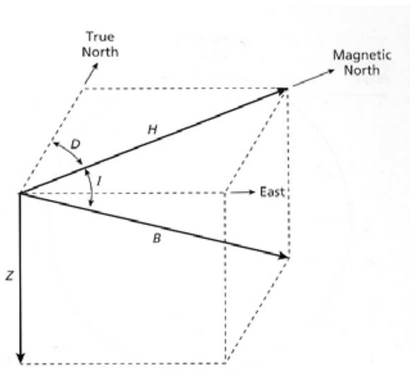
223 C2 The Earth's magnetic field

- Magnetic field of the Earth measured at the surface comes from **three** sources:

97-99%	**Main field** generated by dynamo action in the outer core
1-2%	**External field** generated in space in the magnetosphere
1-2%	**Crustal field** from remnant magnetization above the Curie depth

- **Main field** varies significantly with time scale of years (secular variation)
- **External field** varies with time scales of minutes to days
- **Crustal field** on varies over geological time scales
- At any point the magnetic field is defined by the **magnetic field elements**
- Magnetic field is more complicated in spatial form than gravity field



F = total field strength (also labelled B)

Z = vertical component of F

H = horizontal component of F

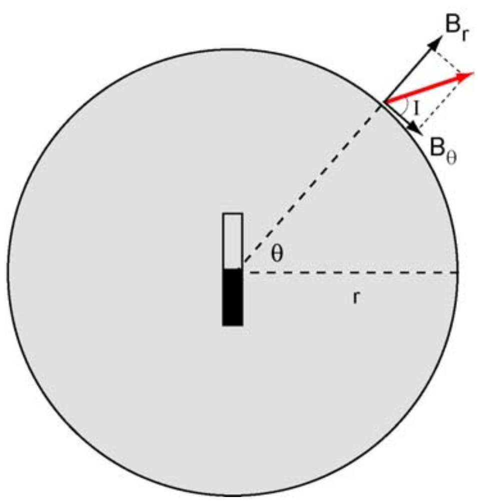
I = inclination (angle between F and surface)

D = declination (angle between H and geographic north)

See my Geophysics 210 notes for a historical perspective on the Earth's magnetic field
http://www-geo.phys.ualberta.ca/~unsworth/UA-classes/210/notes210/D/210D2-2008.pdf

223 C2.1 The internal component of the Earth's magnetic field

C2.1.1 Spatial variation of internal magnetic field - simplified form



Consider the **dipole component** of the geomagnetic field.

At a latitude of θ the **radial** and **azimuthal** components of the magnetic field are given by:

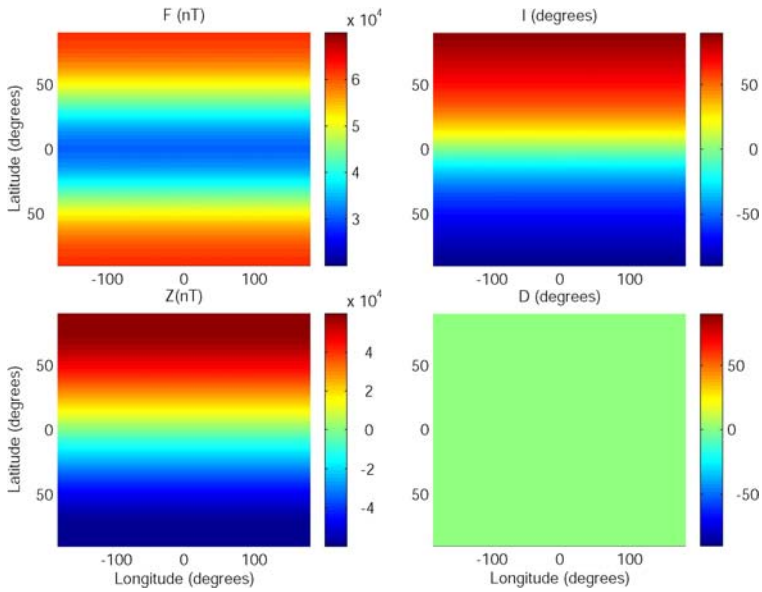
$$B_r = \frac{2M\mu_0 \sin\theta}{4\pi r^3} \quad \text{and} \quad B_\theta \frac{M\mu_0 \cos\theta}{4\pi r^3}$$

where M is the dipole moment, a measure of the strength of the magnetic field.

