Earth magnetic field

Laboratorio di Astrofisica

history

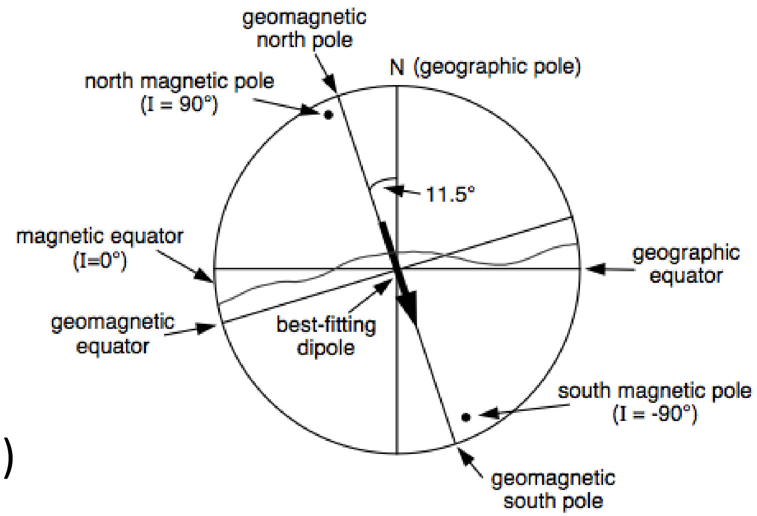
- It has been known for hundreds years that the Earth has a magnetic field.
- Modern geomagnetism:
  - William Gilbert, The Magnete (1600): “Magus magnetis ipse est globus terrestris”
  - 1838, Carl Friedrich Gauss proved 95% of Earth's magnetic field is internal, approx. 5% external

Magnetic bar

- The earth magnetic field can be described ad the field generated by a magnetic bar with the centre corresponding to the centre of the planet.
- To be more accurate, the axis of the magnet :
  - have to be situated about 400 km from the centre of the Earth
  - Have to make an angle of 11.2° with the Earth rotational axis

The 2 points of intersection define the geomagnetic poles:
North: 78.8 ° N, 289.1° E
South: 78.8 ° S, 109.1° E

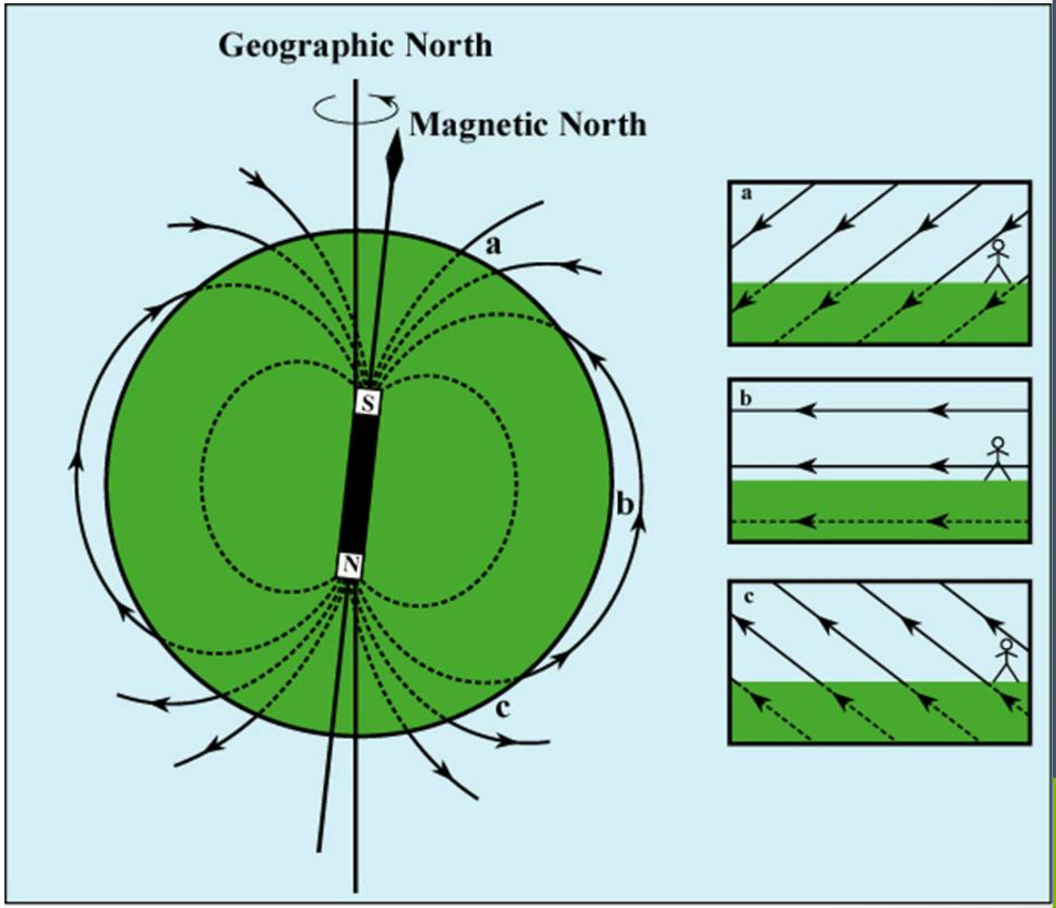
(Magnetic North pole: 75.3 ° N, 101.8 ° W)



Angle of magnetic pole – angle of geographic pole = magnetic declination

Field direction

- Perpendicular to Earth surface at poles
- Parallel to Earth surface at equator
- Field points downward in the Northern Hemisphere
- Field points upward in the Southern Hemisphere.

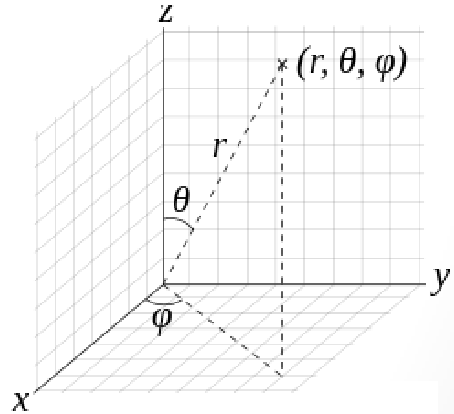


Magnetic potential

- If we neglect the contribute of external current (which is ~ 5%) we can write:

$$\mathbf{J} = 0 \quad \Rightarrow \quad \nabla \times \mathbf{B} = 0$$

- The magnetic field can than be expressed in terms of magnetic potential (due to internal sources)



$$\mathbf{B} = -\nabla\psi$$

$$\nabla^2\psi = 0$$ Laplace eq

$$\psi = \frac{R_E}{\mu_0}\sum_{n=1}^{\infty}\left(\frac{R_E}{r}\right)^{n+1}\sum_{m=0}^{n}\left(g_n^m cos(m\phi) + h_n^m sin(m\phi)\right) P_n^m cos(\theta)$$

Gaussian coefficients

Schmidt normalized associated Legendre functions

Coordinate systems

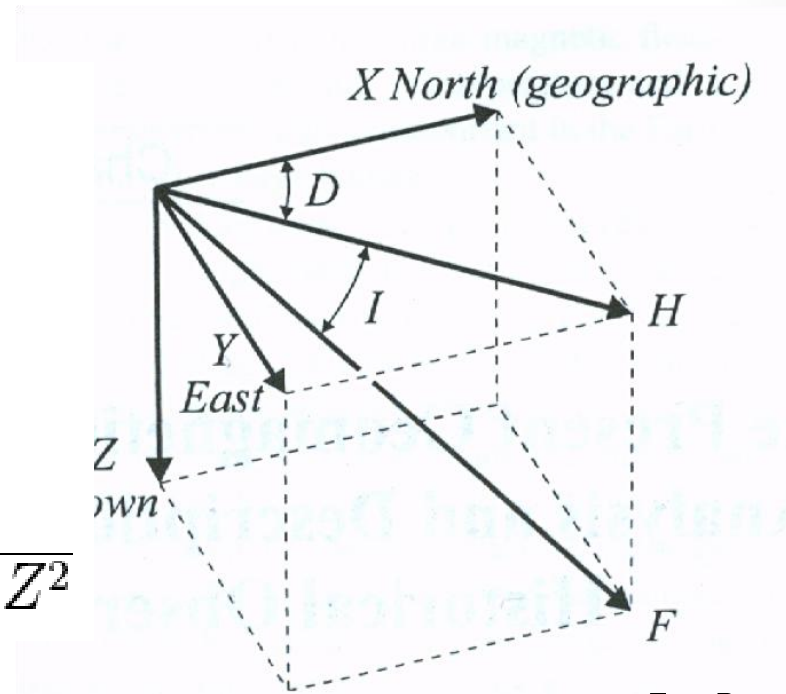
- Components of B at a point on the surface of the Earth -> we use geodetic coordinates (X, Y, Z)

$$H = \sqrt{X^2 + Y^2}$$

$$D = \arctan(X/Y)$$

$$I = \arctan(Z/H)$$

$$B = \sqrt{H^2 + Z^2} = \sqrt{X^2 + Y^2 + Z^2}$$



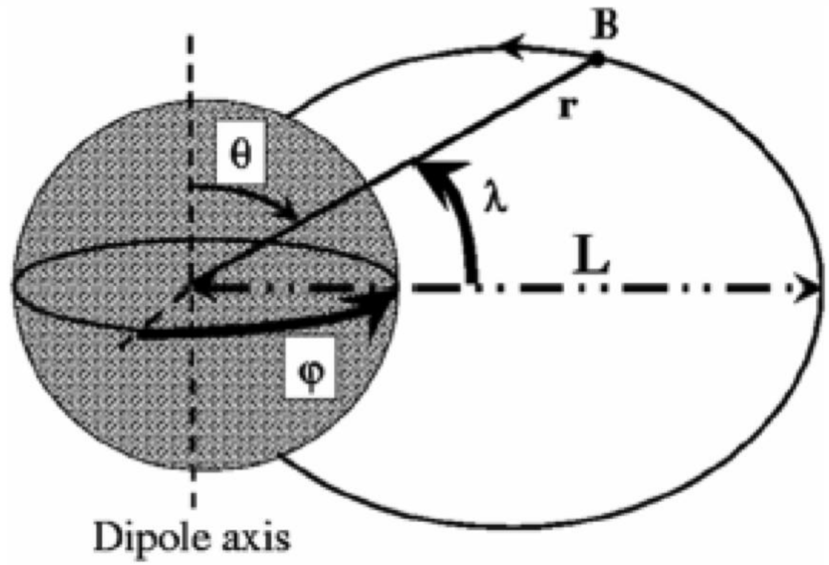
F* = *B

The measured values can be compared with the theoretical values B_r, B_ϑ, B_φ

Coordinate systems

- r = distance from the center of the dipole
- λ = magnetic latitude (angle from the magnetic equator)
- θ = 90 - λ (co-latitude)
- φ = longitude (angle from the Greenwich meridian)
- L = McIlwain parameter

$$B(r,\lambda) = B_0 \frac{\sqrt{1+sin^2\lambda}}{r^3}$$



Magnetic coordinates.

Main dipolar term

- The potential due to the first term is the MAIN DIPOLE term

$$B_r = -\frac{\partial \psi}{\partial r} = 2\left(\frac{R_E}{r}\right)^3 g_1^0 cos(\theta)$$

$$B_\theta = -\frac{1}{r}\frac{\partial \psi}{\partial \theta} = 2\left(\frac{R_E}{r}\right)^3 g_1^0 sin(\theta)$$

$$B = \sqrt{B_r^2 + B_\theta^2} = B_0 \left(\frac{R_E}{r}\right)^3 \sqrt{1 + 3cos^2(\theta)}$$

g/h	Degree n	Order m	IGRF 2010.0	SV 2010-15
g	1	0	−29496.5	11.4
g	1	1	−1585.9	16.7
h	1	1	4945.1	−28.8

