

210 D2 The Earth's magnetic field

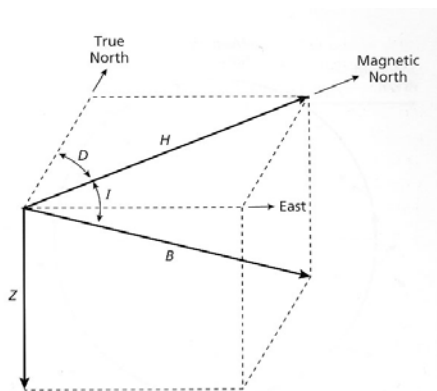
- Magnetic field is more complicated in spatial form than gravity field
- Magnetic field of the Earth measured at the surface comes from **three** sources:

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 (secular variation)
- External field also varies on time scales of seconds to days
- At any point the magnetic field is defined by the **magnetic field elements**



F = total field strength (also labelled B in figure above)

Z = vertical component of F

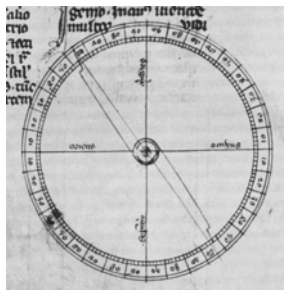
H = horizontal component of F

I = inclination (angle between F and surface)

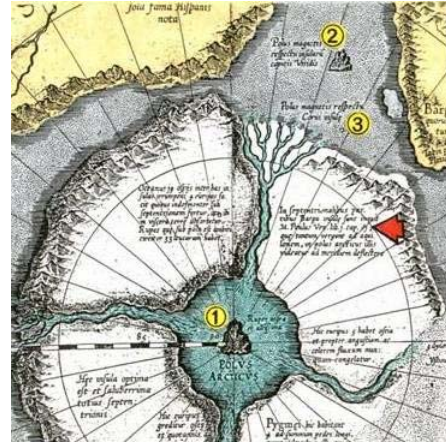
D = declination (angle between H and geographic north)

210D 2.1 Historical perspective on the Earth's magnetic field

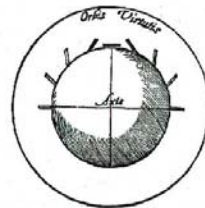
- Pierre Pelerin de Maricourt (1269) was also known as Petrus Peregrinus de Maharncuria.
- Developed idea that a magnetized sphere of lodestone had poles.
- Wrote the first treatise on magnetism "*Epistola de magnete*".
- Interesting details in http://en.wikipedia.org/wiki/Peter_Peregrinus
- Also proposed a perpetual motion machine.



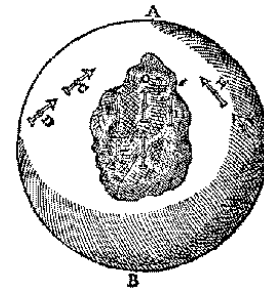
- Observed that magnetic pole and geographic poles do not coincide, which led to the idea of magnetic **declination**. China (500 AD) , British sailors (1400 AD)
- Gerhard Mercator (1574). Quantified differences between magnetic and geographic North. Proposed multiple magnetic poles.
- Geord Hartmann (1544). Realized that a magnetic needle did not balance horizontally. Idea of **inclination** which can be measured with a **dip needle**.



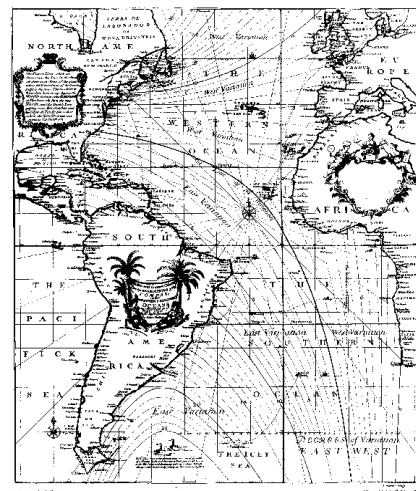
- William Gilbert (1600). Analogy between earth and sphere of lodestone. Explained why the inclination varied with latitude.



Variety in the declinations of iron spikes at various latitudes of a terris.



- Henry Gellibrand (1634). Recorded secular variation in Britain.
- Edmund Halley (1702) compiled a map of magnetic declination in the Atlantic Ocean.
- This map is also claimed to be the first use of contour lines on a map.
- Gauss showed mathematically that the main dipole field must originate within the Earth.