Can calculate how the inclination, I, varies with latitude (θ)

$$\tan I = \frac{B_r}{B_\theta} = \frac{2\sin\theta}{\cos\theta} = 2\tan\theta$$

- At the North Pole, θ = 90° which gives I = 90°
- At the Equator, θ = 0° which gives I = 0°
- This equation allows us to use a measurement of inclination (I) to determine latitude (θ).
- Total magnetic strength is given by $F(r,\theta) = \sqrt{B_r^2 + B_\theta^2}$ which reduces to $F(r,\theta) = \dfrac{M\mu_0\sqrt{3\sin^2\theta + 1}}{4\pi r^3}$. This predicts F(θ = 90°) = 2 x F (θ = 0°)
- Panels below show maps of the predicted values of F, I, Z and D for a **dipolar field** with coincident magnetic and geographic poles.



C2.1.2 Spatial variation of internal magnetic field - actual magnetic field

- Actual magnetic field is described by the International Geomagnetic Reference Field (IGRF) that is shown on page 3.

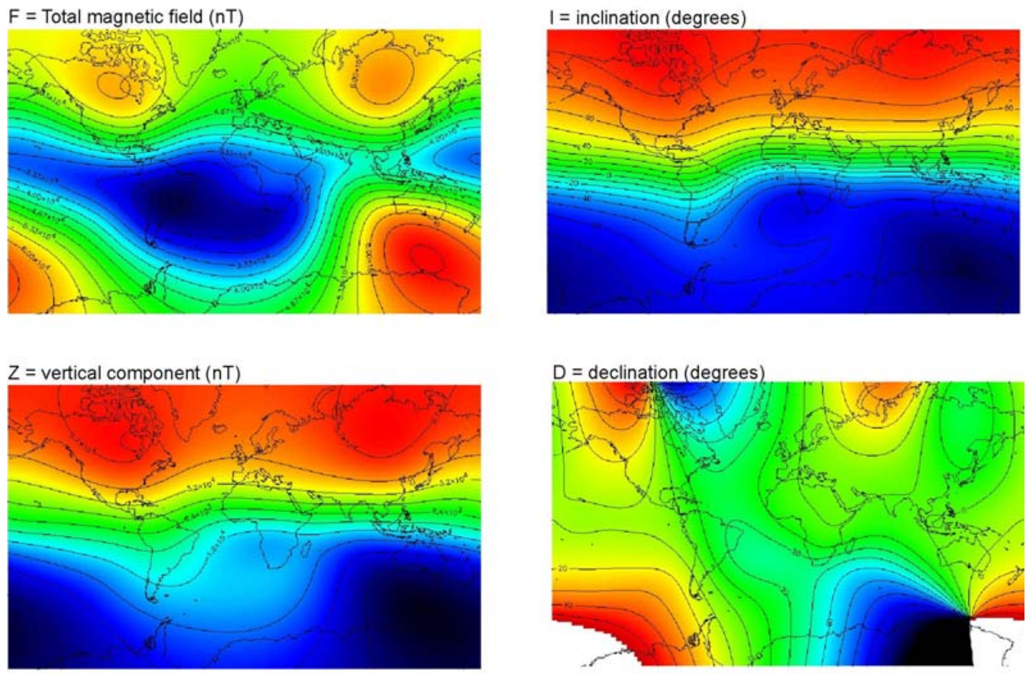
Some characteristics of the IGRF look like a simple dipole field:

- Some characteristics are as predicted for a dipole field.
- Value of F at the poles is approximately double that at the Equator.
- Z changes sign and I = 0° close to the Equator

Complications arise from two factors:

(1) Magnetic and geographic poles are not coincident. This results in D non-zero and contours of F, I and Z do not follow lines of latitude.

