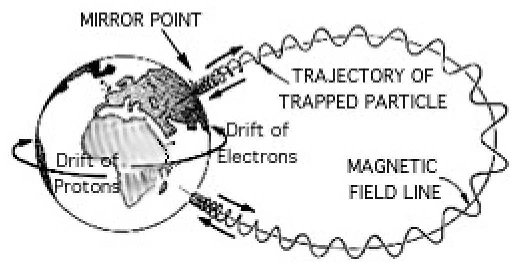
When the magnetic field lines are curved or converge, gyromotion gives rise to an effective repulsive force. In this case, a component of the Lorentz force acts opposite to the direction in which the field lines converge.

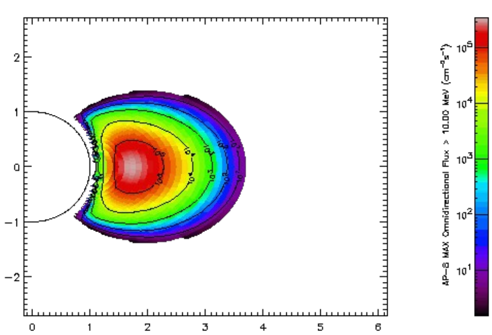


Van Allen Belts

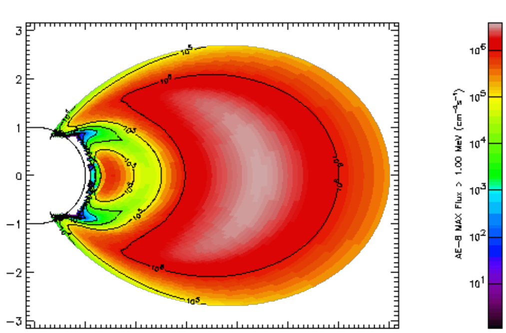
- INNER: R~ 1-3 R_E (max. 2 R_E) Made of: p^+ (10-50 Mev) e^-,p^+,O^+ (1-100 Kev) N^+,He^+, C^+ (~50 Mev)
- OUTER: R ~ 3-9 R_E (max. 4 R_E) Made of: e^- (10 Mev)