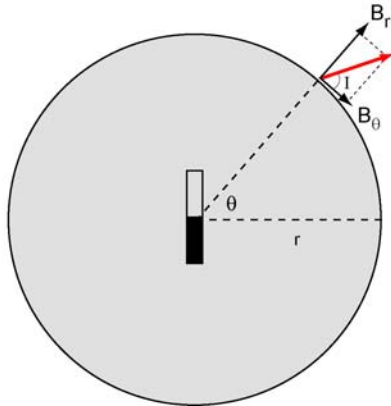


More details at :

http://gsc.nrcan.gc.ca/geomag/nmp/early_nmp_e.php
<http://www.phy6.org/earthmag/dmglis.htm>

210 D2.2 The internal component of the Earth's magnetic field

D2.2.1 Spatial variation



Consider the **dipole component** of the geomagnetic field. At a latitude of θ can show that the radial and azimuthal components of the magnetic field are given by:

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

where M is the dipole moment, a measure of the strength of the magnetic field. Can compute the inclination, I, as :

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

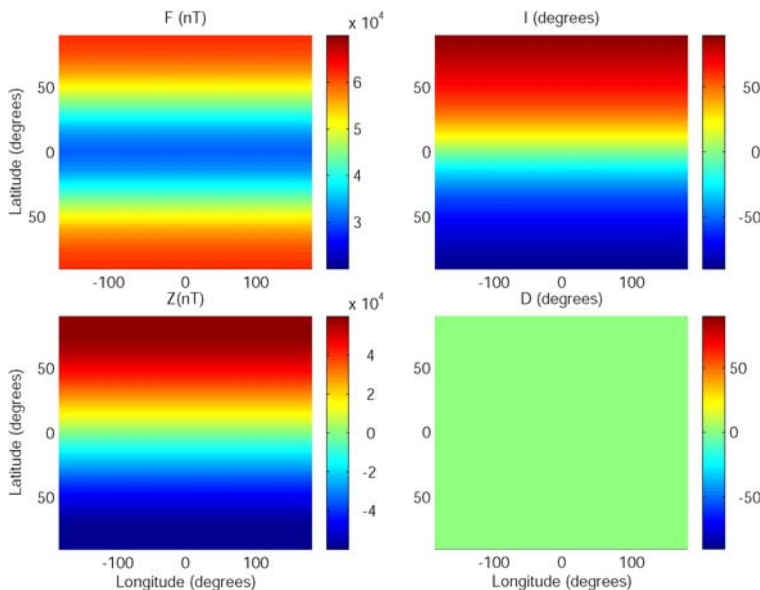
- At the North Pole, $\theta = 90^\circ$ which gives $I = 90^\circ$
- At the Equator, $\theta = 0^\circ$ which gives $I = 0^\circ$

This equation is important because it allows use to use a measurement of inclination (I) to determine our latitude (θ). This was once used by mariners, but is most important in **paleomagnetism**. A rock can record the magnetic field present when it crystallized (temperature fell below the Curie temperature). Thus we can find the latitude of a continent at some time in the past.

$$F(r, \theta) = \sqrt{B_r^2 + B_\theta^2} \text{ which reduces to } F(r, \theta) = \frac{M\mu_0 \sqrt{3 \sin^2 \theta + 1}}{4\pi r^3}$$

- This predicts $F(\theta = 90^\circ) = 2 \times F(\theta = 0^\circ)$

Panels below show maps of the predicted values of F, I, Z and D for a dipolar field with coincident magnetic and geographic poles. Will see that actual magnetic field is more complicated.....