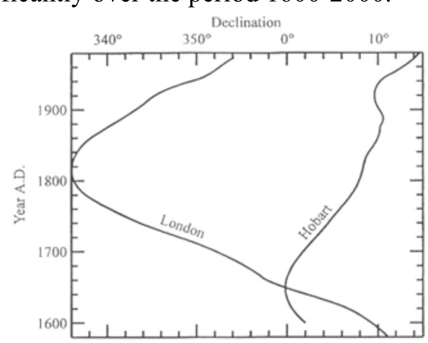
(2) Only 80% of the main field can be represented as a dipole. Note the departures from a pure dipole field, e.g. four regions of high F in high latitudes.



- IGRF in 2000 shown below and updated regularly as the magnetic changes over time.

C2.1.3 Temporal variations (secular variation)

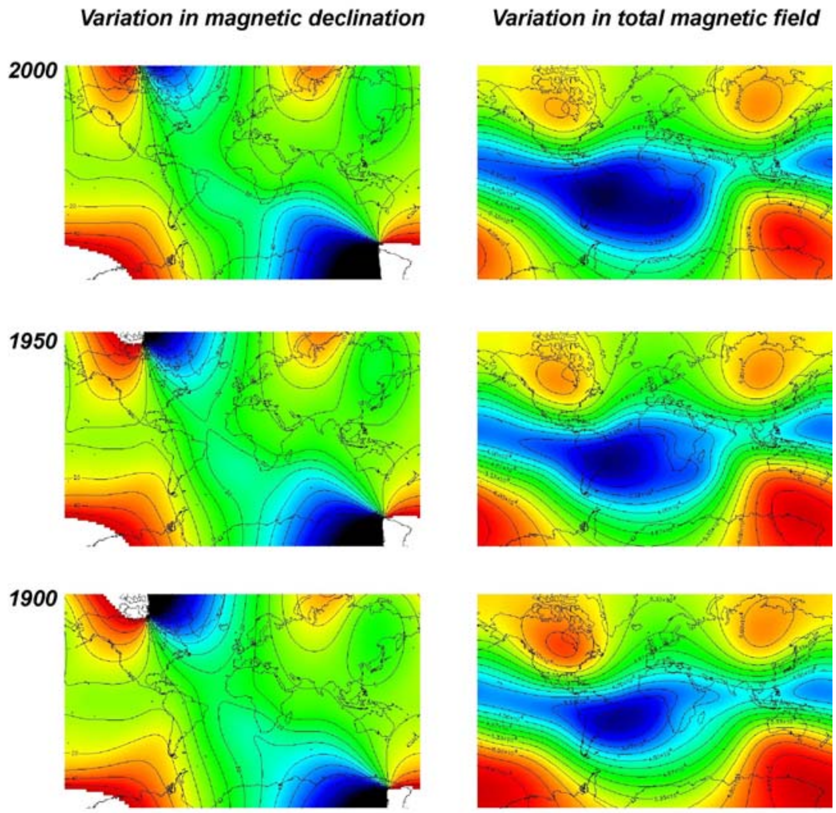
- The compass was invented in China. Variation of declination reported from at least AD720.
- 1635 : The first European record when Gellibrand noted changes in declination.
- The declination in London was found to vary significantly over the period 1600-2000.

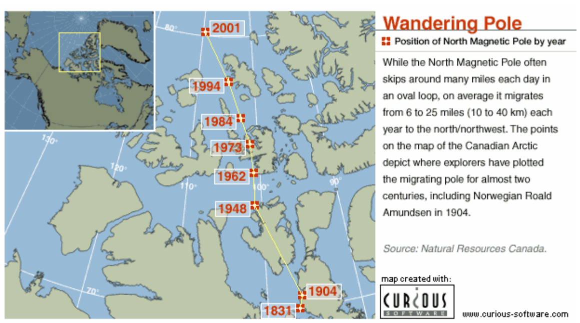


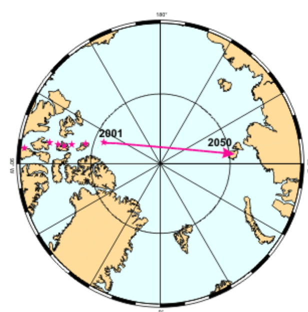
● **Secular variation** in the Earth's magnetic field occurs on many timescales including:

(a) Westward drift: features can be seen to move west over the last century.