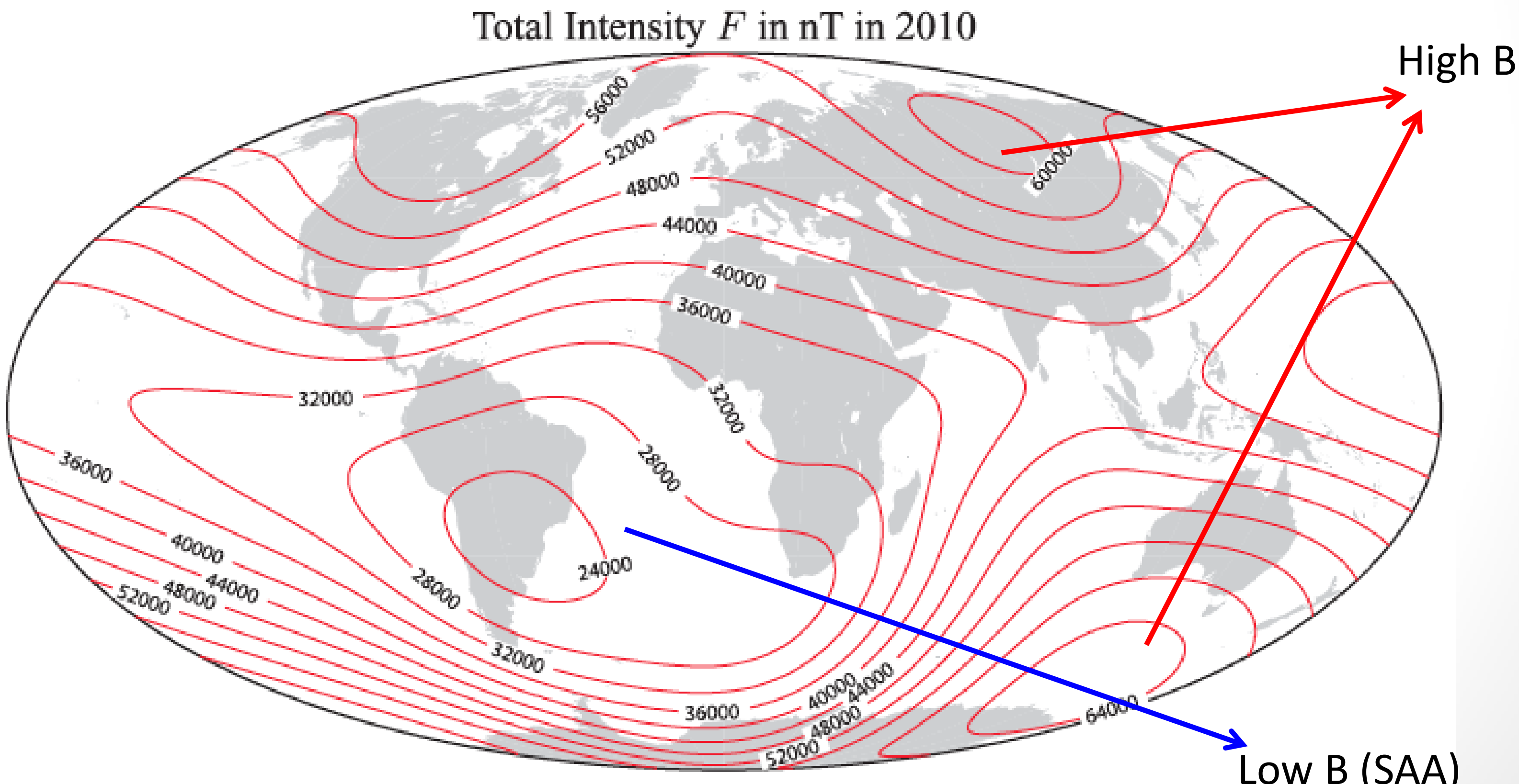
IGRF

- Produced by the International Association of Geomagnetism and Aeronomy (IAGA)
- Definitive Gauss coefficients are updated every 5 years, including a linear trend between epochs.
- Internal field changes through time. Last epoch was 2010.

Total B intensity

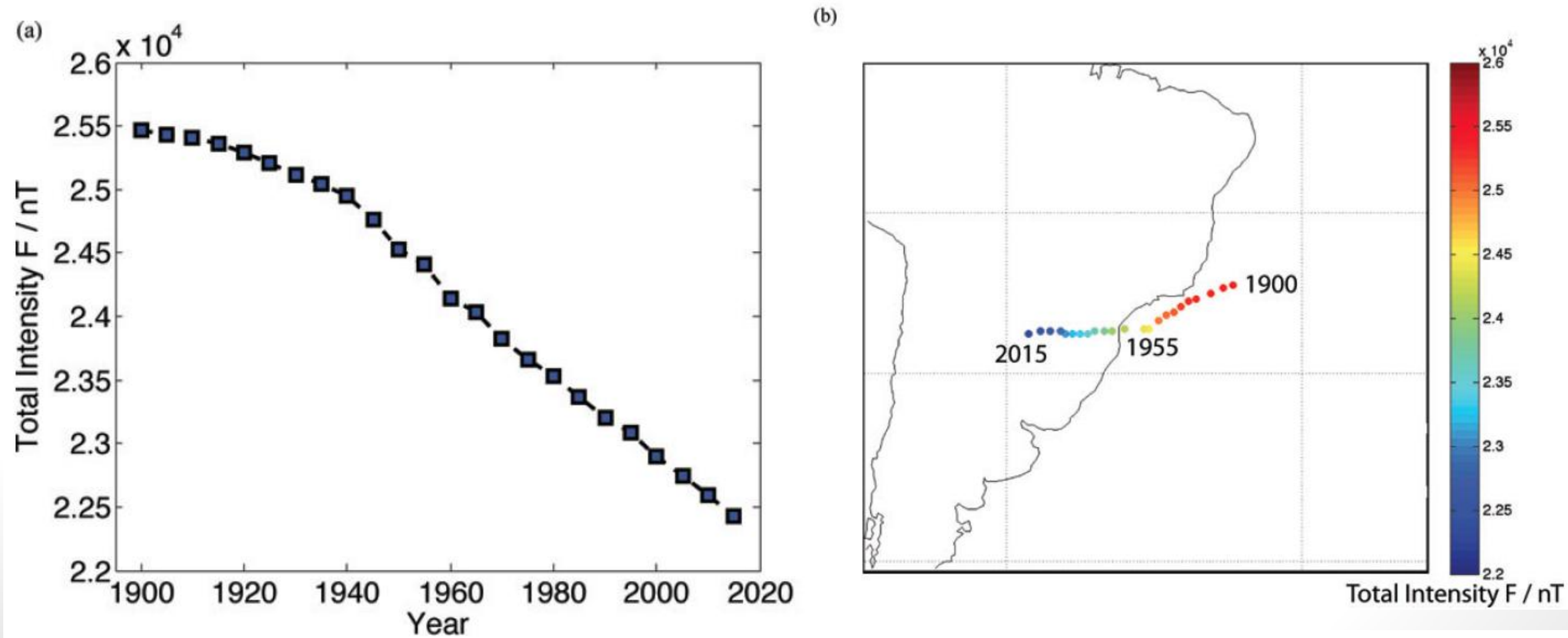
B_{poles} ~ 0.6 x 10^{-4} T

B_{eq} ~ 0.3 x 10^{-4}T



SAA

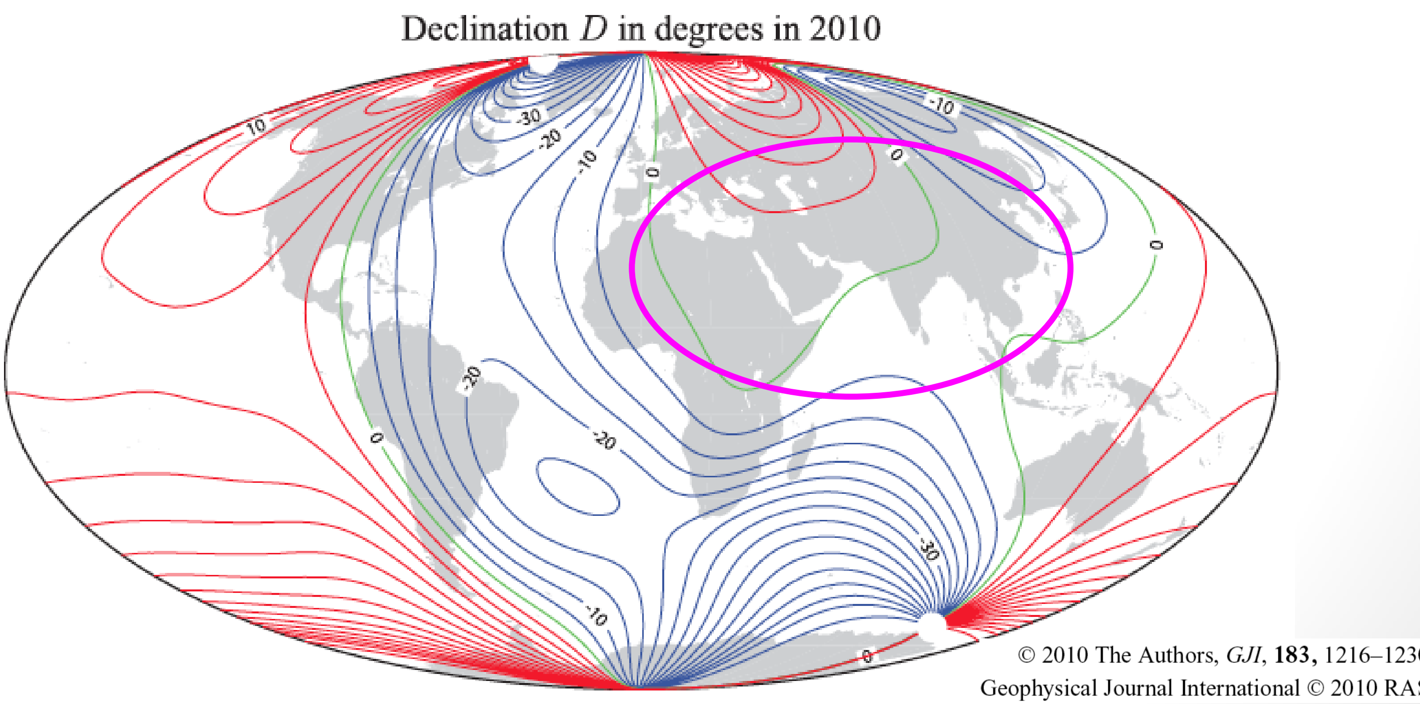
- The South Atlantic Anomaly:
  - B has systematically decreased and since the 1940 until the present the average decrease has been almost linear and equal to 34 nT yr^{-1}
  - The location of the point of lowest field intensity changed southward and westward



Declination

- Map of the magnetic field declination

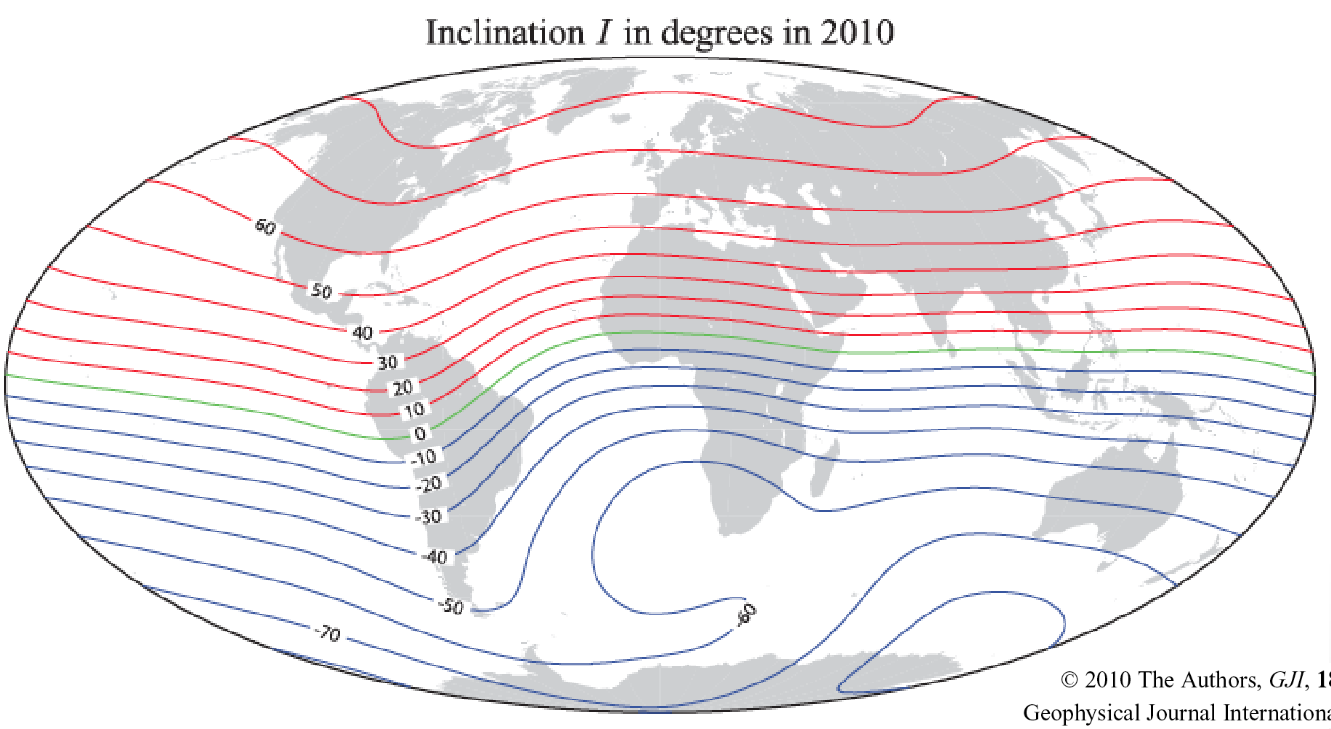
Blue line	Negative contours (W direction)
Red line	Positive contours (E direction)
Green line	Agonic lines



Inclination

- Map of the magnetic field inclination

Blue line	Negative contours
Red line	Positive contours
Green line	Zero line



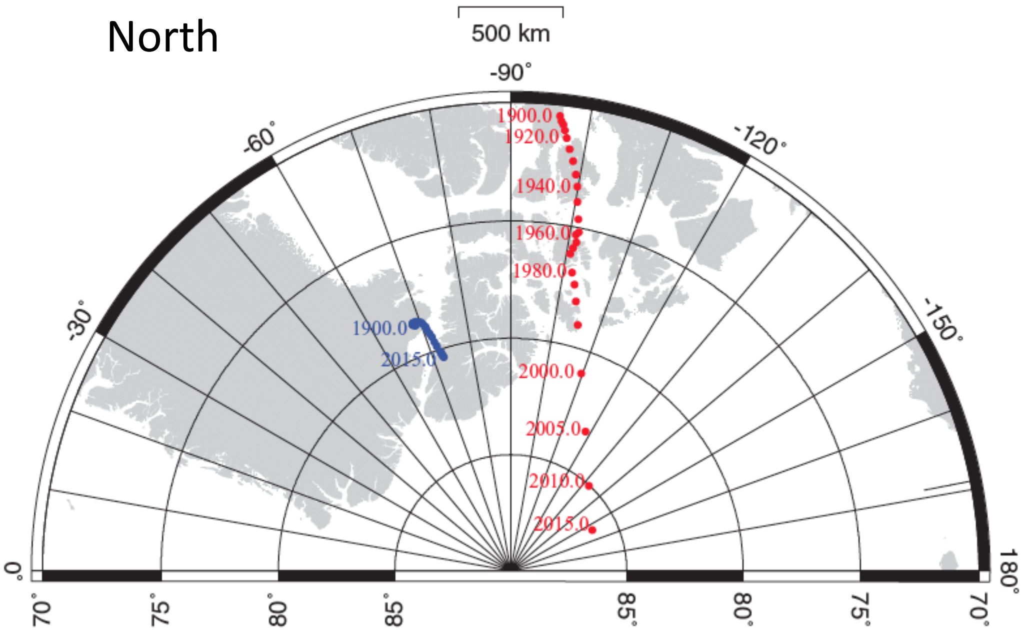
Motion of the poles

- The geomagnetic and magnetic poles moves about the geographic poles: termed secular variation in the magnetic pole position