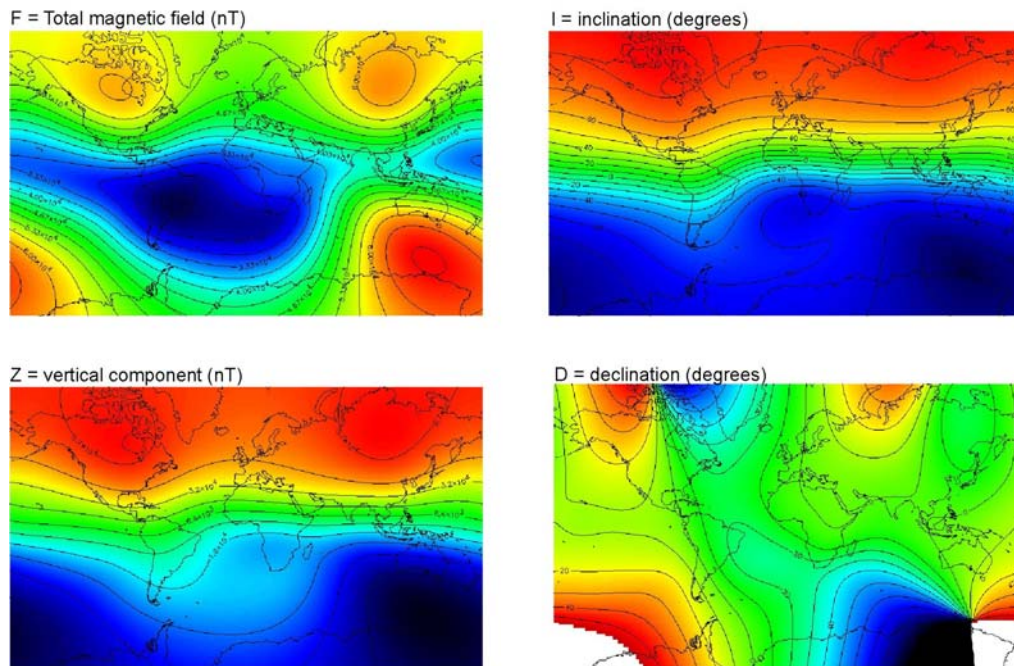
Main field is described by the International Geomagnetic Reference Field (IGRF).

Dipole character

- Some characteristics as expected from dipole field.
- Value of F at poles is double that at Equator.
- Z changes sign and $I = 0^\circ$ close to the Equator

Complications

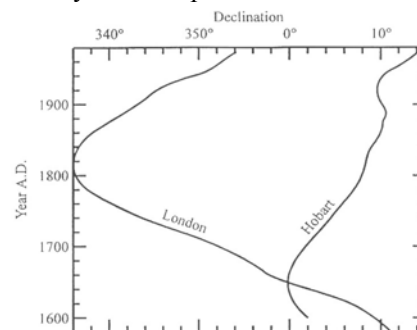
- However pattern is more complicated than the simple dipole field discussed above.
- Magnetic and geographic poles not coincident. This results in D non-zero and contours of F, I and Z do not follow lines of latitude.
- Only 80% of the main field can be represented as a dipole. Note the departures from 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.

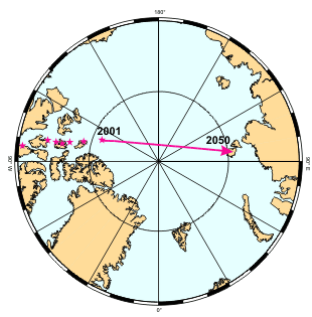
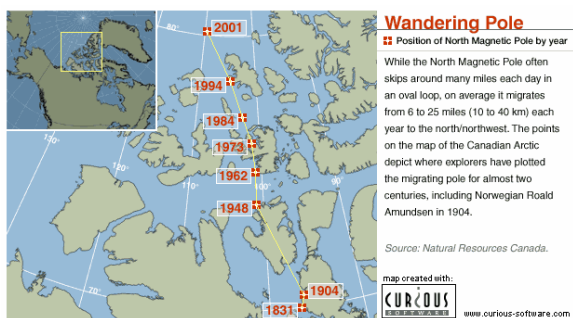
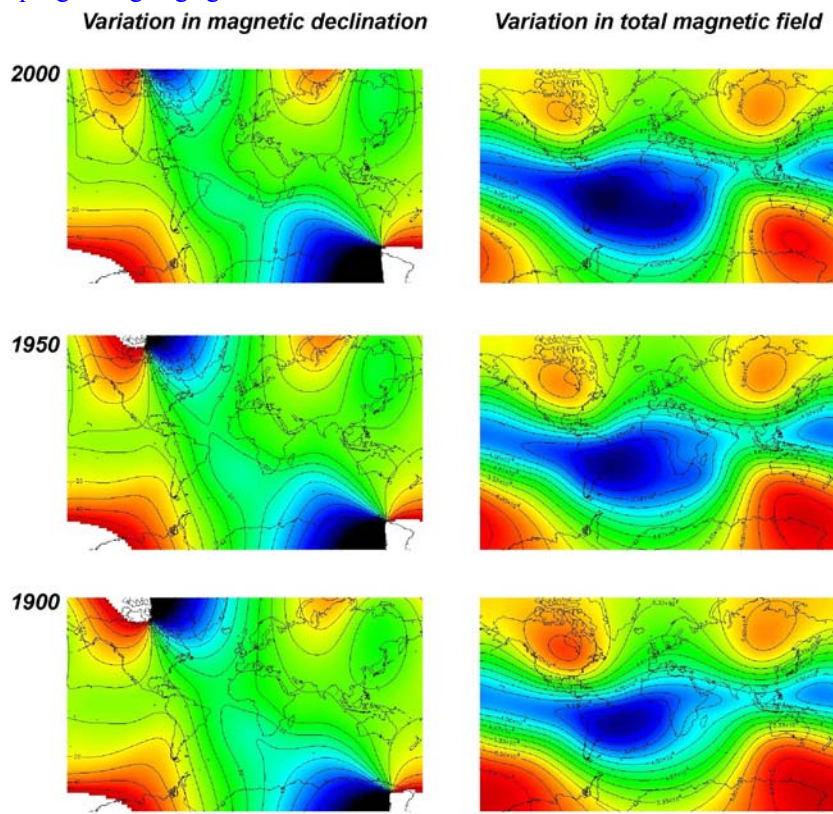
D2.2.2 Temporal variations (secular variation)

