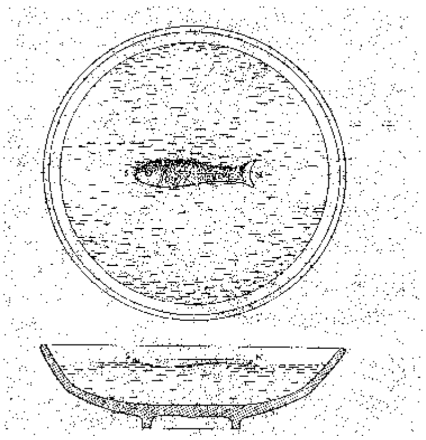
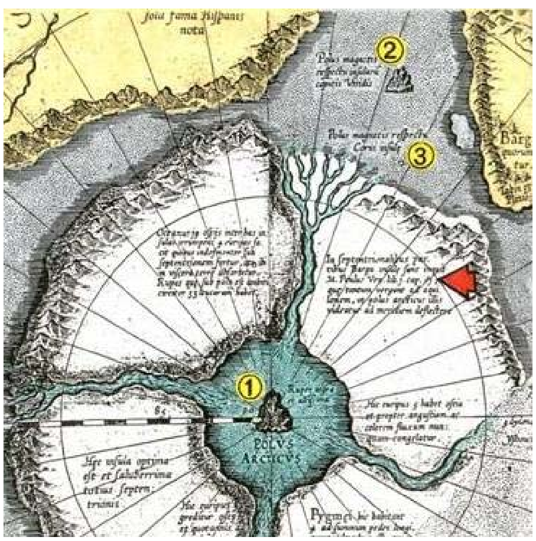
<u>224 D2.1 The internal component of the Earth's magnetic field</u>

D2.1.1 Historical background

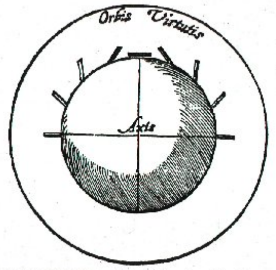


● Petrus Perigrinus (1269) described a floating compass and a vertically pivoted compass (dip needle). He showed that the field of a magnet was **dipolar** by studying a sample of lodestone. At that time the origin of the magnetic field was believed to be the **Pole Star** or a **magnetic mountain** located at the North Pole.

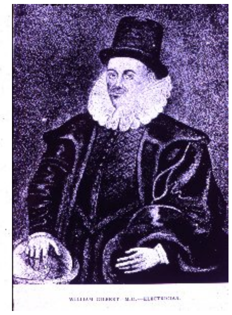


● In 1574 Gerhard Mercator realized that magnetic north and geographic North did not coincide. This represented a discovery of the declination of the Earth's magnetic field. He explained this problem by placing multiple magnetic poles on his map.

● Measurements of the **inclination** of the Earth's magnetic field were described in 1576 by Robert Norman.

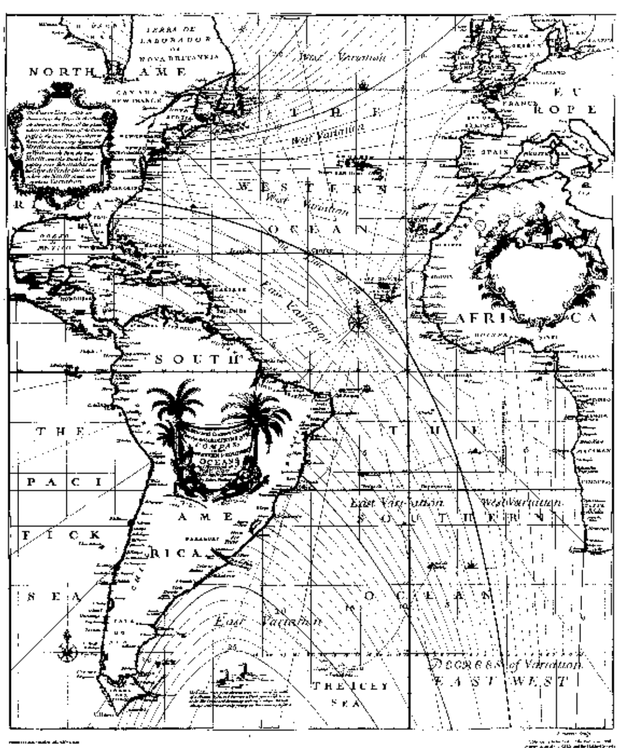


Variety in the declinations of iron spikes at various latitudes of a terrella.



● William Gilbert developed these ideas and was the first to propose that the Earth itself was acting as a large magnet with a dipolar magnetic field (i.e. the magnetism did not originate in the stars or features on the surface at high latitude). He defined the magnetic poles as places where a dip needle would point vertically downwards.