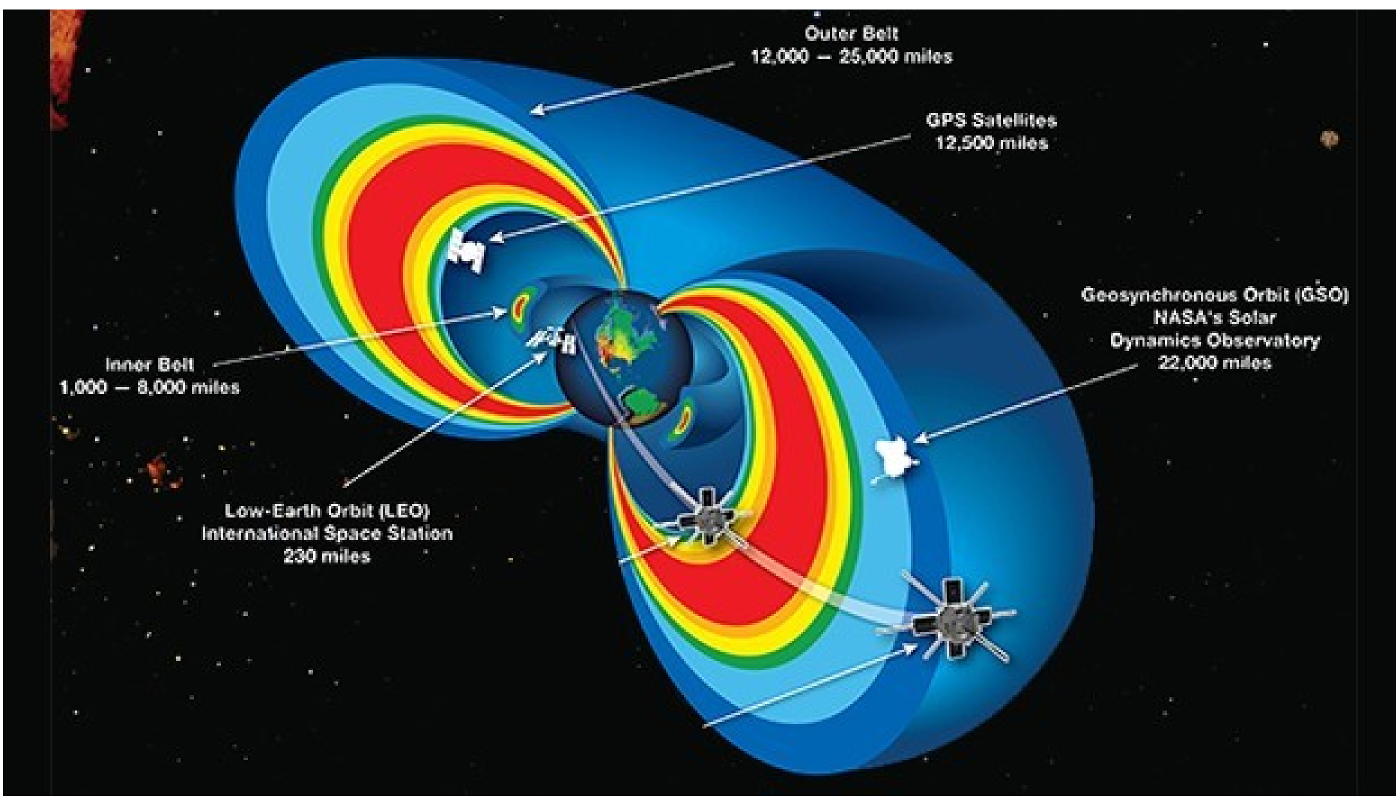


Inner proton belt

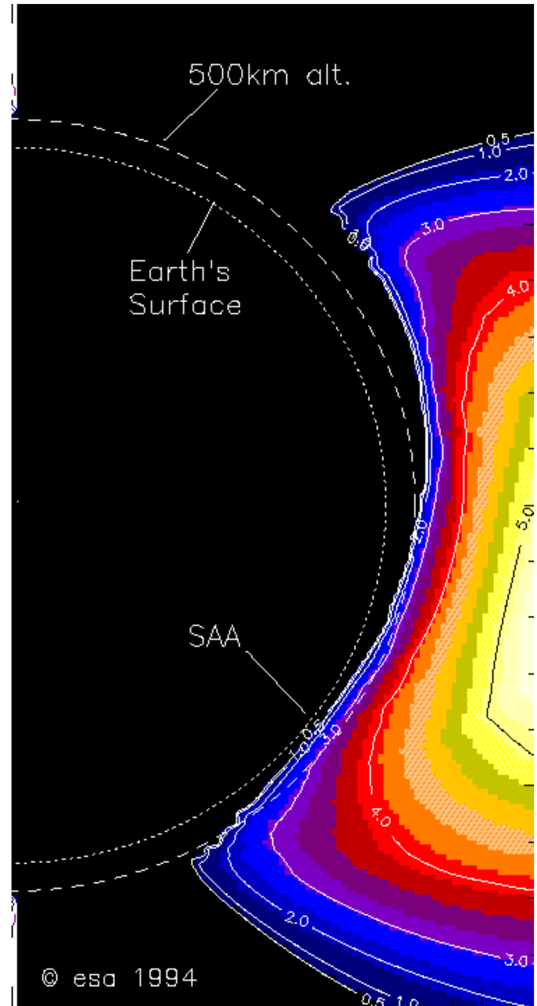


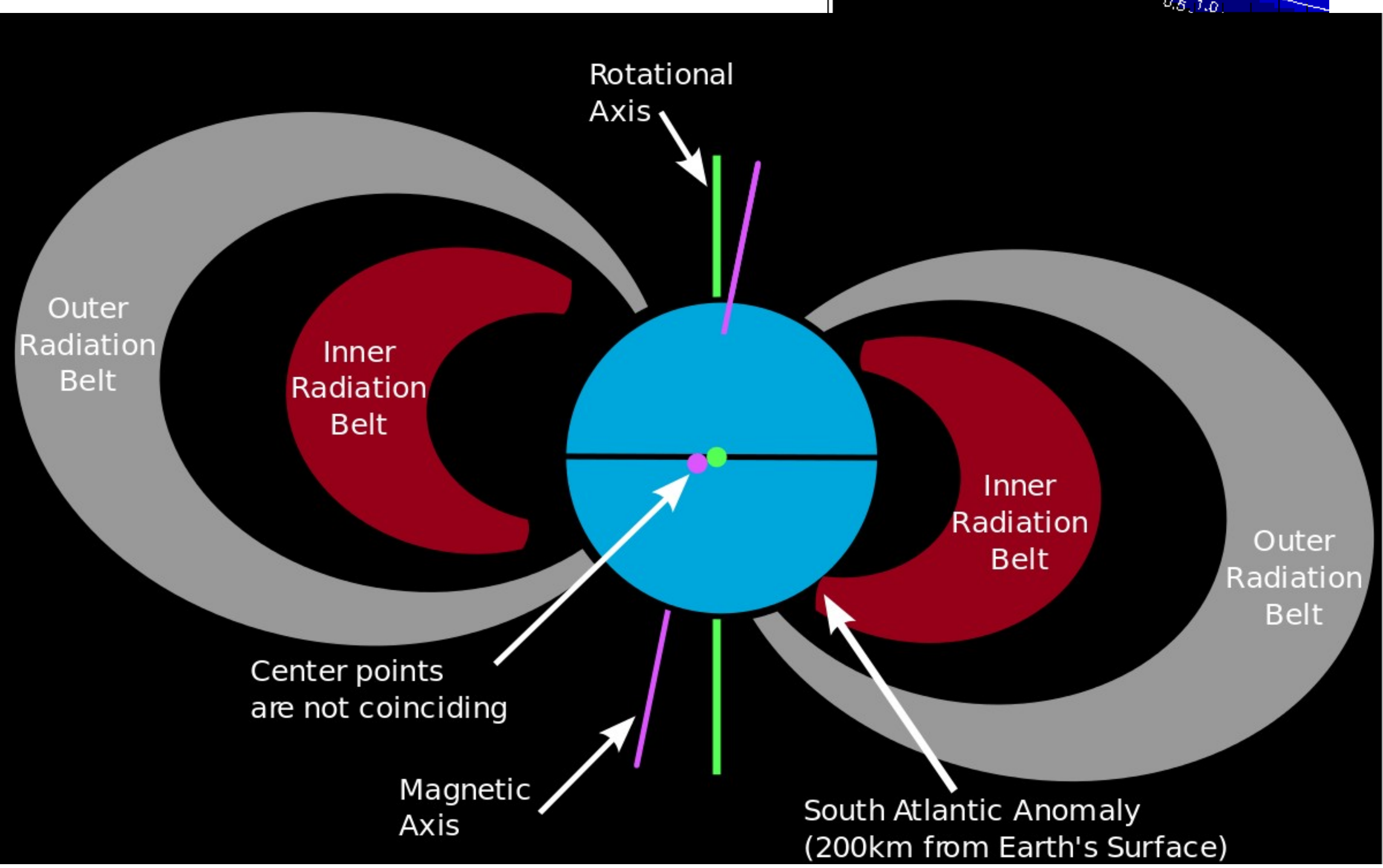
Outer electron belt

Artificial satellites must orbit outside the belts to prevent troubles with instruments.