- 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.

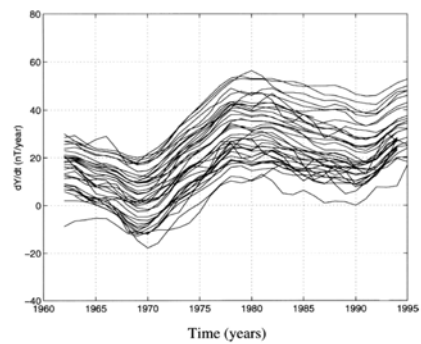


- **Secular variation** in the Earth's magnetic field occurs on many timescales including:

- Westward drift: features can be seen to move west over the last century.
- 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/>



- Short term **geomagnetic jerks** occur on time scales of a decade

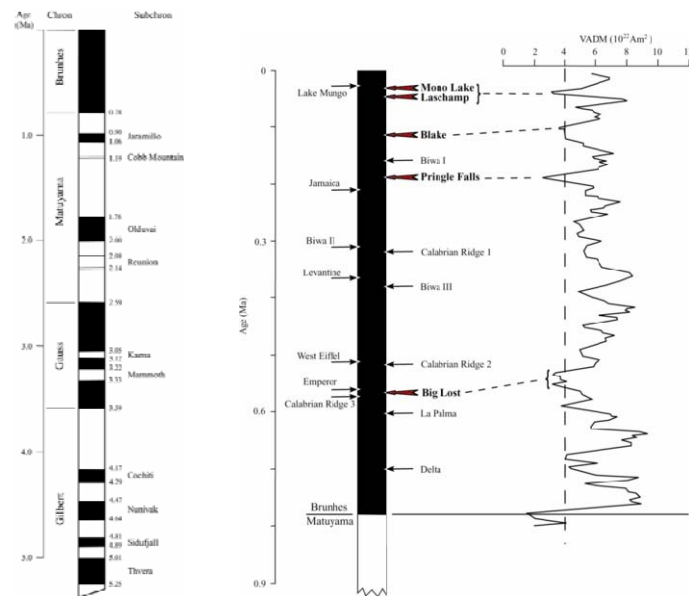


- (d) Continuous **reduction of dipole field** since 1600 ($P = 9.4 \times 10^{22} \text{ Am}^2$ in 1600, $P = 7.94 \times 10^{22} \text{ Am}^2$ today).
- (e) Complex sequence of magnetic field **reversals** over the observed geological record. During a reversal the whole field switches north and south 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.