● Maps of declination were refined, including the 1702 map drawn by Sir Edmund Halley, who proposed that two north magnetic poles and two south magnetic poles were needed to produce the observed field. Halley also observed that the declination was varying over time.

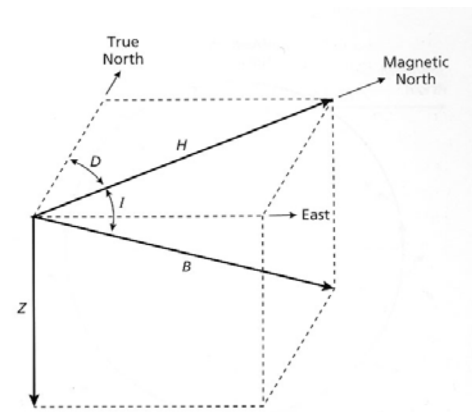


● Subsequent analyses required an ever increasing number of magnetic poles to describe the increasingly complex detail in the magnetic field that was determined by new observations. A more suitable mathematical description using **spherical harmonics** was developed by Gauss in 1839.

D2.1.2 Spatial variations

- The dipole accounts for about **80%** of the observed magnetic field. The axis of the dipole is inclined at **11.5 degrees** to the Earth's rotation axis. The magnetic dipole moment, P = 7.94 x 10^{22} Am^2 in 2000.

- At any point the magnetic field is defined by the **magnetic field elements**



F = total field strength

Z = vertical component of F

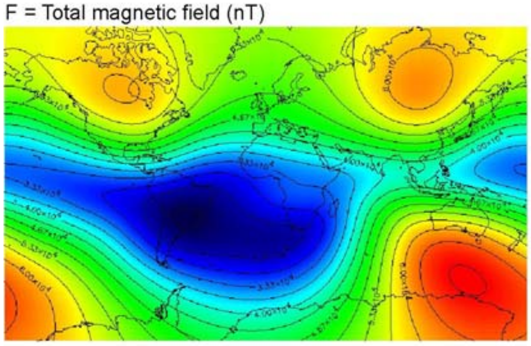
H = horizontal component of F

i = inclination (angle between F and surface)

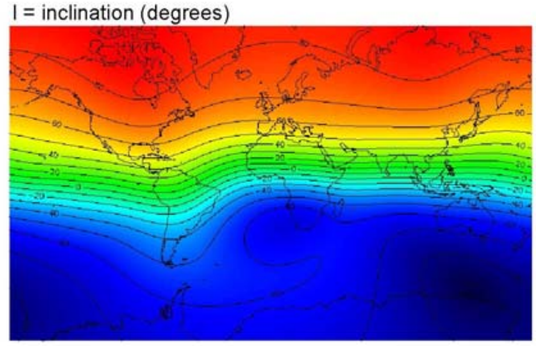
d = declination (angle between H and geog. north)

- The magnetic field is described by the *International Geomagnetic Reference Field* (*IGRF*). The figure below shows the IGRF in 2000 and the database is updated regularly as the magnetic changes over time. Note the departures from a pure dipole field, especially the four regions of high F in high latitudes.

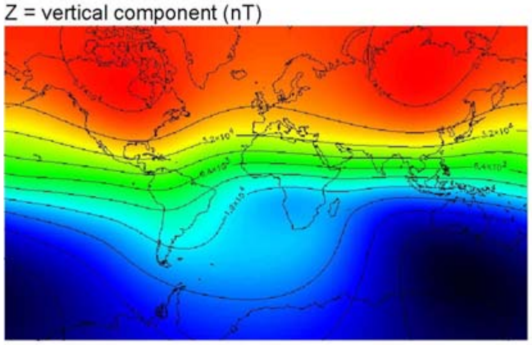
F = Total magnetic field (nT)



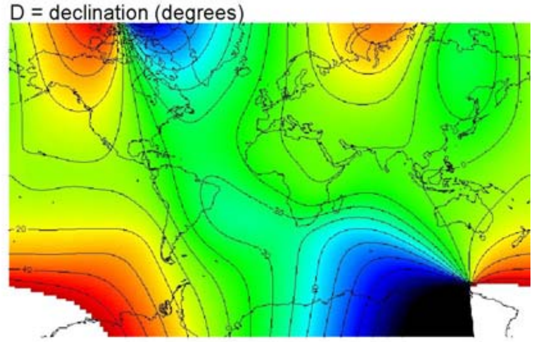
I = inclination (degrees)



Z = vertical component (nT)