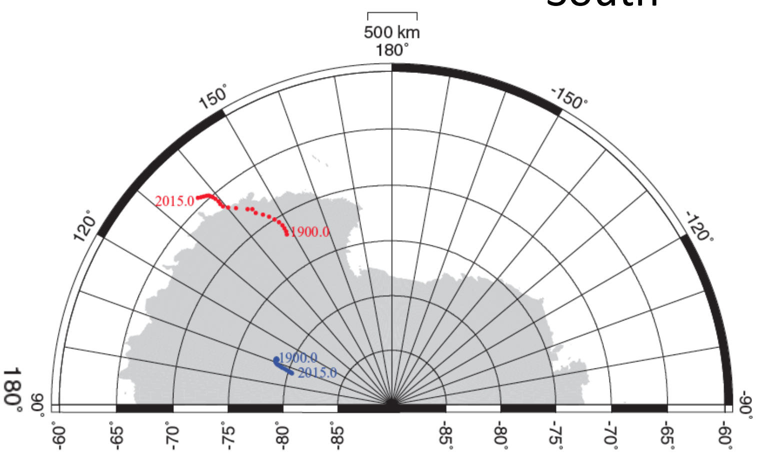
Magnetic pole

Geomagnetic pole

North



South



V ~ 50 km yr^{-1}

Source of geomagnetic field

- The power of the sinusoidal components of the magnetic field can be measured by satellites. The different slopes in the plot discriminate sources in the core of the Earth from crustal anomalies

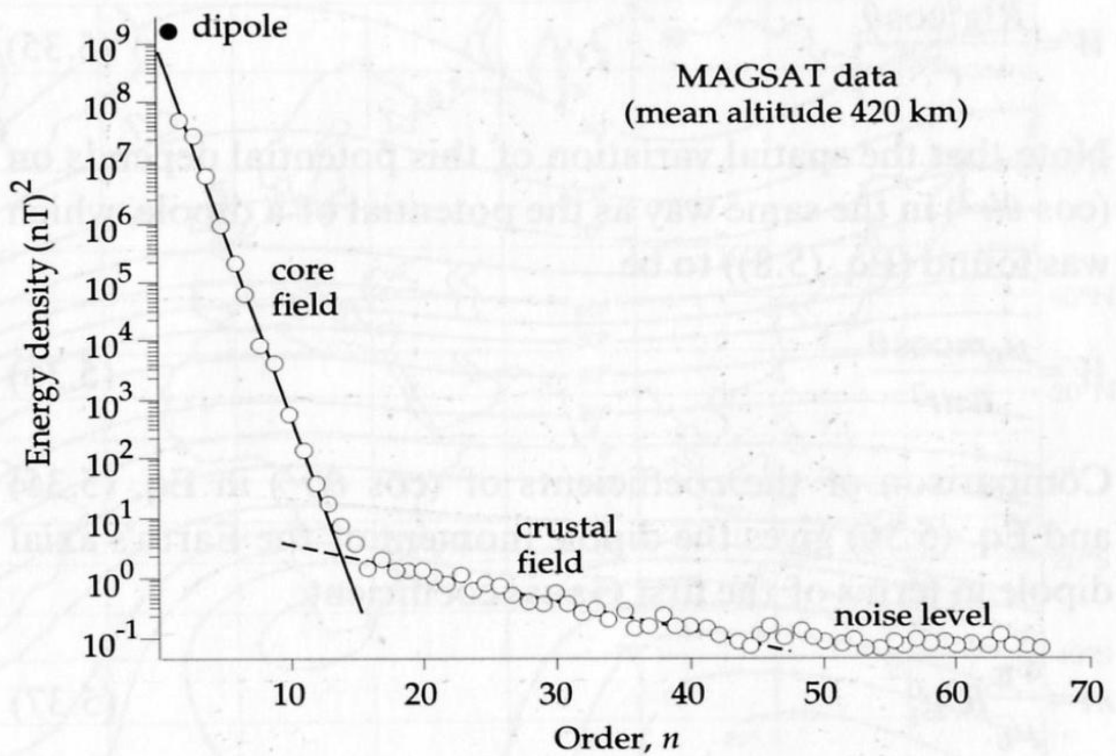
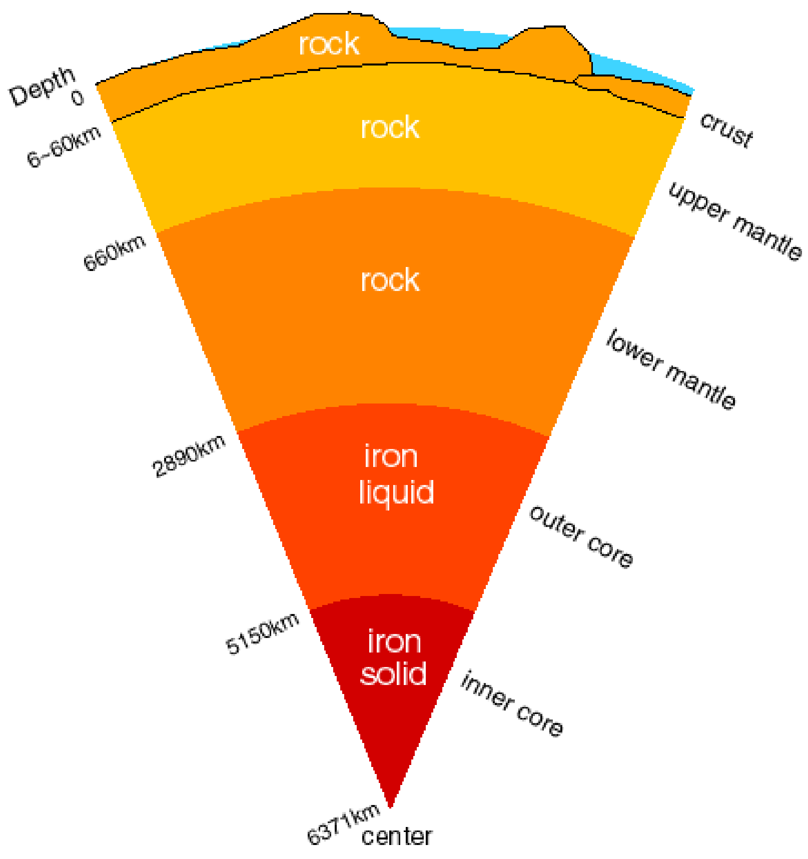


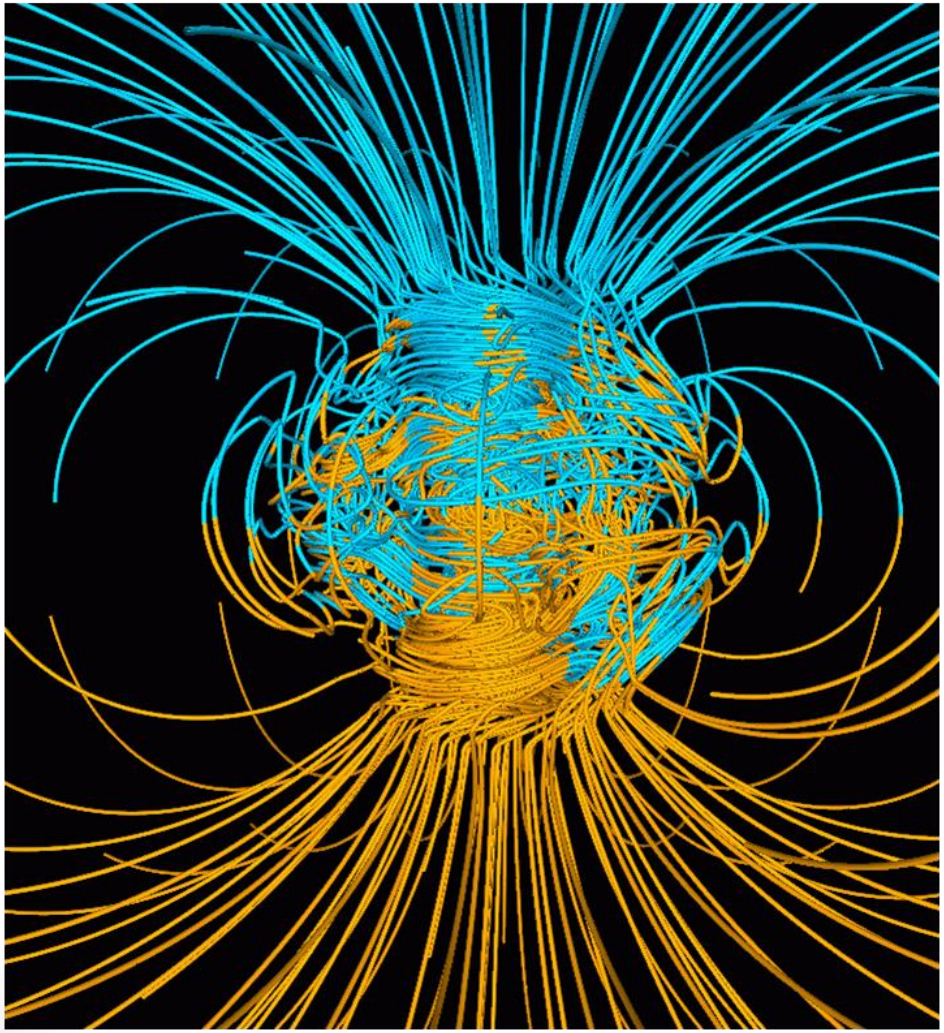
Fig. 5.33 The energy density spectrum derived from measurements of the geomagnetic field made by the MAGSAT Earth-orbiting satellite (after Cain, 1989).

Core field: geodynamo

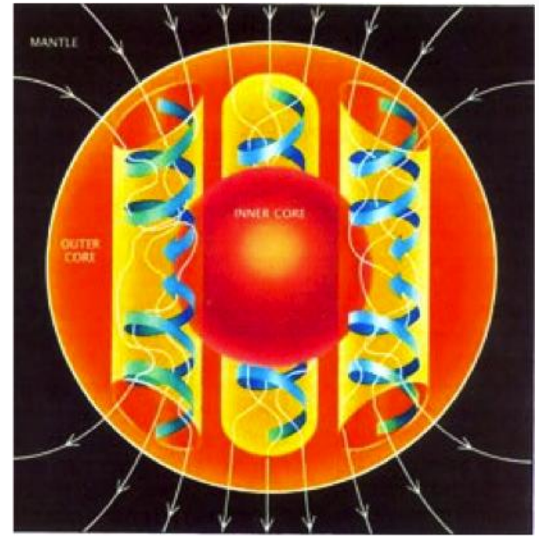
- The Earth's magnetic field is generated by electric currents in the outer liquid core, which mainly consists of iron
- The iron in the core moves turbulently. When the electrically conductive metal moves in the magnetic field, a new magnetic field is generated which may amplify the existing field
- This self-amplifying effect is called the Geo-dynamo