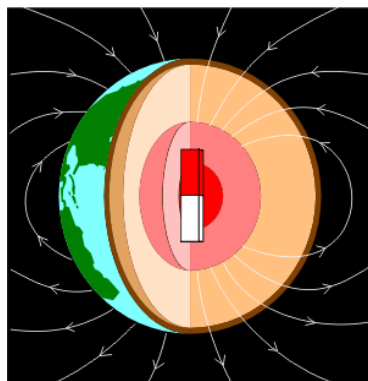


Periods without a reversal for 10^7 - 10^8 years are called **superchrons**.

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?

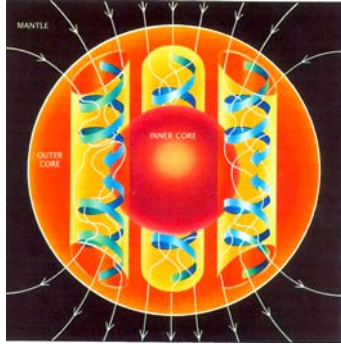
D2.2.3 Origin of the internal magnetic field



- 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. Arguments for a young Earth based on the declining magnetic field over historical time, must take this into account.

- 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.

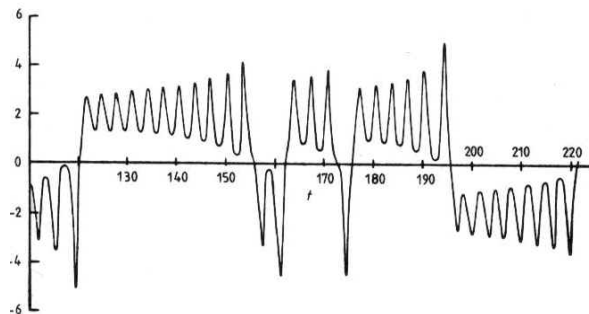
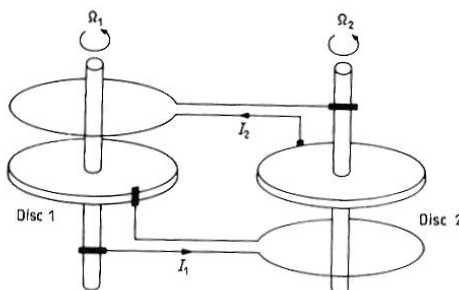
- This occurs through the process of electromagnetic induction, explained by Faraday where a change in magnetic flux produces a voltage.
- Familiar dynamos (generators) use a coil of wire that is forced to rotate in a magnetic field.
- How can such an arrangement occur in a volume of convecting liquid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

Self-exciting dynamo

- See Fowler 8-24 for example. Developed in 1940's by Elasser and Bullard
- Self-exciting dynamo this does not need a permanent magnet to produce a magnetic field from rotation.
- Also note this dynamo will work if the disc is rotated either forward or backwards!
- This suggested that this type of dynamo model could explain a reversal of the magnetic field.
- However, it is too simple to be able to spontaneously reverse.

Rikitake dynamo

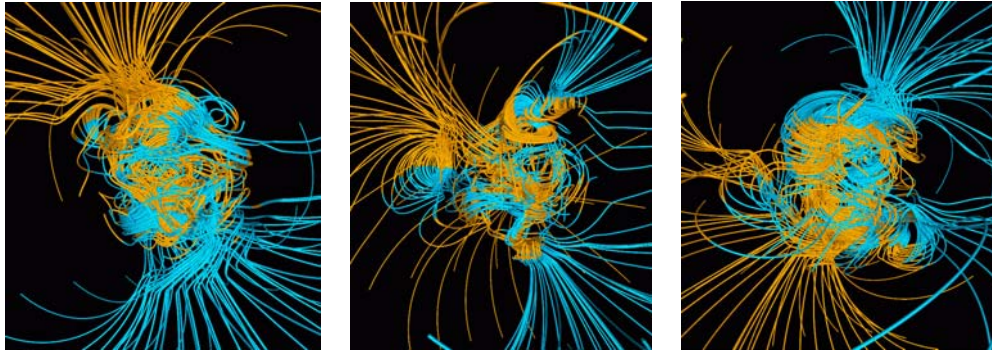
- A more complicated dynamo model used two self-exciting dynamos coupled together. The motion of one disc produces the magnetic field for the other, and vice versa.
- This system has more degrees of freedom and can show much more complicated behaviour. This includes "reversals" and aspects that can be considered chaotic.