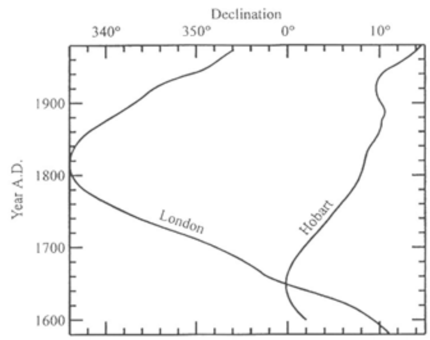


D = declination (degrees)



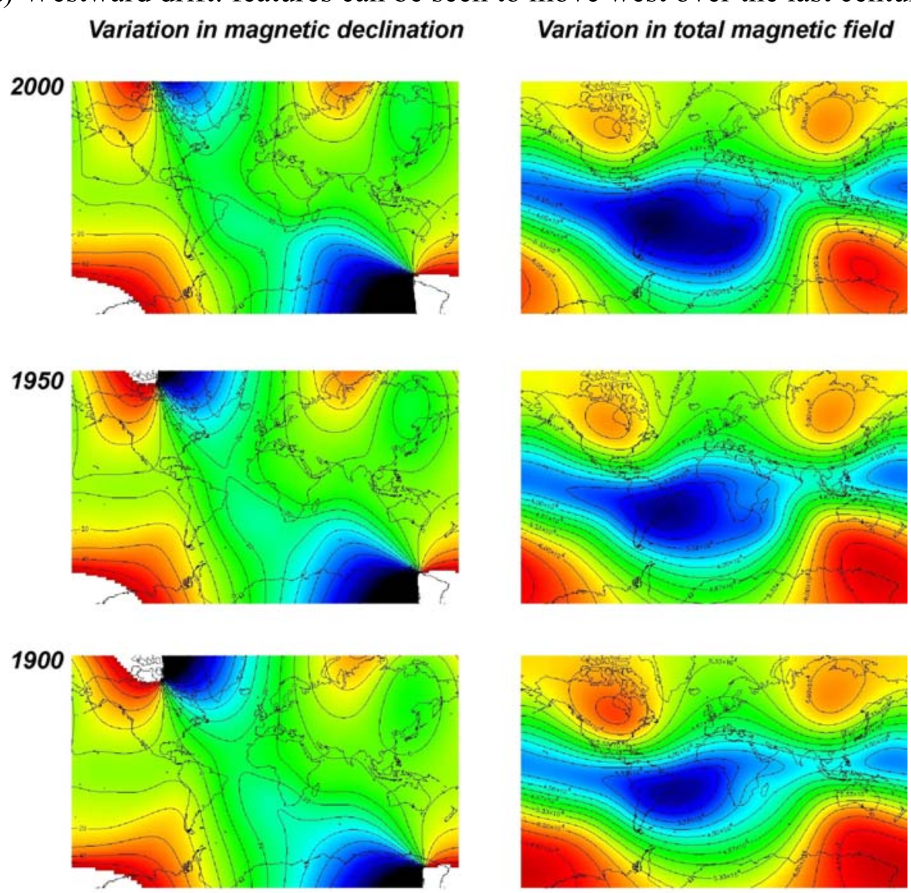
D2.1.3 Temporal variations in the internal magnetic field

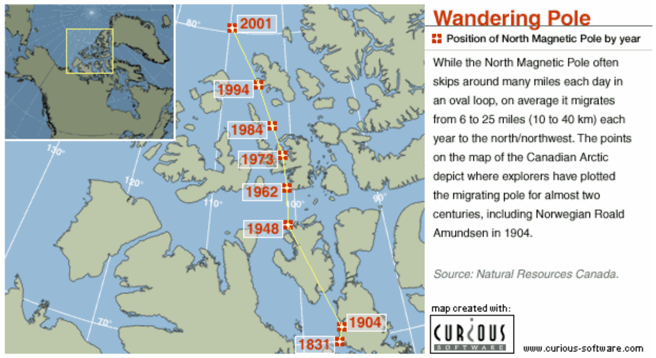
● The compass was invented in China, and ancient texts record the variation of declination from at least AD720. It took a while for Europeans to catch on, and the first record of temporal changes was in 1635 when Gellibrand noted that declination varies with time. The declination in London was found to vary significantly over the period 1600-2000.



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

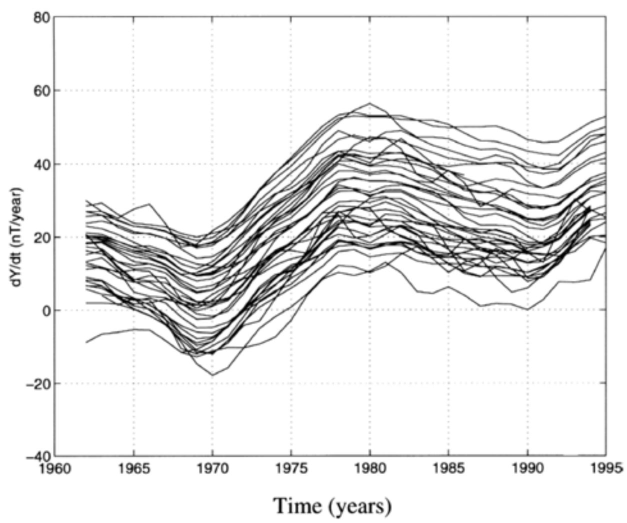
(a) Westward drift: features can be seen to move west over the last century.