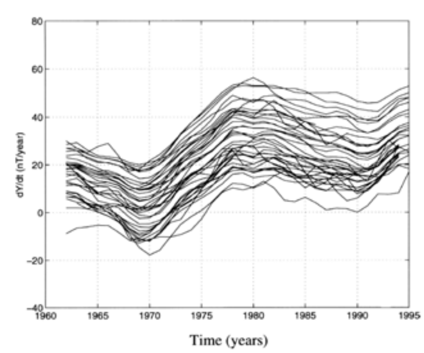
(b) Investigations of historical records from early navigators and explorers has extended these records back to the 1600's (Jackson et al., 2000) and are displayed as movies at http://geomag.usgs.gov/movies/







(c) Short term **geomagnetic jerks** occur on time scales of a decade



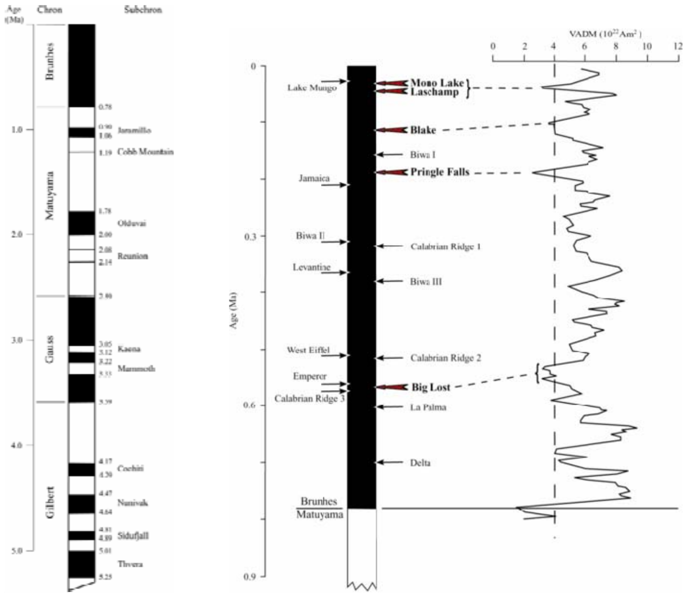
(d) Continuous **reduction of dipole field** since 1600 ($P = 9.4 \times 10^{22}$ Am^2 in 1600, $P = 7.94 \times 10^{22}$ Am^2 today).

(e) Complex sequence of magnetic field **reversals** over the observed geological record. During a reversal the whole field switches north and south poles.

Between reversals there is evidence that the magnetic dipole axis and the Earth's rotation axis are approximately parallel.

The sequence of reversals appears to be **chaotic** with no regular frequency.

The present normal polarity (Brunhes chron) has lasted for 780,000 years.

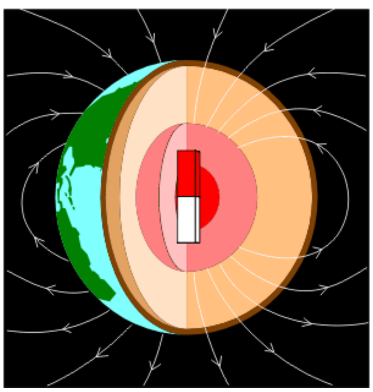


Periods without a reversal for 10^7-10^8 years are called **superchrons**.

Cretaceous normal superchron	118-83 Ma
Permo-Carboniferous (Kiaman) reverse superchron	312-262 Ma

The reduction in the main field over the last 400 years could indicate we are approaching a reversal. How might reversals affect life on Earth?