<http://pagesperso-orange.fr/olivier.granier/meca/vulga/chaos/chaos.htm>
<http://baudolino.free.fr/Noyau/page32~.htm>

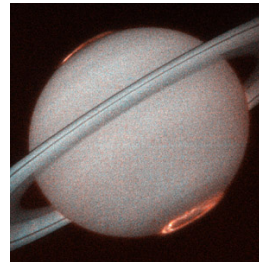
Computer simulations of the geodynamo

- 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.



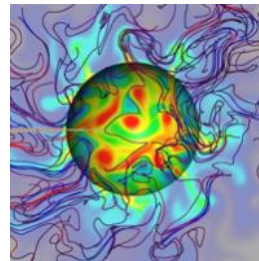
Computer simulation of a geomagnetic reversal (*Glatzmaier and Roberts, 1995*)

- 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.

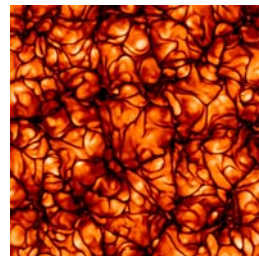


- Geodynamo research program at the University of Alberta led by Dr. Moritz Heimpel. See Heimpel et al., (2005) and other research papers at <http://www-geo.phys.ualberta.ca/~mheimpel/>

Figure by Moritz Heimpel shows magnetic field lines and field strength at the surface of the core during a magnetic reversal.



- Dynamo models can also explain how the Sun generates a magnetic field



Origins of geomagnetic reversals

http://en.wikipedia.org/wiki/Geomagnetic_reversal

Is the origin of reversals internal or external?

Internal origin for reversals ?

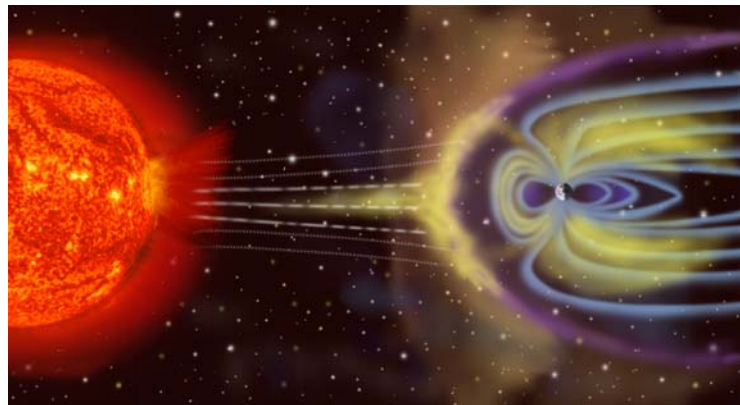
- Spontaneous dynamo process?
- This occurs in the solar dynamo with a reversals every 7-15 years.
- Note that solar magnetic field is a maximum during a reversal whereas the geomagnetic field is a minimum at reversal.

External origin for reversals?

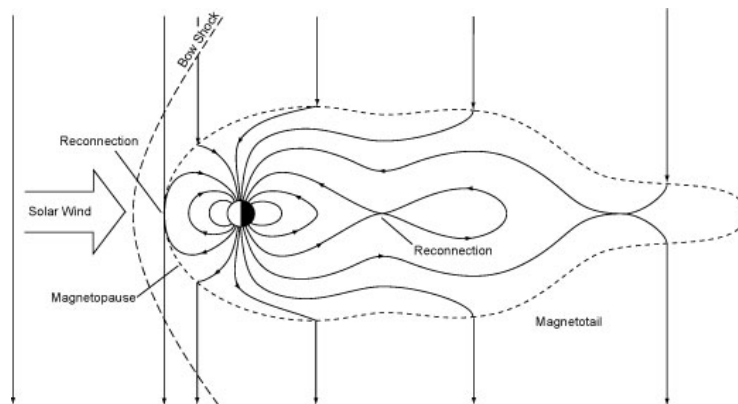
- Arrival of subducted slabs at the CMB?
- See Richard Muller papers. Initiation of plumes?
- Idea that these events can shut down the geomagnetic field and it returns in a state that can have either polarity.
- Note occurrence of geomagnetic excursions that are brief events with the field going to zero but returning with same polarity.

D2.3 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 Earth's 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.