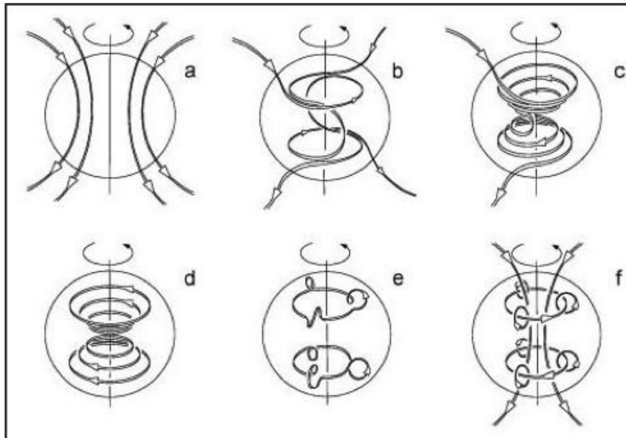


Core field: geodynamo



G. Glatzmaier and P.H. Roberts, *Nature*, 1995



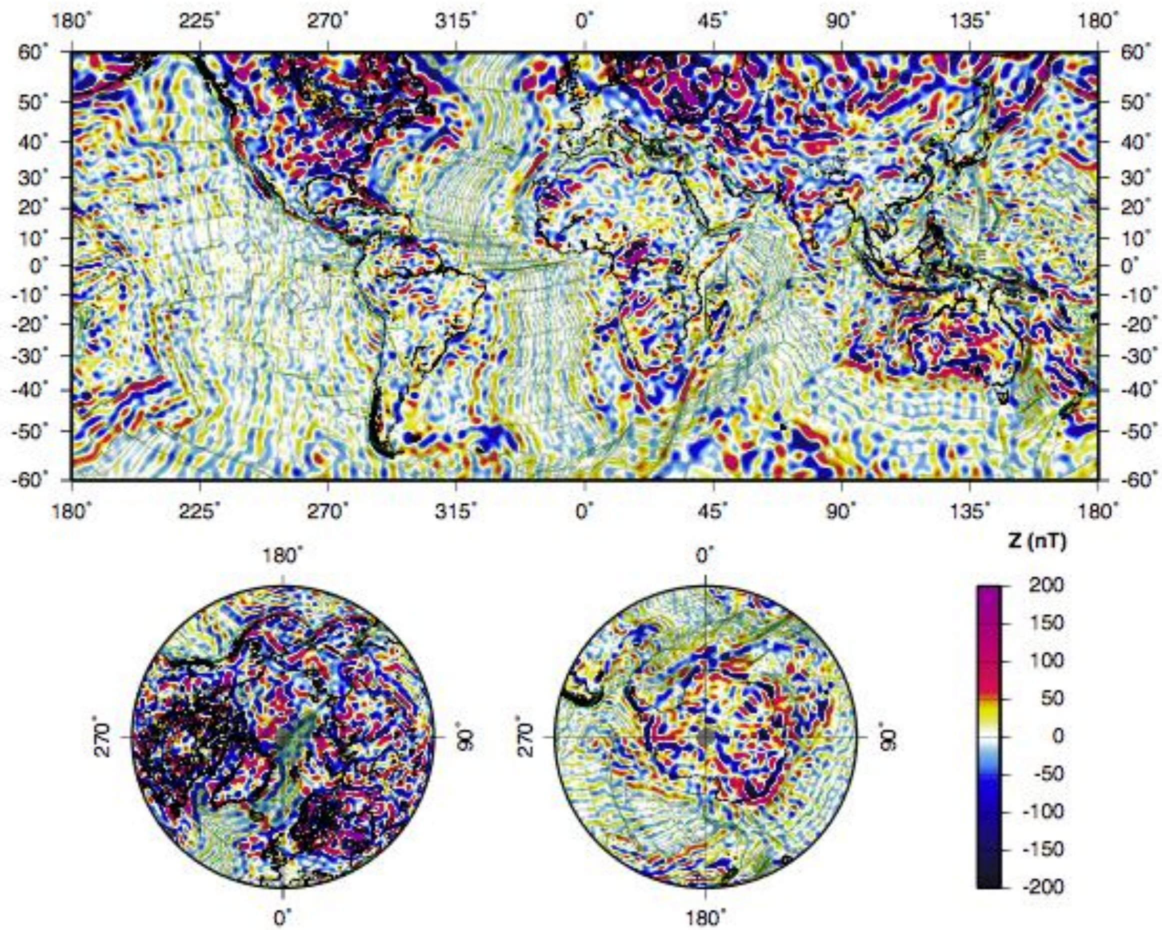


Love, J. J., 1999. Astronomy & Geophysics, 40, 6.14-6.19.

Crustal magnetic field

- The field arising from magnetic materials in the Earth's crust varies on all spatial scales and is often referred to as the anomaly field.

Vertical component of the MF7 crustal magnetic field at the Earth surface, overlain with the isochrons of an ocean-age model inferred from independent marine and aeromagnetic data by Muller et al. (2007) and plate boundaries by Bird (2003).

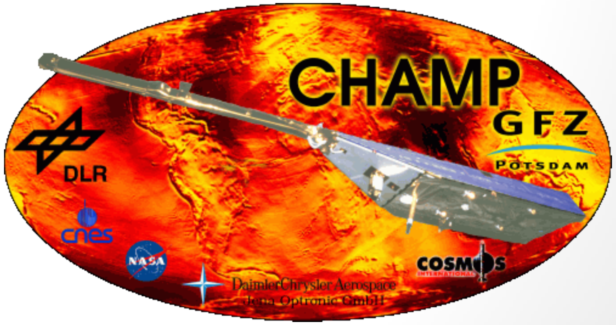


Crustal magnetic field

- Magnetic Field Model MF7:
  - produced using CHAMP (low earth orbit satellite) measurements from May 2007 to April 2010
  - resolves the crustal magnetic field to spherical harmonic degree 133, corresponding to length scales down to 300 km

CHAMP (**CHA**llenging **M**inisatellite **P**ayload) is a German small satellite mission for geoscientific and atmospheric research and applications.

CHAMP will generate for the first time simultaneously highly precise **gravity** and **magnetic** field measurements over a 5 years period.

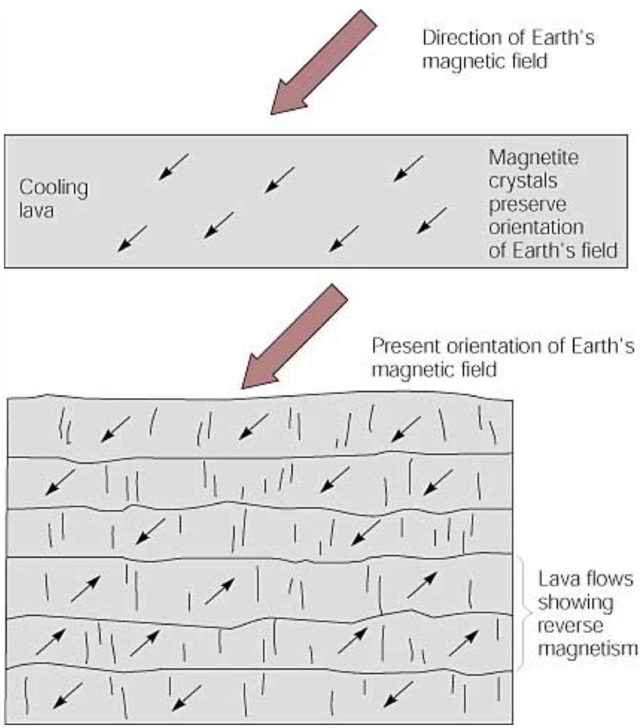


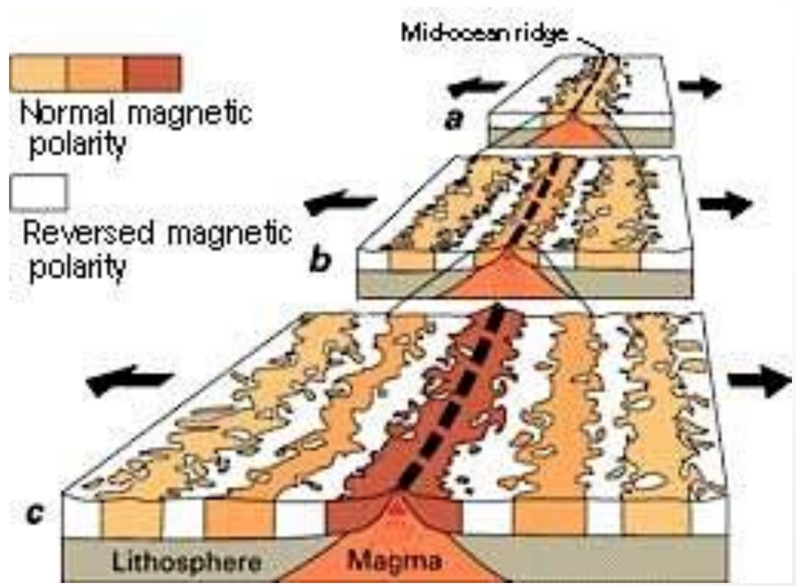
Paleomagnetism

- While direct measurements of the Earth's field go back only a few hundred years, we have information on its behaviour going back **several billion years** through paleomagnetic measurements, see for example Merrill et al.(1996).
- Though most rock forming minerals are non-magnetic, all **rocks exhibit some magnetic properties** due to the presence of traces of iron oxides.
- The magnetisation of these may be used to determine both the local direction and intensity of the Earth's field at the time the rock was formed.
- Relatively short time-scale behaviour can be determined from sequences of lava flows, and longer time-scale behaviour from sedimentary rocks.

Igneous rocks magnetization

- Igneous rocks record direction + intensity at time of formation. Look at sequence of lava flows – find N-S reversals.
- Magnetism "frozen" in when lava drops below **Curie Point** – this is 580˚C for magnetite.

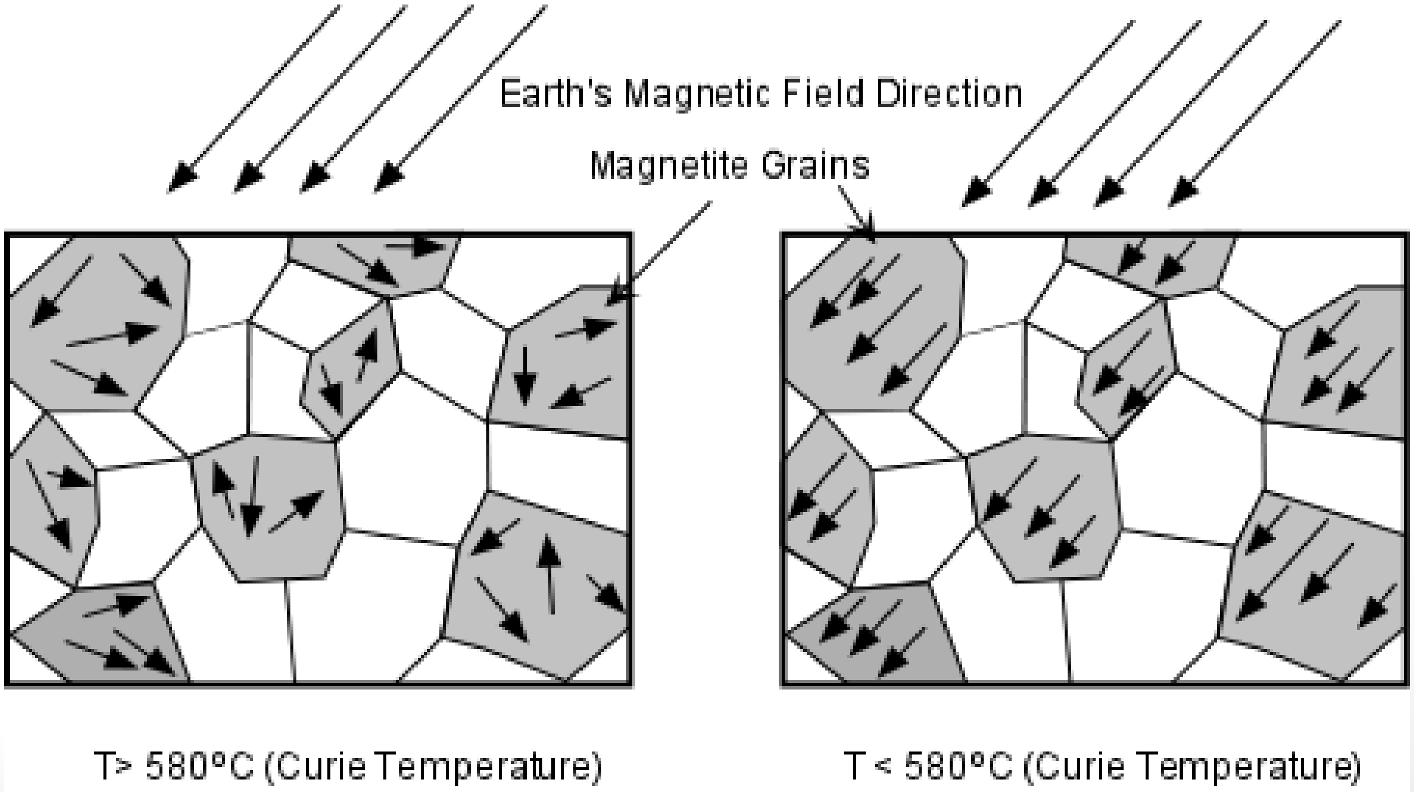




Curie point

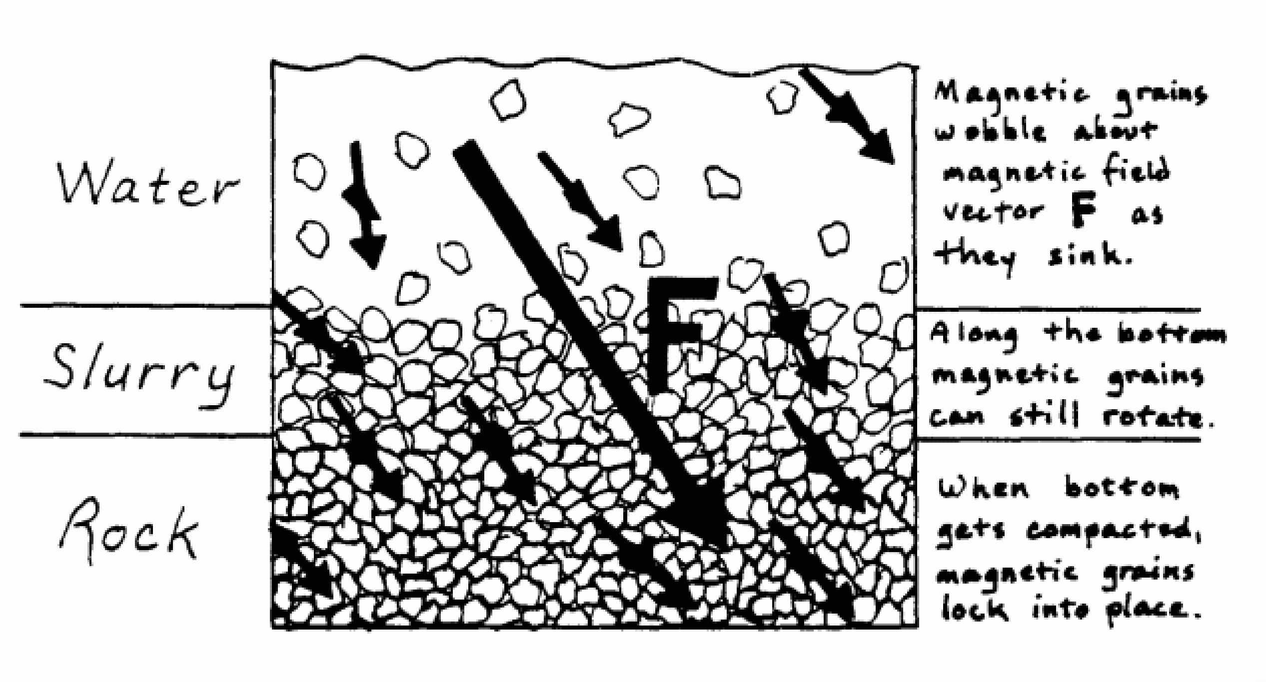
- Above the Curie Point, atoms within crystals vibrate randomly and have no associated magnetic field.