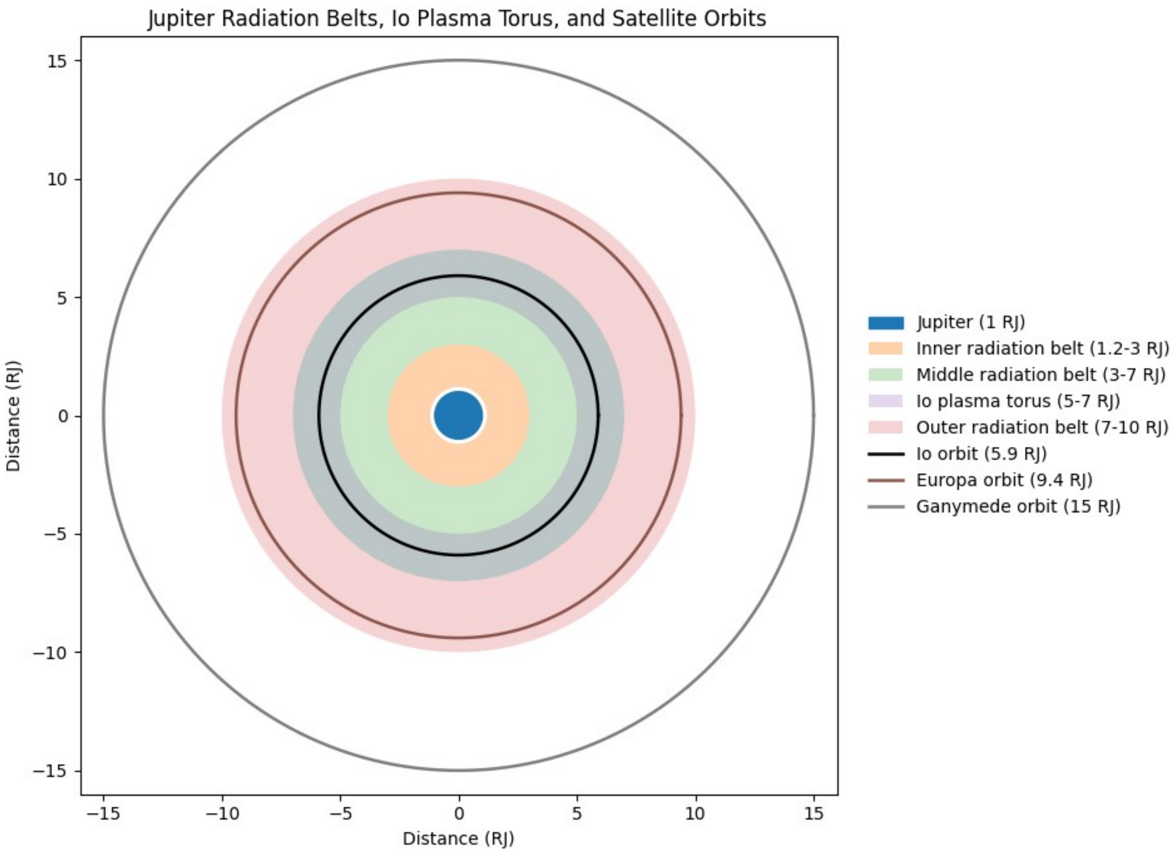
South Atlantic Anomaly: The inner Van Allen belt is organized along Earth's magnetic field, whose axis is inclined with respect to the planet's rotational axis. In addition, the center of the dipolar magnetic field is offset from the center of the Earth. As a consequence, in the South Atlantic region the magnetic field — and therefore the inner Van Allen belt — lies closer to the Earth's surface.





Jupiter has three Van Allen belts and a plasma torus.