C2.1.4 Origin of the internal magnetic field



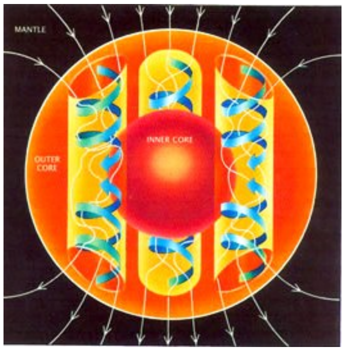
- High temperatures inside the Earth (above Curie temperature) exclude the possibility of remnant magnetization generating the magnetic field. See Fowler Figure 8-22. There is no large bar magnet inside the Earth!

- Field has been present at least since 3.5 Ga so a viable model must explain how a field can be generated and sustained.

- The secular variation, and alignment of dipole with rotation axis, suggest that the magnetic field originates in the relatively rapid fluid motion in a part of the Earth with a high electrical conductivity.

- This only leaves the outer core (composed of liquid iron) as the place where the magnetic field is generated.

The Geodynamo

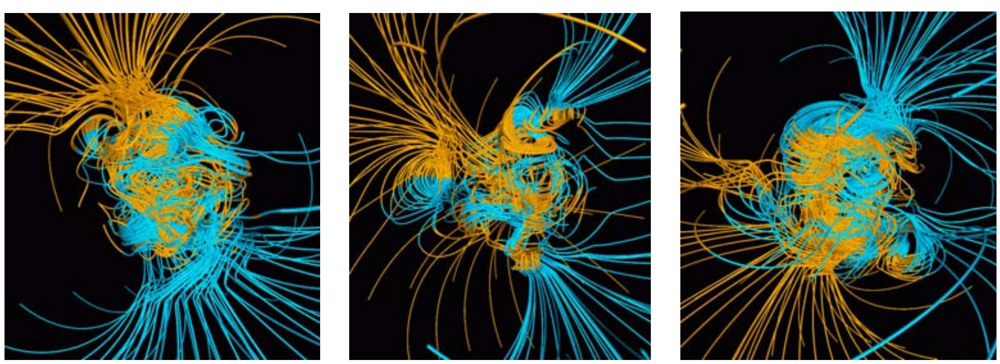


- A complex fluid motion is believed to act as a self sustaining dynamo.
- Convection occurs in the outer core. Inner core grows as liquid iron freezes. This releases heat that drives convection in the liquid iron of the outer core.
- Additional heat comes from radioactive decay
- A dynamo works by converting **motion** into **electric current**. The electric current then generates a magnetic field.

- This occurs through the process of electromagnetic induction, explained by Faraday where a change in magnetic flux produces a voltage.
- Familiar dynamos (generators) use a coil of wire that is forced to rotate in a magnetic field.
- How can such an arrangement occur in a volume of convecting liquid iron?

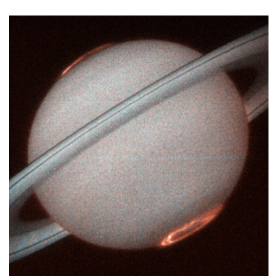
Computer simulations of the geodynamo

- Computer simulations of the **geodynamo** can partially explain the observed spatial and secular field variations, including reversals.
- These models include convection, Coriolis forces and magnetohydrodynamics.
- With ever increasing computer speed and memory, these numerical simulations are becoming more realistic. However many details remain unanswered, partly because the fluid flow pattern has a high Rayleigh number and is essentially turbulent.



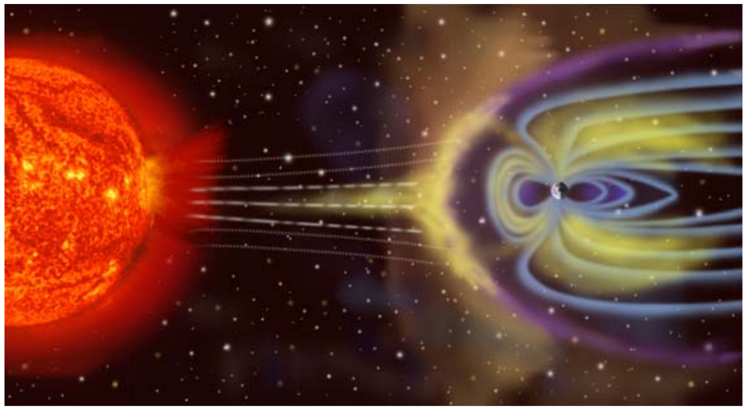
Computer simulation of a geomagnetic reversal (*Glatzmaier and Roberts*, 1995)

- These dynamo models can also be applied to generation of magnetic fields in other planets.
- For example the gas giant planets (including Jupiter and Saturn) have a metallic hydrogen shell that may generate the observed magnetic field.