- Below the Curie Point the magnetic fields of the minerals act like tiny compass needles: they become aligned to the Earth's magnetic field.



Sedimentary rocks magnetization

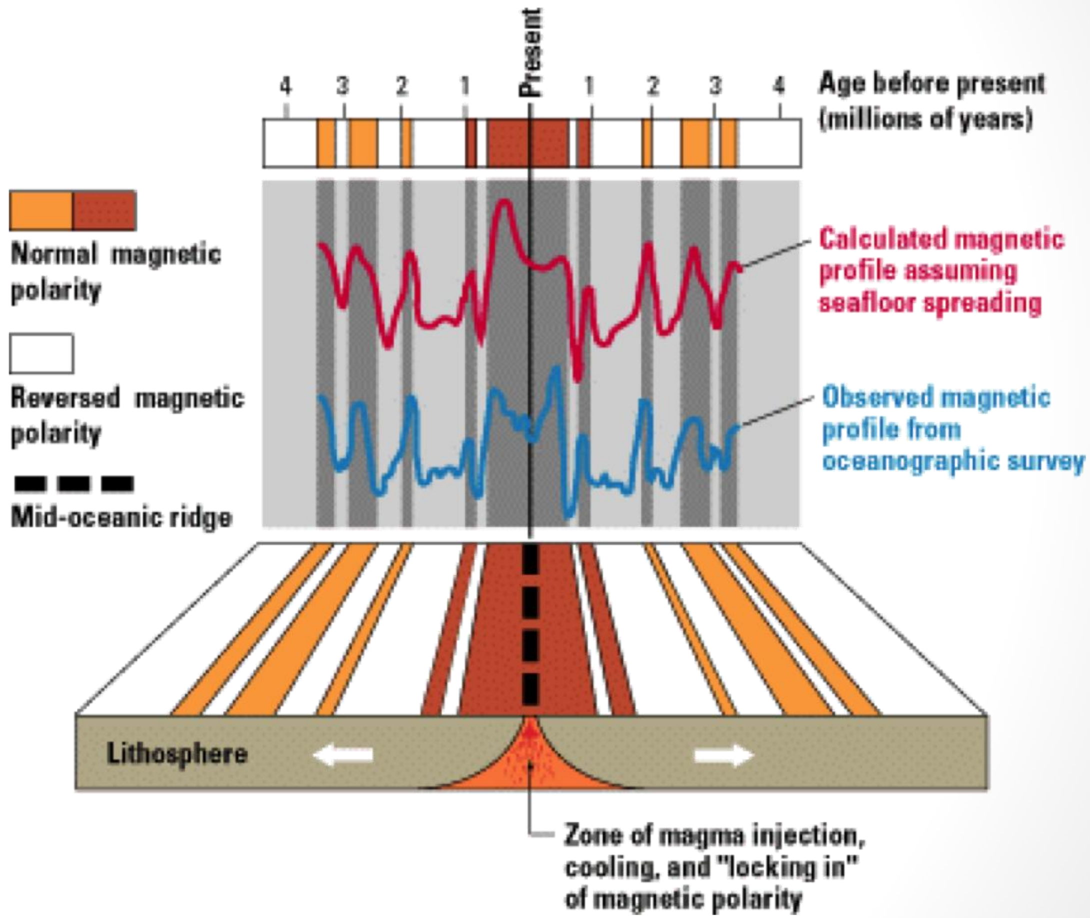
- Acquire a stable NRM through the statistical alignment of magnetic grains during their settling in the water column
- This detrital remanent magnetization is then fixed during burial and compaction



http://roma2.rm.ingv.it/en/research_areas/2/paleomagnetism_and_rock_magnetism

Paleomagnetism

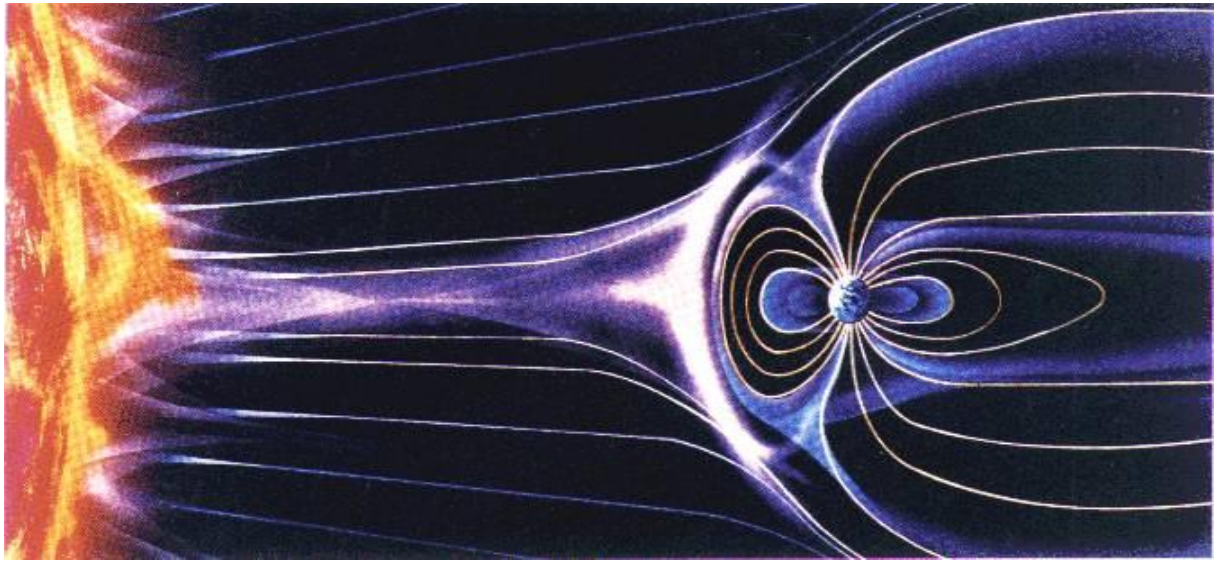
- Magnetic reversals recorded in ocean flow Record back to late Jurassic.
- Earth magnetic field reversed 9 times in 4 milion years



Magnetosphere

Magnetosphere

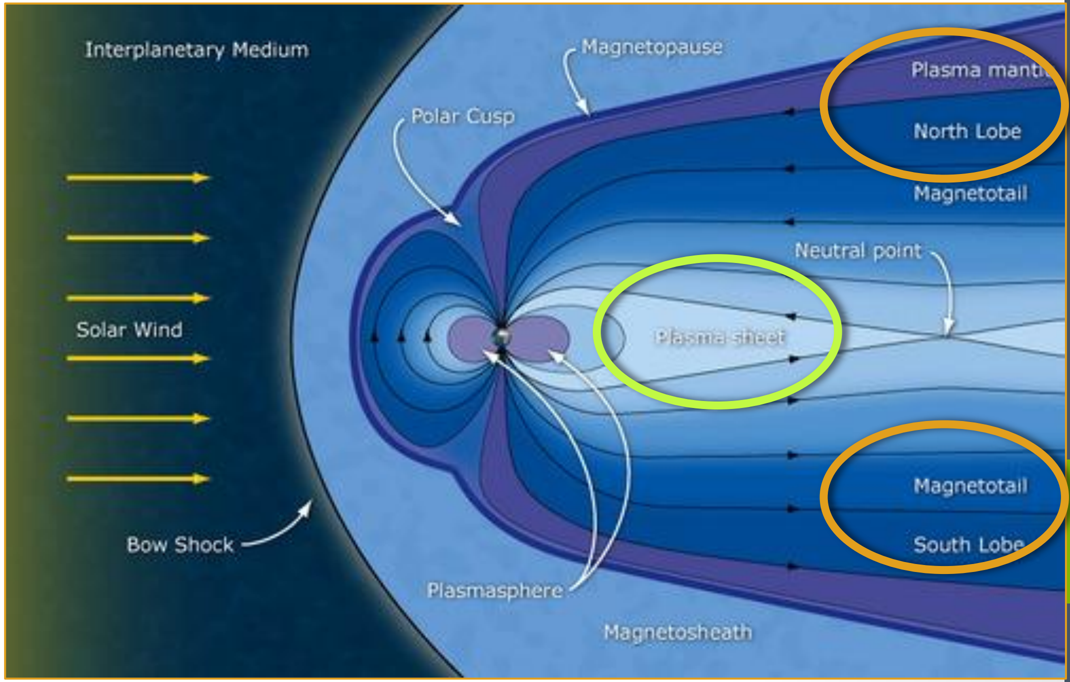
- After 5 – 6 R_E the characteristics of the magnetic field change due to the effect of the solar wind which confine the Earth magnetic field in a cavity called magnetosphere.
- The shape of the magnetosphere is similar to the shape of a bulled, compressed in the direction of the sun and elongated in the opposite direction



Magnetotail

- The night-side region of the megnetosphere is called magnetotail
  - 2 separate lobes of oppositely-directed magnetic flux
  - well-defined even at 200-220 R_E (ISEE-3 and Geotail)
  - is quite dynamic (ions and electrons are often energized)
  - Separating the two tail lobes is the "plasma sheet"

Region	Particle density
Solar wind near Earth	6 ions/cm^3
Dayside outer magnetosphere	1 ion/cm^3
"*Plasma sheet*" separating tail lobes	*0.3 -- 0.5 ions/cm^3*
Tail lobes	**0.01 ions/cm^3**



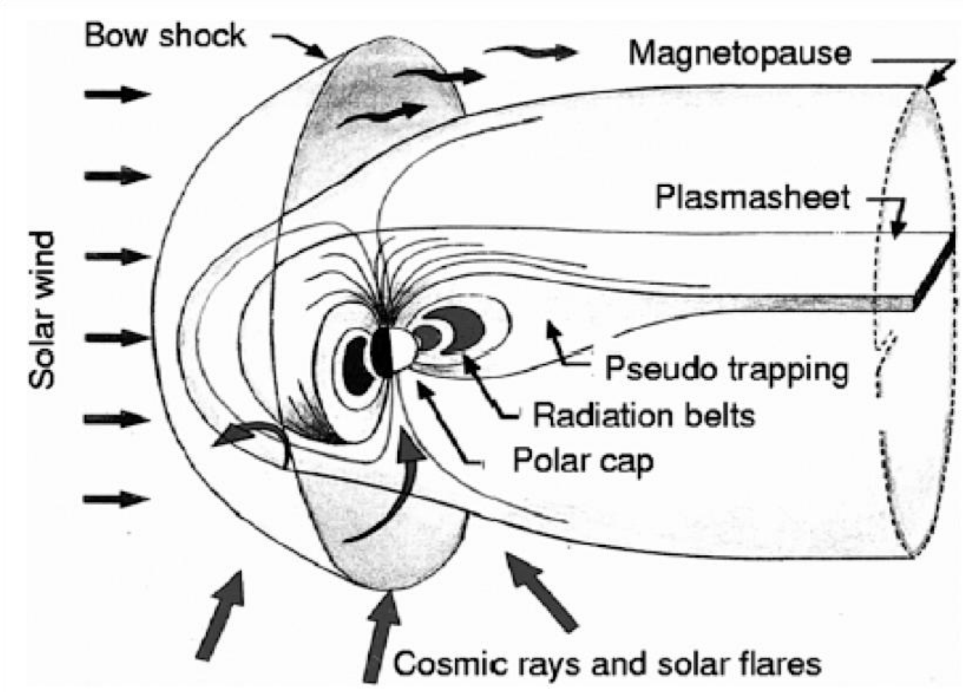
Bow shock

- The bow shock is the boundary at which the speed of the solar wind abruptly drops as a result of its approach to the magnetopause
  - Thick ~ 17 km (ESA's Cluster mission)
  - Position ~ 90 000 km from Earth (~ 15 R_E)

$V_b >$ $$c_s^2 = \frac{\gamma p}{\rho}$$

$V_b <$ $$c_s^2 = \frac{\gamma p}{\rho}$$

γ = Cp/Cv, p= pressure, ρ = density



Magnetopause

- The magnetopause is the area of the magnetosphere in which the pressure from the planetary magnetic field is balanced with the pressure from the solar wind
- Here the Earth magnetic field is dynamically dominating

$$(\rho v^2)_{sw} \approx \left(\frac{4B(r)^2}{2\mu_0}\right)_m$$

Solar wind dynamic pressure ≈ Earth' magnetic pressure

$$\rho v^2 \approx \frac{2B_0^2}{r^6\mu_0}$$

Dipolar field: $B \sim B_0/r^2$

$$r \approx \sqrt[6]{\frac{2B_0^2}{\mu_0 \rho v^2}}$$

Magnetopause distance

Exercise

- Calculate the distance of the magnetopause as function of solar wind conditions.
  - $B_0 \sim 0.3 \div 0.6$ nT
  - $\mu_0 \sim 4\pi\ 10^{-7}$ N A^{-2}