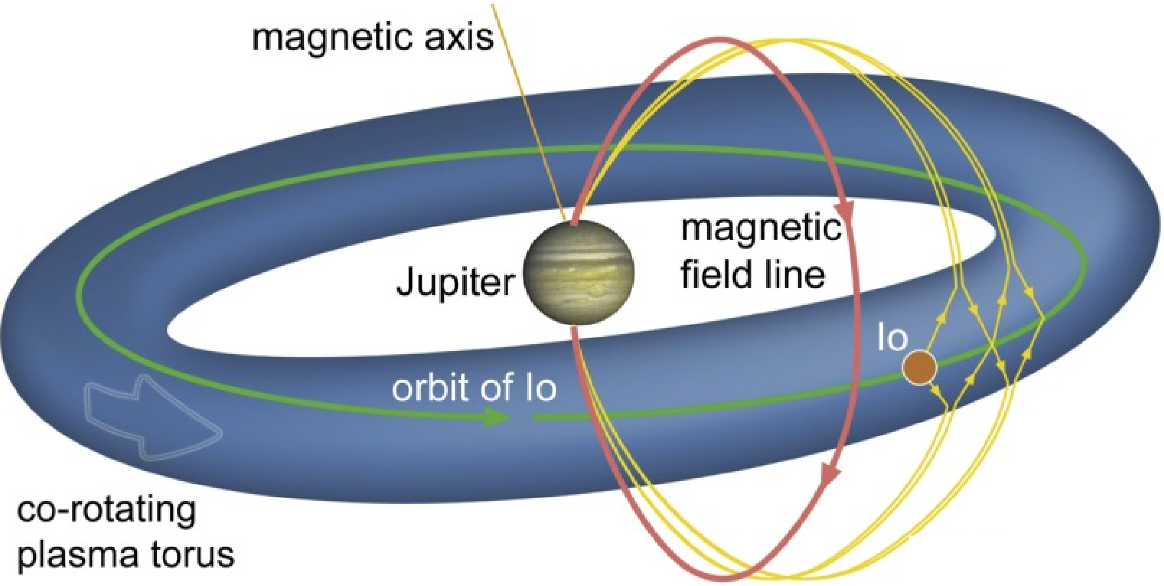
- -Inner belt: 1-3 R_J, very energetic e^- and ions
- -Middle belt: 3-7 R_J (it overlaps Io's plasma torus)
- -Outer belt: 7-10 R_J

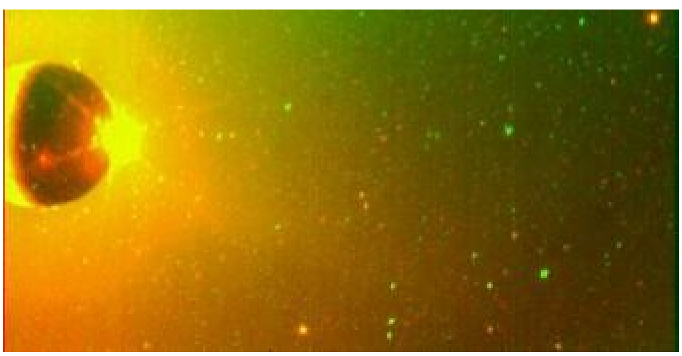


The belts corotate with the planets because the rapid rotation of the planet and the intense magnetic field produce an electric field forcing corotation.

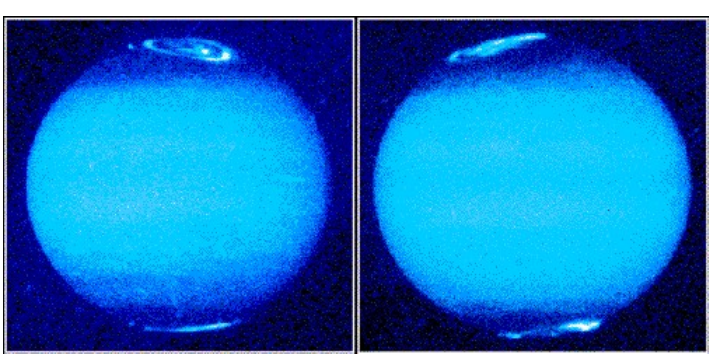
The main ions present in the plasma torus are Oxigen (once or twice ionized) and Sulfur (once, twice or three times ionized).

The ionization occurs because of the UV radiation from the sun and the electron flux in the plasma surrounding Jupiter.





The plasma torus is produced by the molecules ejected from vulcanic activity on Io.



‘Northern lights’ on Jupiter.

Recent measurements of Jupiter's magnetic field by magnetometer of JUNO mission.