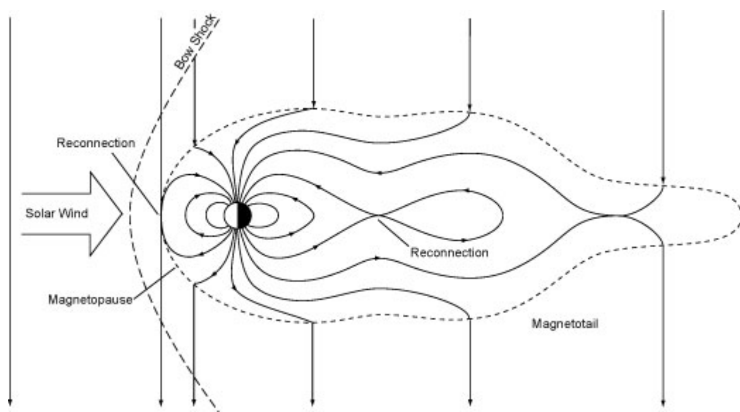


C2.2 External component of the Earth's magnetic field

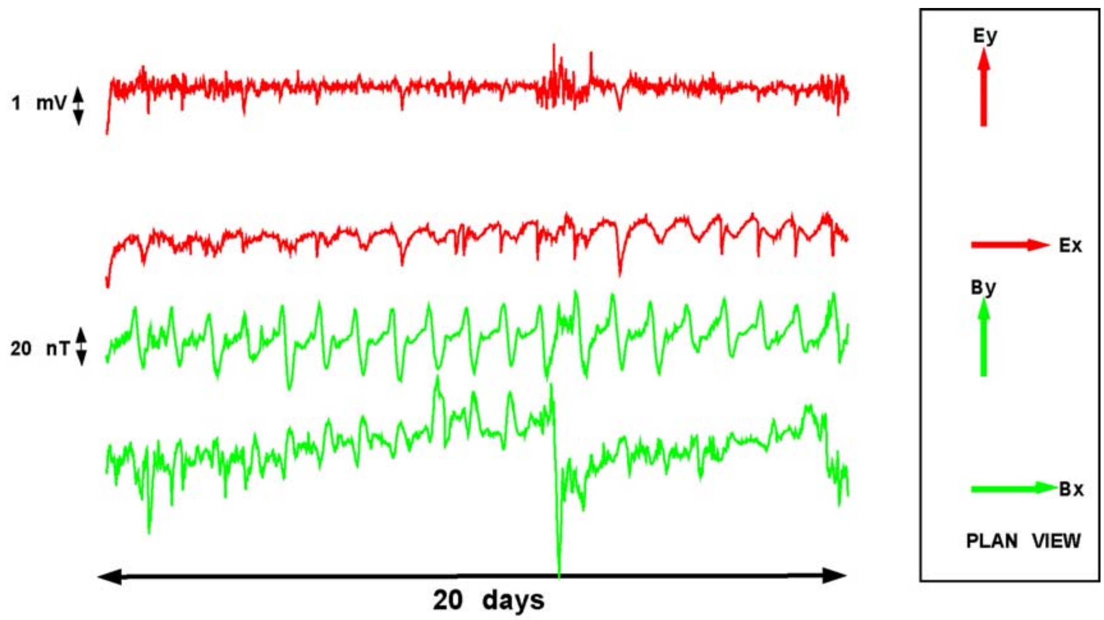
The external component of the magnetic field is generated in the atmosphere and magnetosphere.



- The solar wind (a stream of *H* and *He* ions) is deflected by the Earths internal magnetic field to create the magnetosphere.
- The interactions between the solar wind and the Earth's magnetic field are very complex.
- Temporal changes in the solar wind, due to sunspots, solar flares and coronal mass ejections can produce a change in the magnetic field at the surface of the Earth.