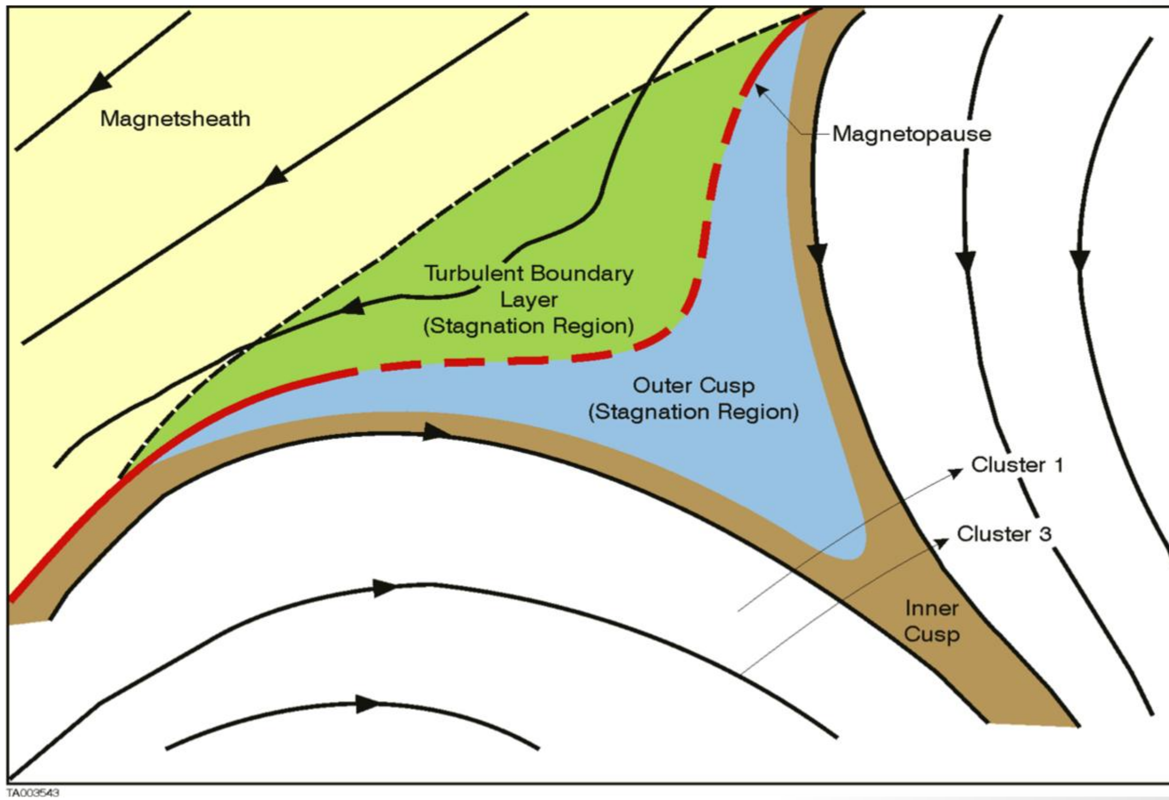
Wind Parameter	Slow wind	Fast wind
number density	~ 15 cm^{-3}	~ 4 cm^{-3}
bulk velocity	~ 350 km s^{-1}	~ 600 km s^{-1}
magnetic field	~ 6nT	~ 6nT

http://solarphysics.livingreviews.org/open?pubNo=lrsp-2005-4&page=articlese12.html

Polar cusps

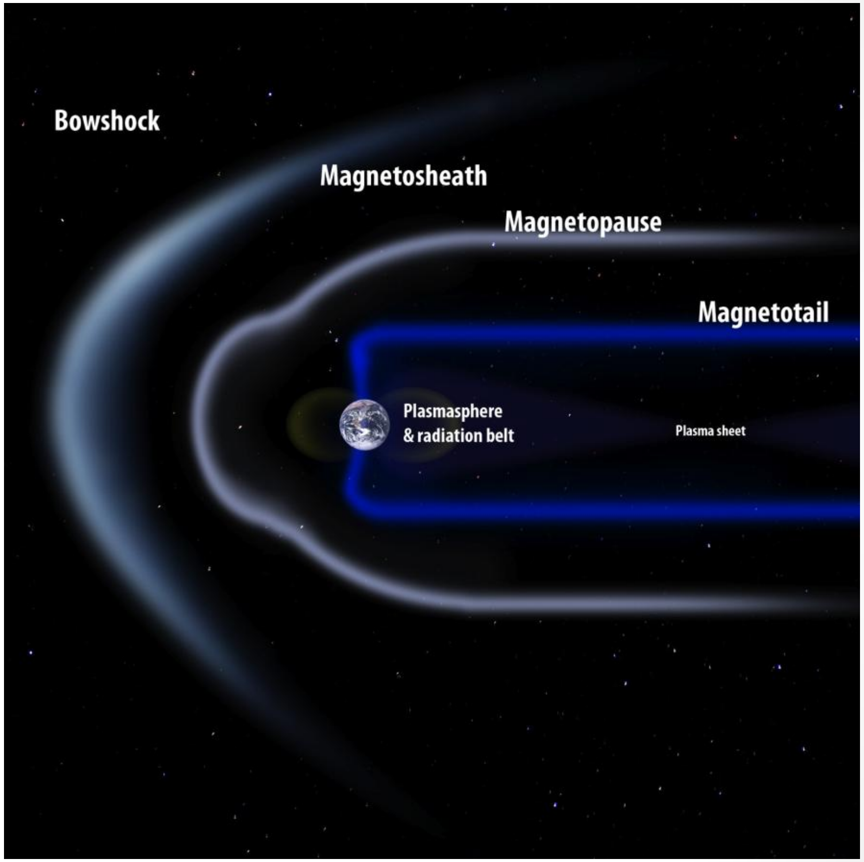
- The polar cusp is a region where the magnetic field lines switch from closing on the dayside to being swept back into the tail in which the magnetosheath plasma has direct access to the ionosphere

Position: approximately 15 degrees of latitude equatorward of the north and the south magnetic poles.



Magnetosheath

- The region between the bow shock and the magnetopause, characterized by very turbulent plasma. For the Earth, along the Sun-Earth axis, the magnetosheath is about 2 Earth radii thick.



Magnetosferic currents

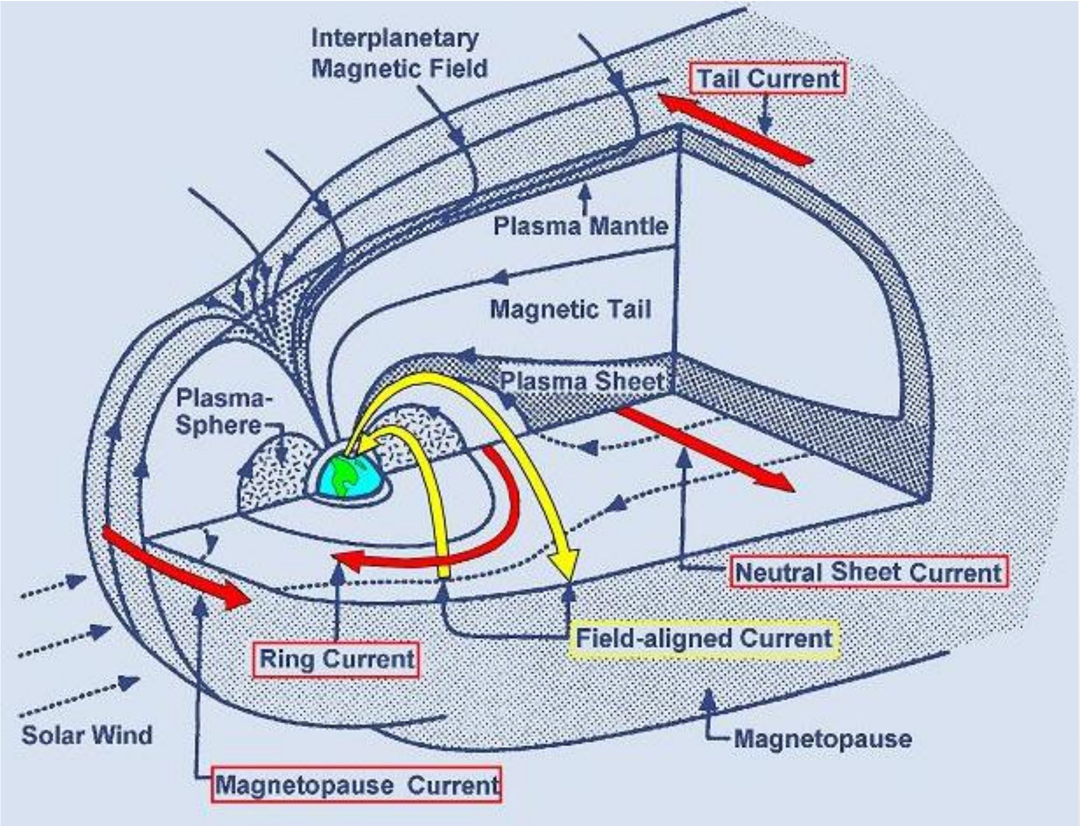
- Earth's magnetosphere present a really complicated current system, whose structure is influenced by the interaction with the interplanetary magnetic field

Magnetopause currents

Cross-tail currents

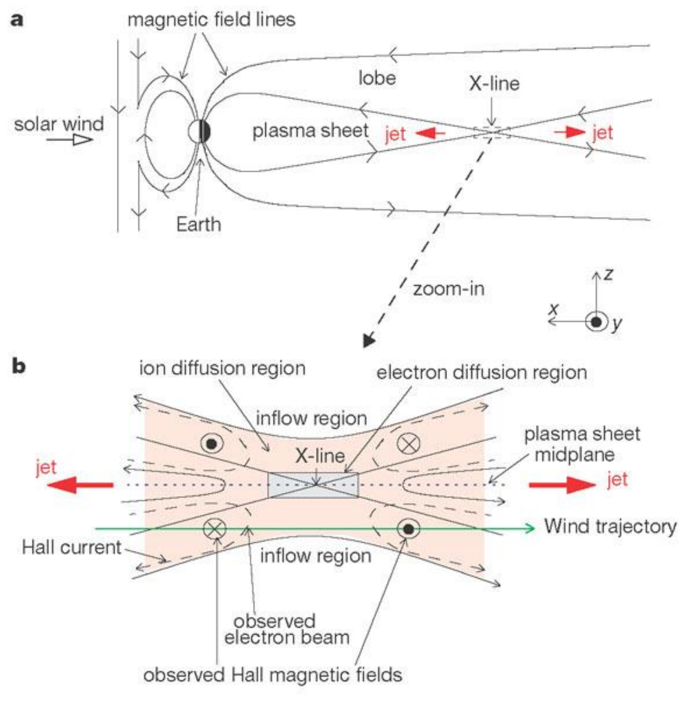
Ring currents

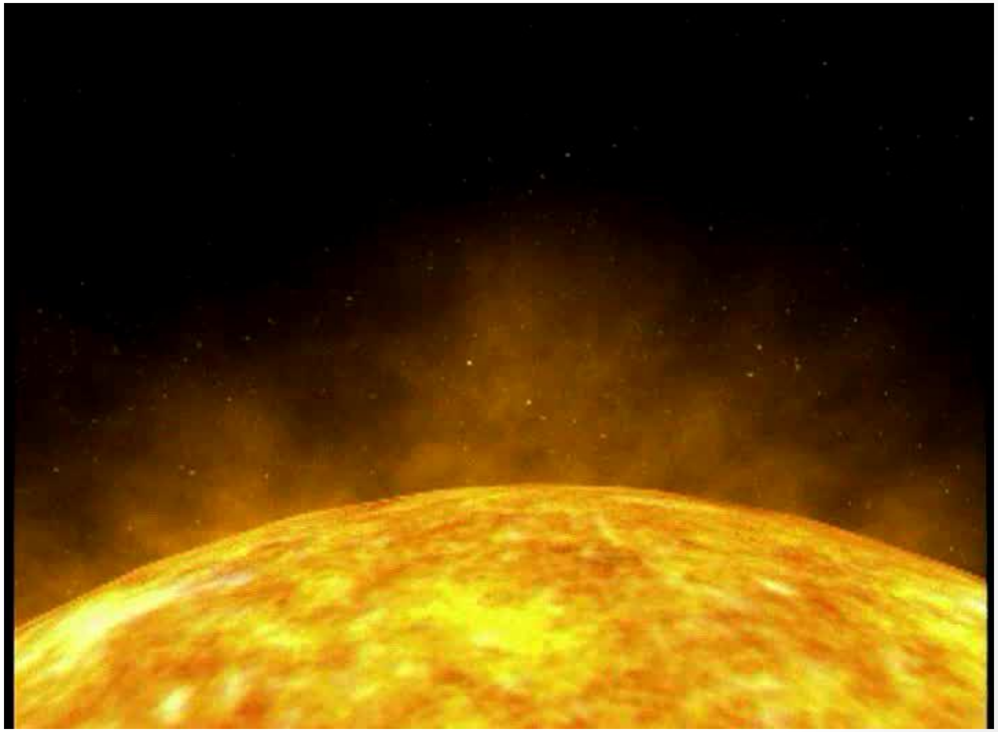
Field-aligned currents



Geomagnetic activity

- It is due to the interaction with the interplanetary medium and consist of
  - Storms
  - Substorms
  - Aurora





Storms

- Geomagnetic storms are large disturbances in the near-Earth environment, which are caused by coherent solar wind and interplanetary field structures that originate from solar disturbances such as coronal mass ejections. These storms are associated with:
  - Major disturbances in the geomagnetic field.
  - Strong increase of energetic (tens to hundreds of keV) ions in the (ring current) region.
  - Occasionally intense fluxes of relativistic (MeV) electrons in the outer van Allen radiation belt.