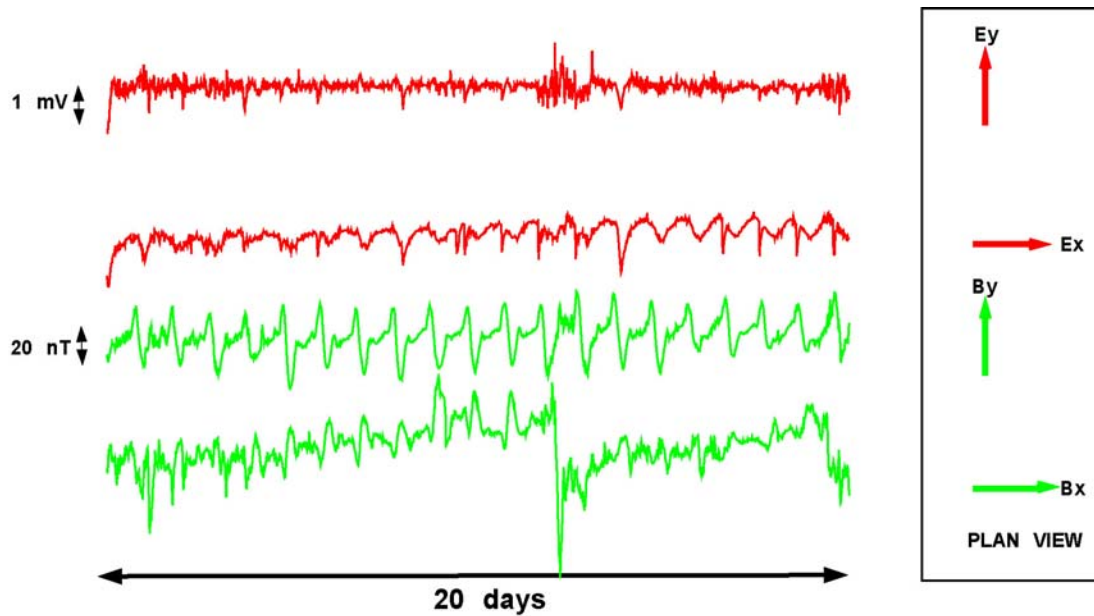
- From 50-1500 km above the Earth's surface is the **ionosphere**, a region of plasma with high electrical conductivity. Changing magnetic fields from the magnetosphere can induce large electric currents in the ionosphere. Changes in these currents produce large changes in the magnetic field measured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

- Large currents flow in specific locations including:

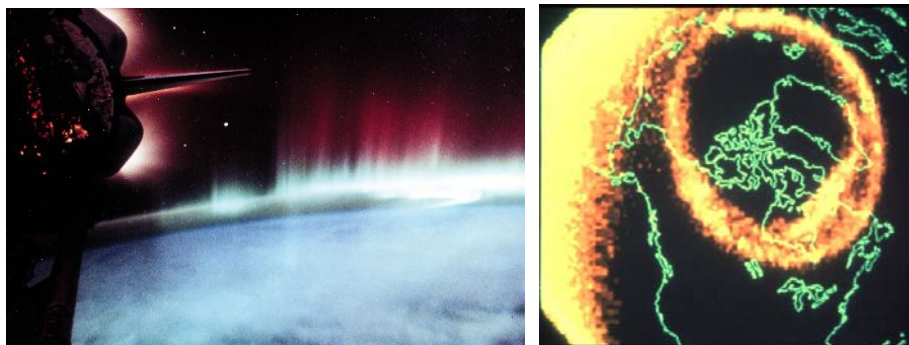
(A) Equatorial electrojet flows on magnetic equator on side facing sun