- From 50-1500 km above the Earth's surface is the **ionosphere**, a region of plasma with high electrical conductivity.
- Changing magnetic fields from the magnetosphere can induce large electric currents in the ionosphere.
- Changes in these currents produce large changes in the magnetic field measured at the Earth's surface.



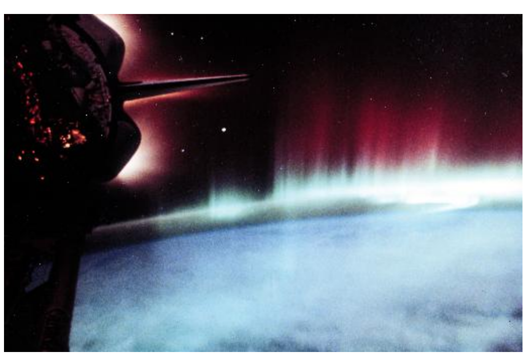
- When the solar wind is in a steady state, the Earth's magnetic field shows a daily variation that is due to the Earth turning within the current systems of the magnetosphere and ionosphere. The typical variation is called the **solar quiet day variation** (S_q). The amplitude is typical 10-20 nT and varies with latitude. Clearly seen in time series above.

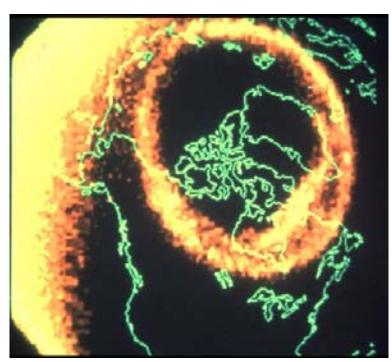
- When the solar wind is active, the Earth's magnetic field is said to be disturbed. **Magnetic storms** occur when the current systems change over a period of several days and the field at the Earth's surface can change by 100's of nanotesla. These changes are largest beneath major ionospheric current systems. A small substorm can be seen in the middle of the time series plotted above.

- Smaller magnetic field disturbances are classified as substorms and bays and have timescales of several hours.

- Solar activity is characterized by an **11 year cycle** and we are currently in a minimum.

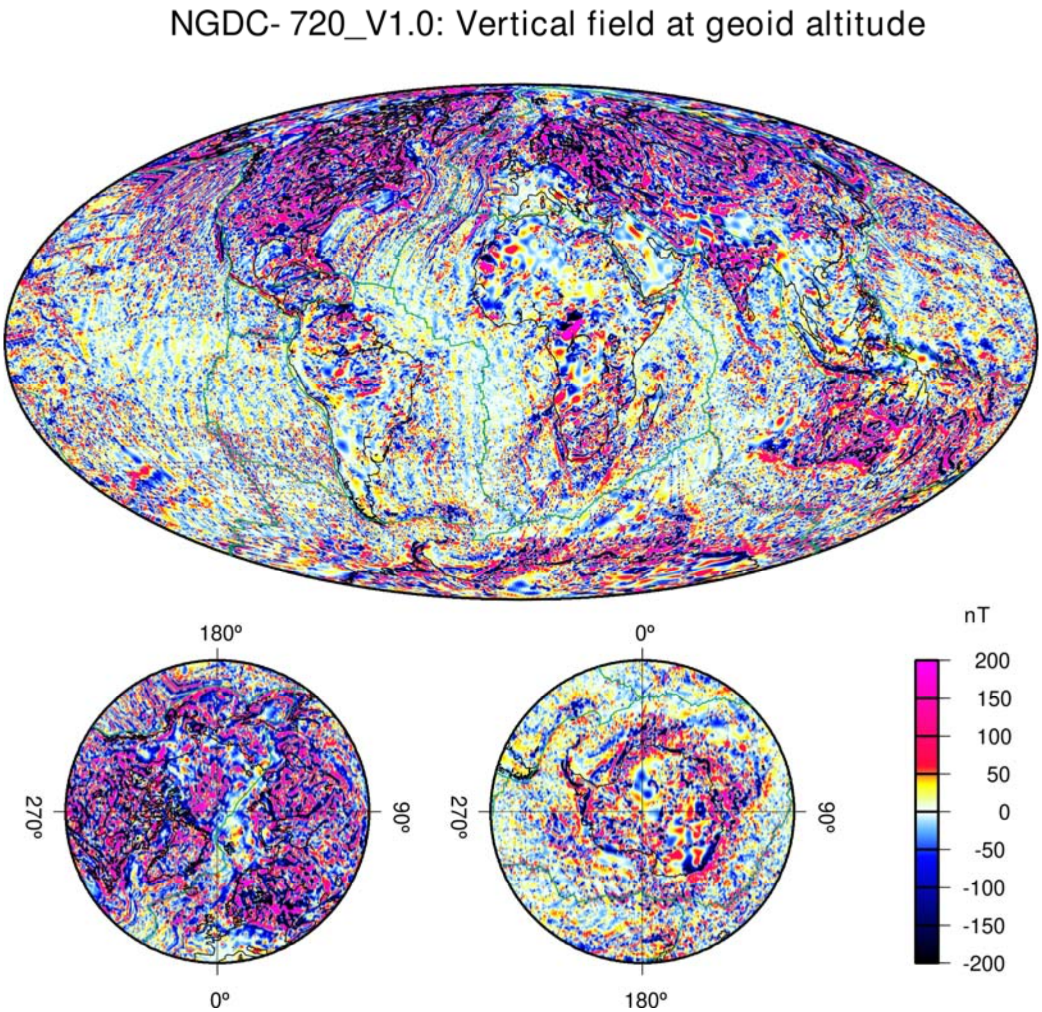
- Maximum solar activity results in high levels of activity in the Earth's external magnetic field and frequent magnetic storms and strong auroral displays.