http://www.esa-spaceweather.net/spweather/BACKGROUND/PHYS_PROC/MAGNETOSPHERE/intro_magnetospheric.html

Substorms

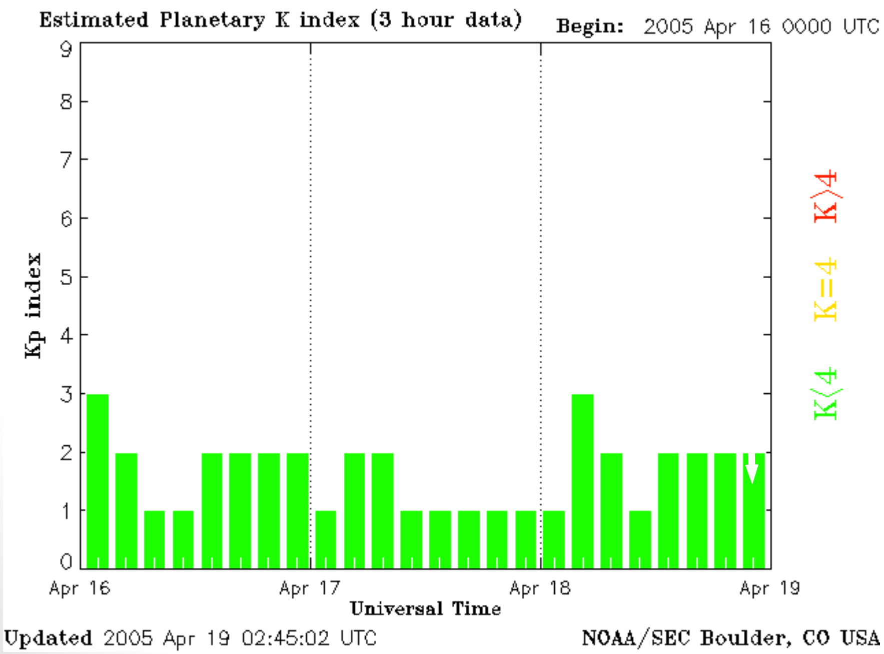
- Magnetospheric substorms are caused by the dynamic response of the magnetosphere to varying solar conditions. The energy input from the solar wind is governed by the orientation of the interplanetary field and as long as the magnetospheric region remains stable energy is stored as magnetic energy. At some critical point the magnetotail becomes unstable and the magnetic energy will be released via the "substorm expansion phase", which involves:
  - Injection of energetic (tens to hundreds of keV) particles (electrons and ions) to the vicinity of the geostationary orbit.
  - Strong electric currents in the auroral region.
  - Rapid fluctuations and configurational changes of the magnetospheric magnetic field.

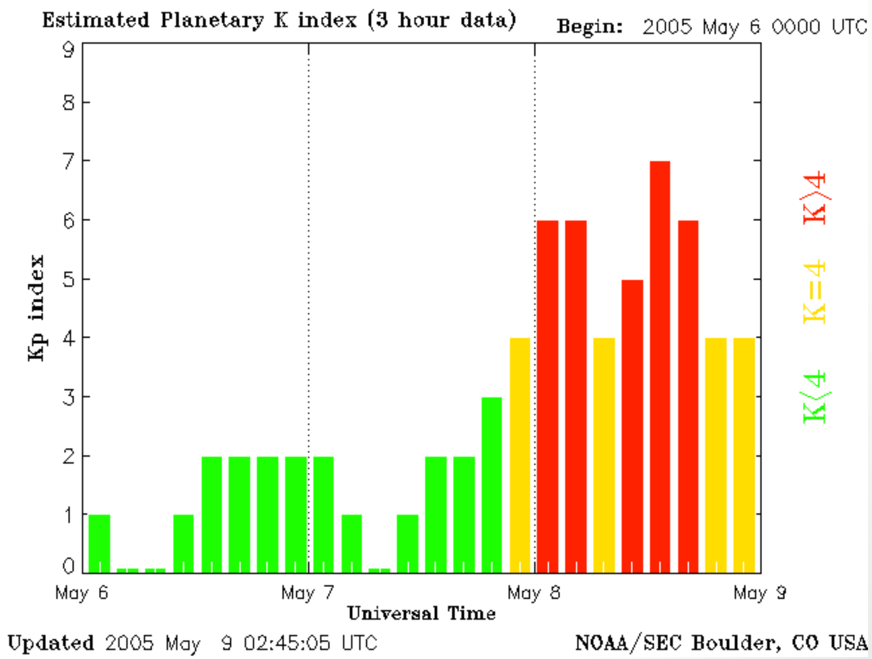
http://www.esa-spaceweather.net/spweather/BACKGROUND/PHYS_PROC/MAGNETOSPHERE/intro_magnetospheric.html

Kp Index

- Kp index is a numerical value calculated from a global distribution of magnetometers at mid-latitudes that allows scientists to keep track of the level of geomagnetic activity on a given day.

- Kp range from 0 (very quiet) to 9 (very disturbed) in 28 discrete steps, resulting in values of 0, 0+, 1-, 1, 1+, 2-, 2, 2+,...9.





Radiation belts

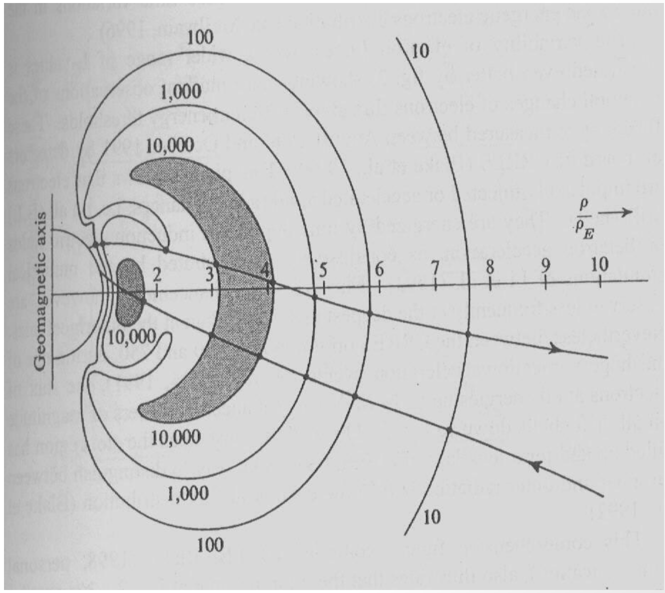
Radiation Belts

- Jan 1958: Explorer 1 (US)
  - *Geiger-Muller counter; J. van Allen*
  - LEO elliptical
  - > n cosmic rays up to 800km. At higher r no counts

Too much interactions saturated the receiver

- Explorer 2 =failed,
- March 25, **1958** Explorer 3:
  - Data recorder
  - Saturate
- Explorer 2 with 2 Geiger counter for different energy range

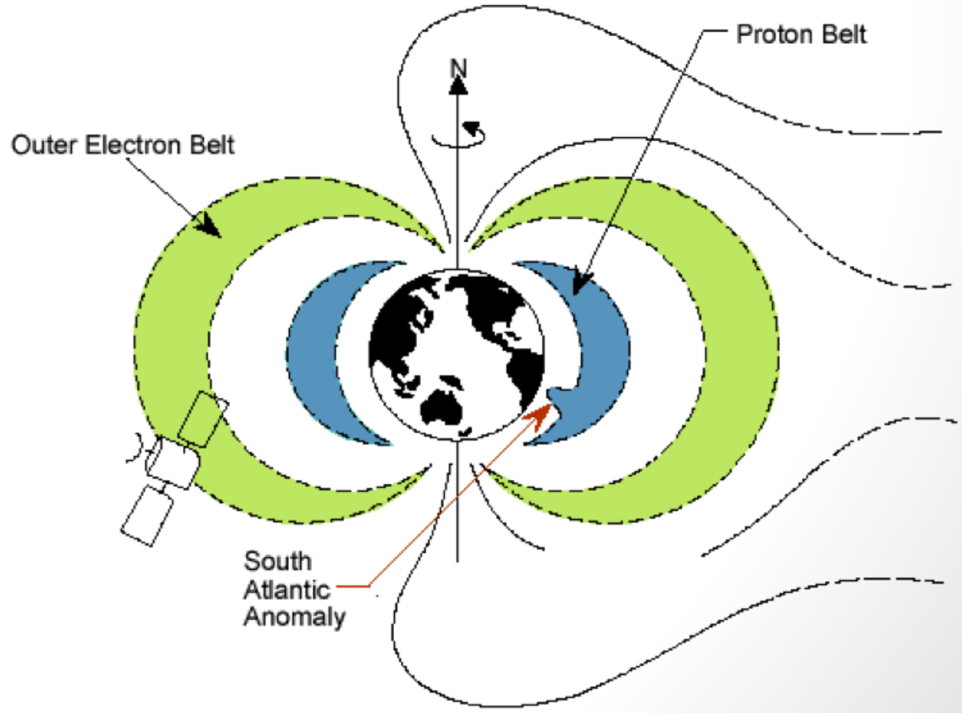
Toroidal ring filled with charged particles



Inner & outer belts

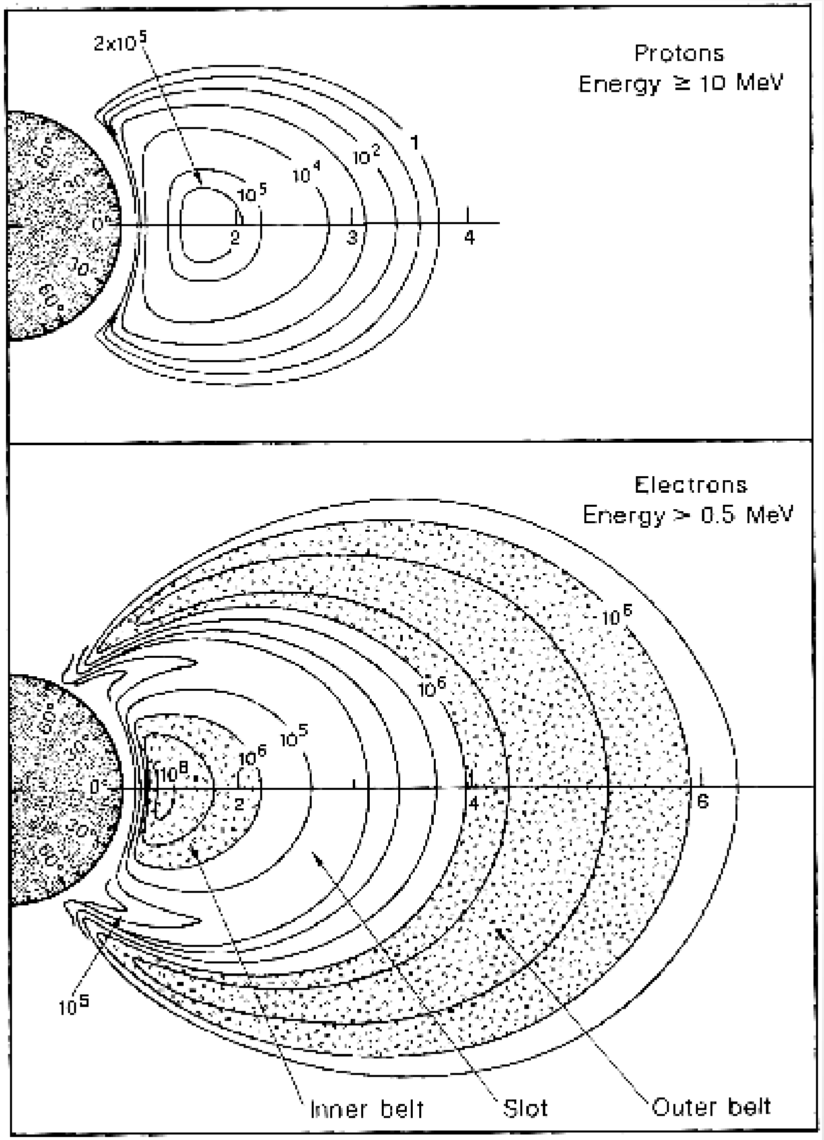
	Inner belt	Outer belt
Particles	p, e^-	e^-
Position	$< 2.5\ R_E$	$> 2.5\ R_E$, $< 12\ R_E$
Energies	~100 keV (e^-), ~ 100 MeV (p)	0.1 ÷ 10 MeV

Due to the tilt of the geomagnetic axis relative to Earth's rotation axis the bottom of the belts is only 500 km above the southern Atlantic.



Inner & outer belts

- Earth's radiation belts. The numbers give the omnidirectional flux in particles per square centimeter per second.