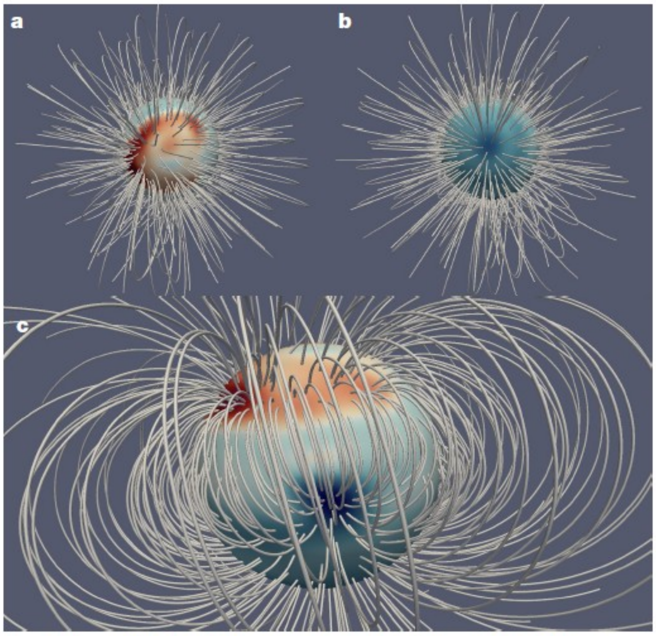
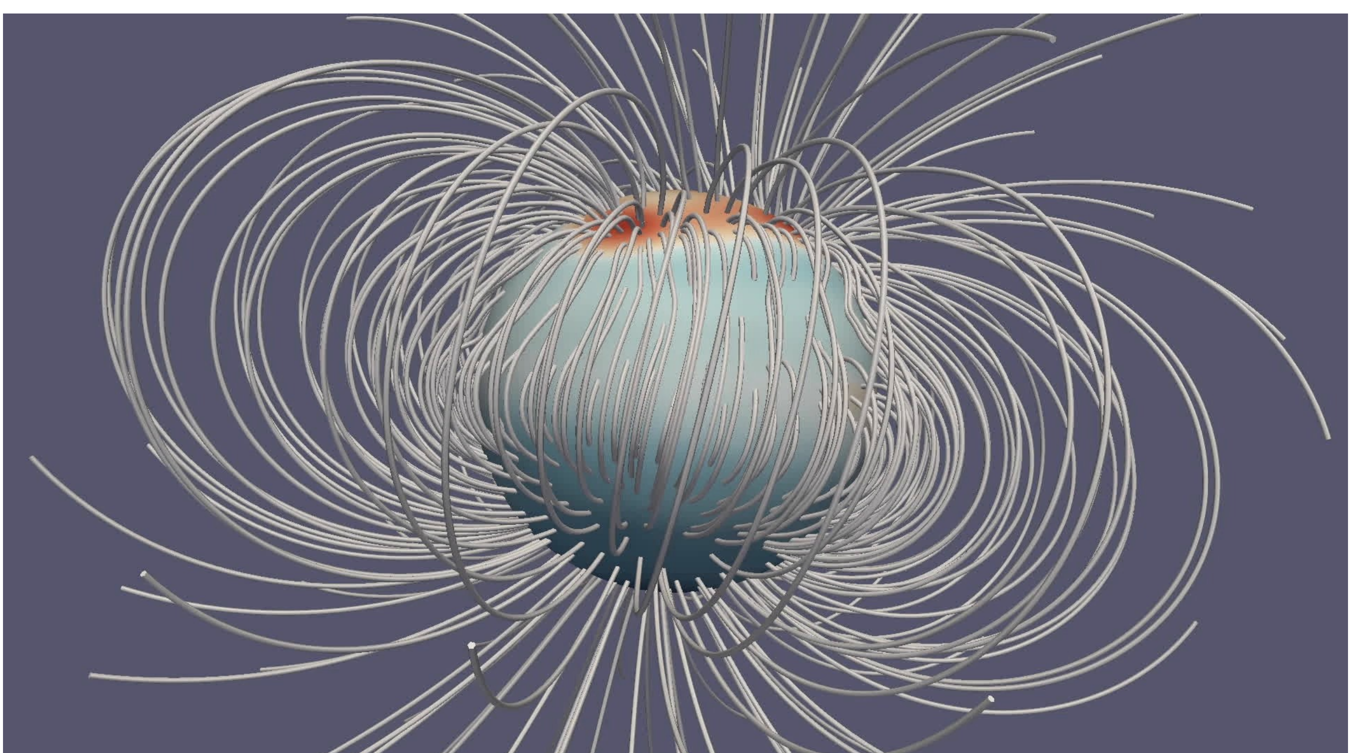
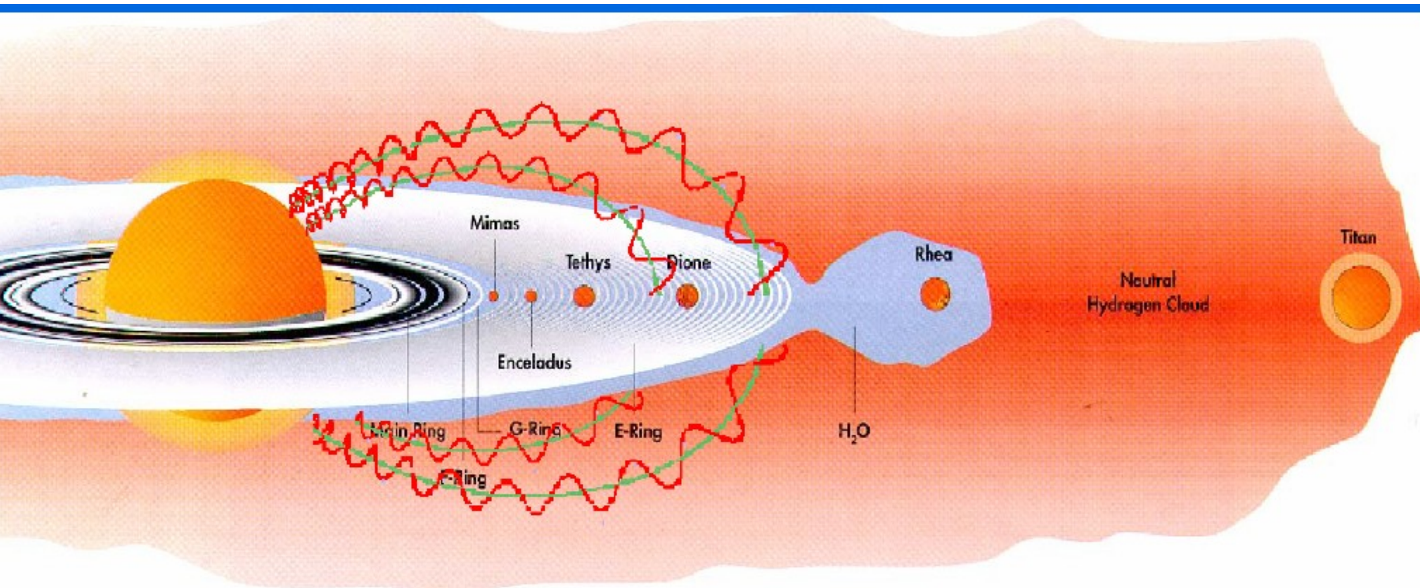


Fig. 2 | **Magnetic field lines.** **a**, North polar view; **b**, south polar view; **c**, equatorial view. The non-dipolar nature of the magnetic field in the northern hemisphere and the dipolar nature in the southern hemisphere is apparent. The equatorial view is centred near the Great Blue Spot and shows the linkage of magnetic field lines that enter through the Great Blue Spot. The contoured surface on which the field lines shown start and end is at $r = 0.85R_J$, where the density of field lines is proportional to the radial magnetic field strength and is depicted by the colour scale (red outward flux, blue inward flux). An animated version of this figure is available at https://doi.org/10.6084/m9.figshare.6828953.

Moore et al.
Nature, 2018.

The magnetic field is not dipolar in the north emisphere and it enters also the big red spot. In the south emisphere it is dipolar.
Origin in the transition region of metallic hydrogen?




Mimas
Tethys
Dione
Rhea
Titan
Neutral
Hydrogen Cloud
Enceladus
Main Ring
G-Ring
E-Ring
H_2O
F-Ring