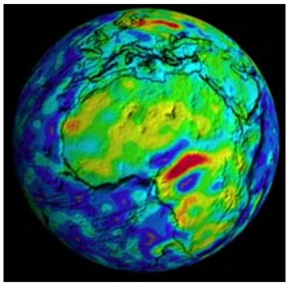
C2.3 Crustal magnetic field

- Permanent (remnant) magnetization only possible above the Curie depth
- Direction of remnant magnetization depends on main field polarity at time rocks became magnetized



http://www.ngdc.noaa.gov/seg/EMM/emm.shtml

- note magnetic stripes in ocean formed by seafloor spreading
- strong anomaly patterns in oldest parts of continental crust



"*The cause of the* ***Bangui anomaly*** *(the red or high magnetization region situated over the Central African Republic) is controversial. In 1992 Girdler, Taylor and Frawley (Tectonophysics, vol. 212, p.45-58) proposed that this anomaly was produced by a large meteorite impact at least 1 billion years old. Others have suggested it results from a major fracturing of the crust or the implacement of a large igneous body*."

From : http://denali.gsfc.nasa.gov/research/crustal_mag/prep/

C2.4 Comparison of the Earth's gravitational and magnetic fields

	Gravitational field	*Magnetic field*
Overall field geometry	Approximate spherical symmetry **g** varies as $1/r^2$	80% dipole **B** varies as $1/r^3$
Direction	Down, by definition	Inclination varies from +90˚ to –90 ˚
Spatial variations	978,000 mgal at Equator 983,000 mgal at poles GRS formula simple and accounts for variation of **g** with latitude	25,000 nT at Equator 61,000 nT at high latitude IGRF is a complex series of spherical harmonics
Temporal variations with internal origin	Signal produced by plate motion and mantle convection????	Secular variation, jerks, westward drift and north-south field reversals Poles moving at ~ 15 km/yr
Temporal variations with external origin	Tidal signals (< 0.5 mgal)	Diurnal S_q variation (50 nT) Magnetic storms (100-1000nT) 11 year sunspot cycle
Latitude variation in Edmonton	~ 1 mgal km^{-1}	~3 nT km^{-1}
Elevation variation in Edmonton	~ 0.3 mgal m^{-1}	~ 0.03 nT m^{-1}

References

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