(B) Auroral electrojet flows at high magnetic latitude





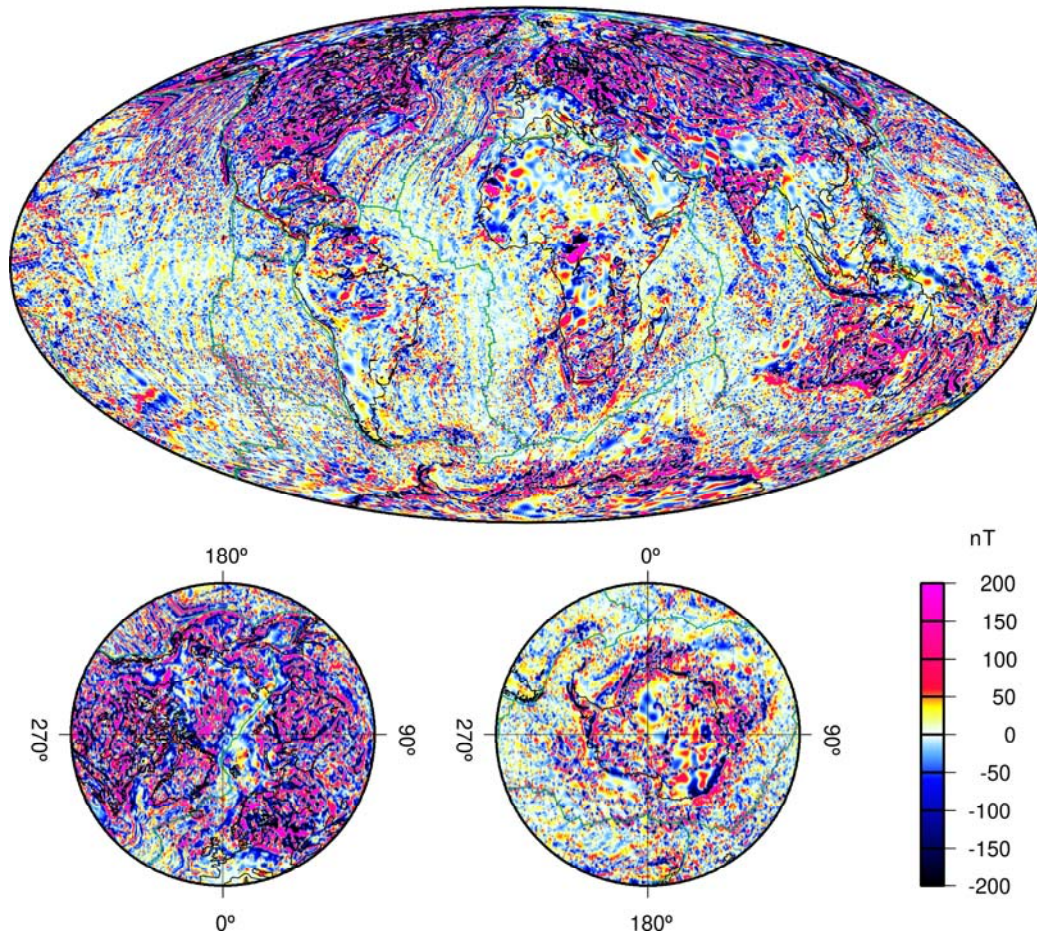
- When the solar wind is in a steady state, the Earth's magnetic field shows a daily variation that is due to the Earth turning within the current systems of the magnetosphere and ionosphere. The typical variation is called the **solar quiet day variation** (S_q). The amplitude is typical 10-20 nT and varies with latitude. Clearly seen in time series above.
- A much smaller variation is seen every 25 days and is caused by the orbit of the moon.
- 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 have just passed the maximum. Maximum solar activity results in high levels of activity in the Earth's external magnetic field and frequent magnetic storms and strong auroral displays.



D2.4 Crustal magnetic field

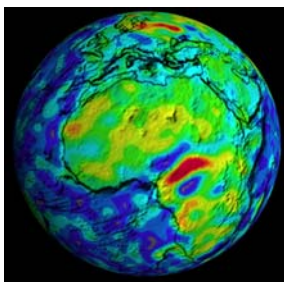
- Permanent (remnant) magnetization only possible above the Curie depth
- Direction of remnant magnetization depends on main field polarity at time rocks became magnetized

NGDC- 720_V1.0: Vertical field at geoid altitude



<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/

D2.5 Comparison of the Earth's gravitational and magnetic fields

	<i>Gravitational field</i>	<i>Magnetic field</i>
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 $+90^\circ$ 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

Buffett, Bruce A. and Gary A. Glatzmaier, Gravitational braking of inner core rotation in geodynamo simulations, *Geophys. Res. Lett.*, 27 (19) 3125-8, 1 October 2000.

Glatzmaier, G.A. and P.H. Roberts, A three-dimensional self-consistent computer simulation of a geomagnetic field reversal, *Nature*, 377, 203-209 (1995).

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Jackson, A., Jonkers, A. R. T. & Walker, M. R., 2000. Four centuries of geomagnetic secular variation from historical records, *Phil. Trans. R. Soc. London, A* 358, 957-990.