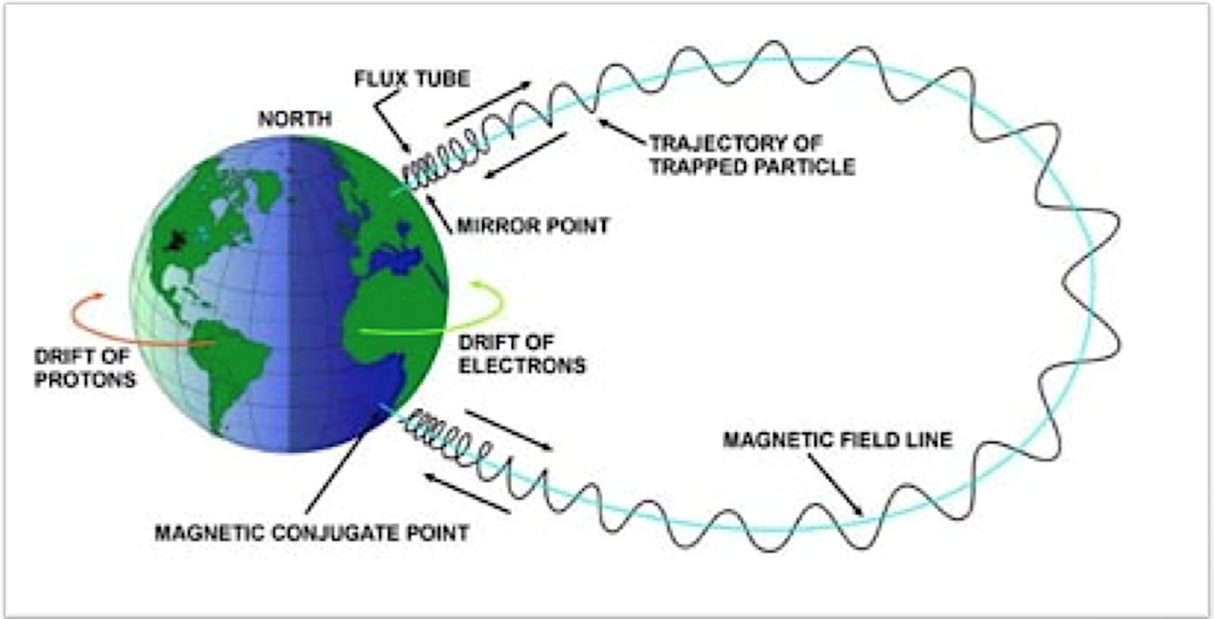


(from Kivelson and Russell, 1995)

Trapped particles motion

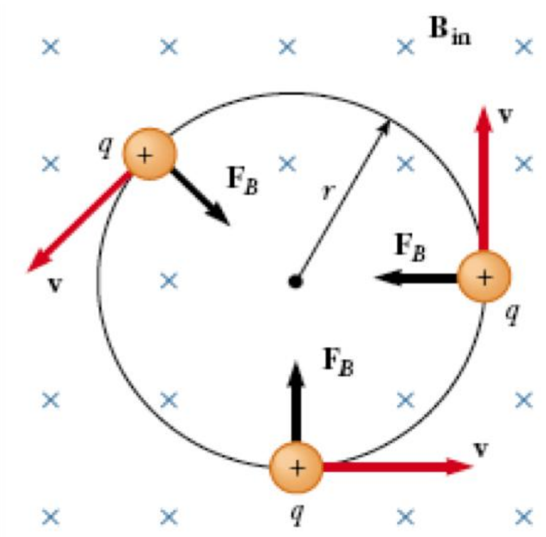
- A charged particle became trapped in those regions where the magnetic field lines are closed. Tree possible effects:

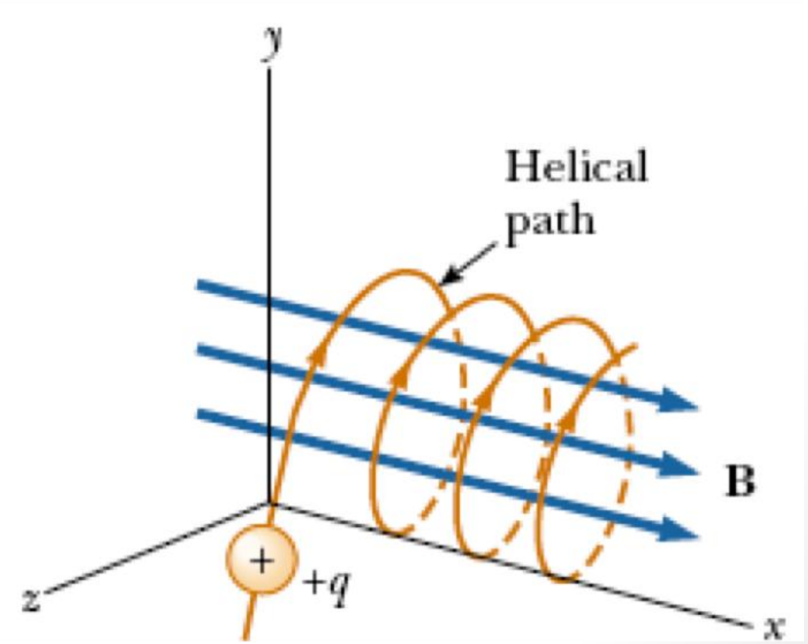
Circular motions with gyro-radius about the field line
Bounce back and forth along a field line. Reversing direction at a mirror point
Drift of particles around the Earth: Electrons drift to east, protons drift to west



Trapped particles motion

- Particles moving in a UNIFORM magnetic field moves on spiral trajectory along the field line (r = costant)
  - If v is orthogonal to B the path is circular
  - If v is at some angle θ to B, its path is a helix.





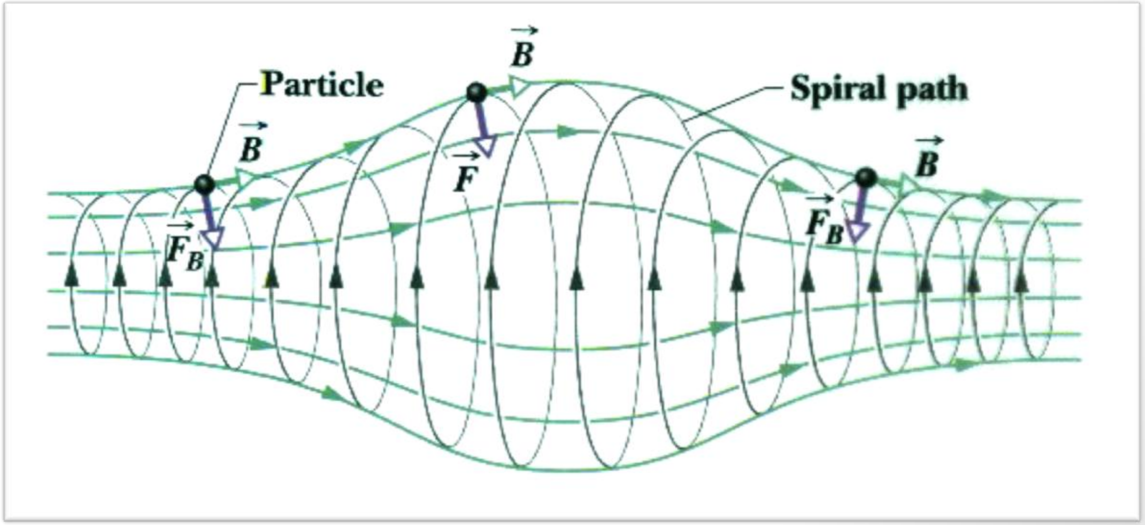
Trapped particles motion

If the field is not uniform the trajectory is complicate

THE MAGNETIC BOTTLE
The magnetic field is strong at the ends and weak in the middle. A charged particle starting at one end will spiral along the field lines until it reaches the other end, where it reverses directions and spirals back

$r = m_{part}\, v_{ort}\, c / eB$

$B_{mirror} = B_1 / \sin^2\theta_1$



Solar Energetic Particles

SEP or SPE (Solar Proton Events)

(Solar Cosmic Rays)

Origin: **Solar flares** and **Coronal Mass Ejections** (CME)

p, e & **He** emitted by the sun in burst during **'solar storms'**

-energies > 10 MeV/nucleon

-access to open magnetic fields of polar cap.

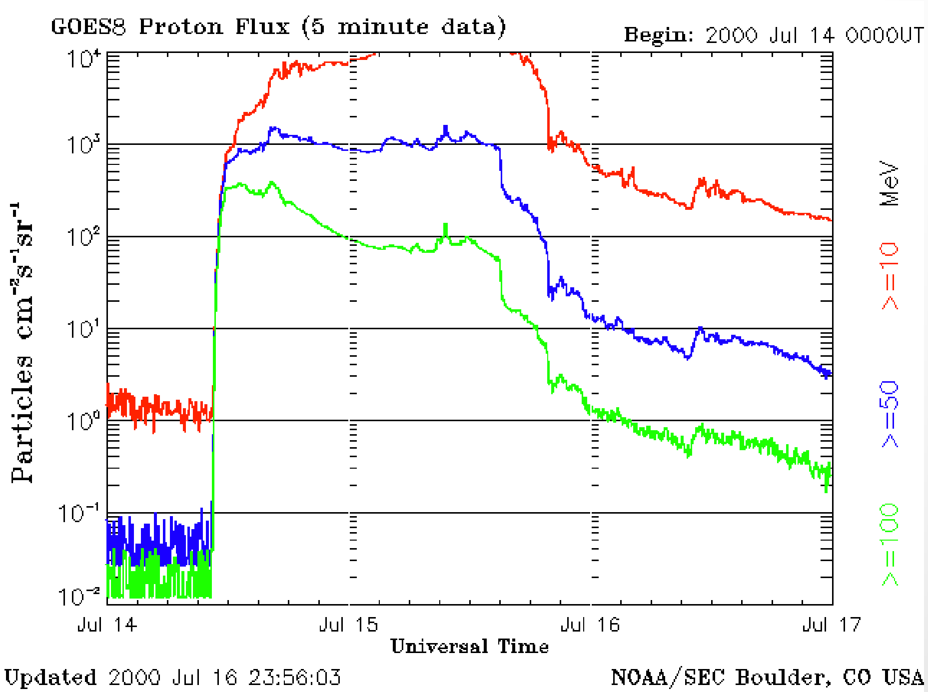
Produce also : X-rays; gamma-rays, UV light burst and very fast wind flow which can inject protons into the trapping region (even create 'second proton belt')

Fluence: from 10^5 to 10^11 part/cm^2

Duration of event: from one to several days

"Bastilia" Solar Event

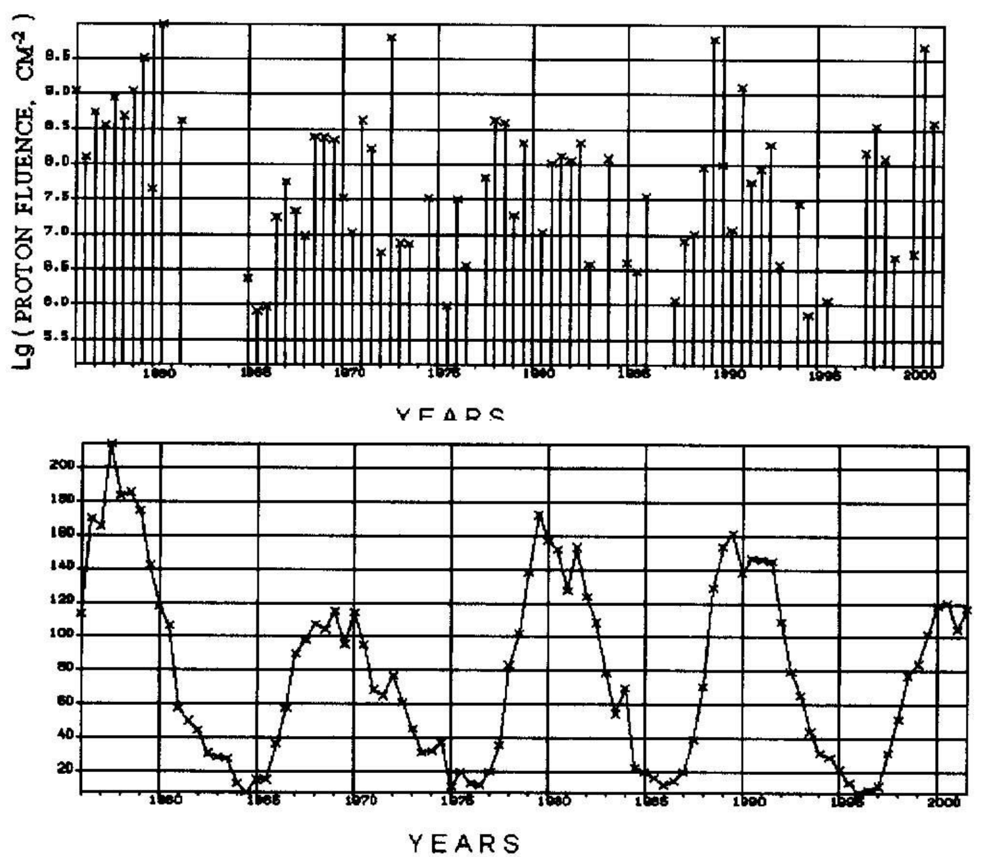
14 July 2000

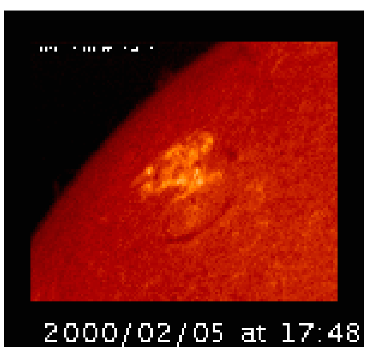


SPE Periodicity:

Frequency spectra of solar proton fluence
of Energy > 30 MeV → periods of ~ 11 years and 3-4 years.
Impossible to predict

-greater occurrence frequency
during **maximum** solar activity
- and **during decline** of cycle





NASA SOHO Image Solar Flare

Cosmic Rays

Galactic Cosmic Rays:

fully ionized particles of all stable elements (90% p ~7% He)

Origin: galactic and extragalactic; Energies up to TeV

Energy spectrum max at 0.3-1 GeV/nucleon

The incoming charged particles are '**modulated**' by the **solar wind** and **IMF** which decelerates and **partially excludes the lower energy** GCR from the inner solar system. There is a significant **anticorrelation** between solar activity and the intensity of the CR with E< 10 GeV.

Variations of proton counts E=80-215 MeV of MEPED detector aboard the TIROS/NOAA spacecraft