(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

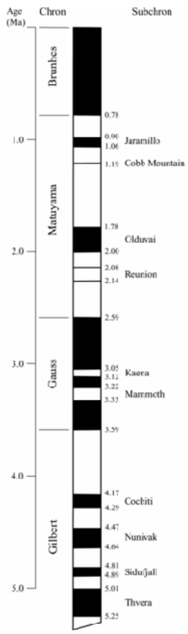


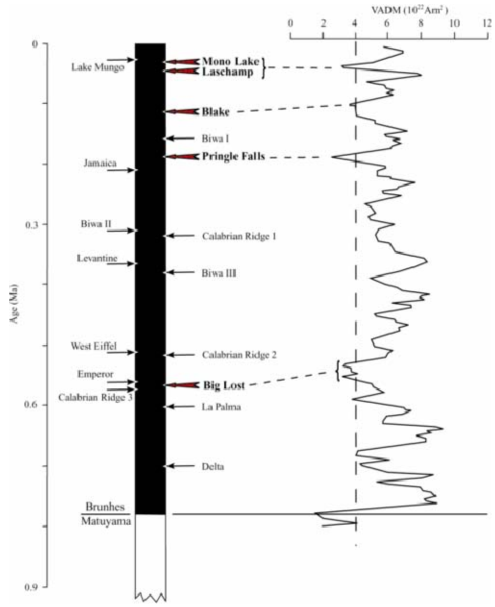
(d) Continuous **reduction of dipole field** since 1600 (P = 9.4 x 10^{22} Am^2 in 1600, P = 7.94 x 10^{22} Am^2 today)

(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.



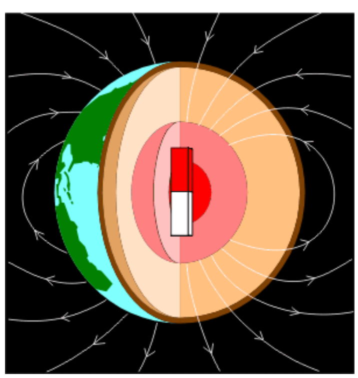


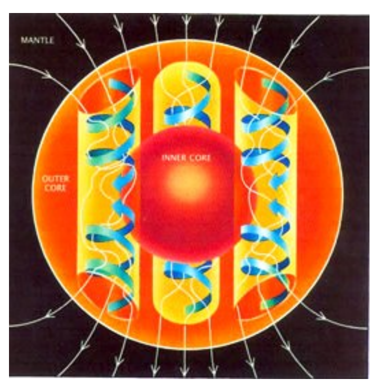
Periods without a reversal for 10^7-10^8 years are called **superchrons**.

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?

D2.1.4 Origin of the internal magnetic field

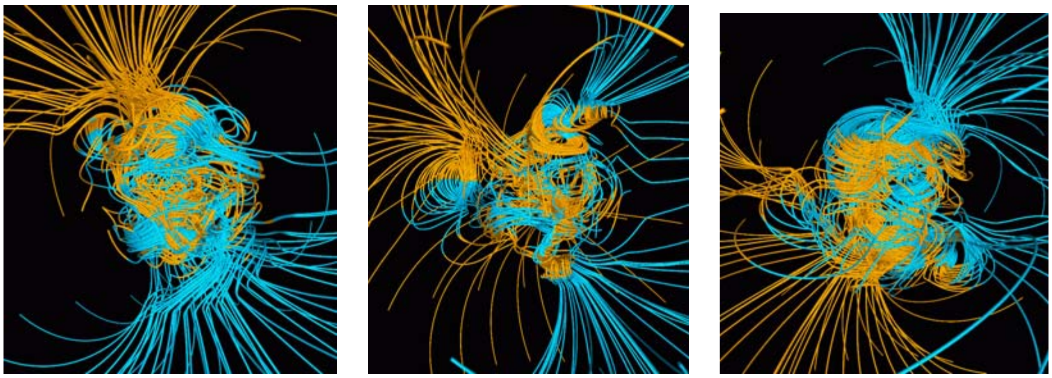




- High temperatures inside the Earth (well above Curie temperature) exclude the possibility of remnant magnetization generating the magnetic field. There is no large bar magnet inside the Earth!

- 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.

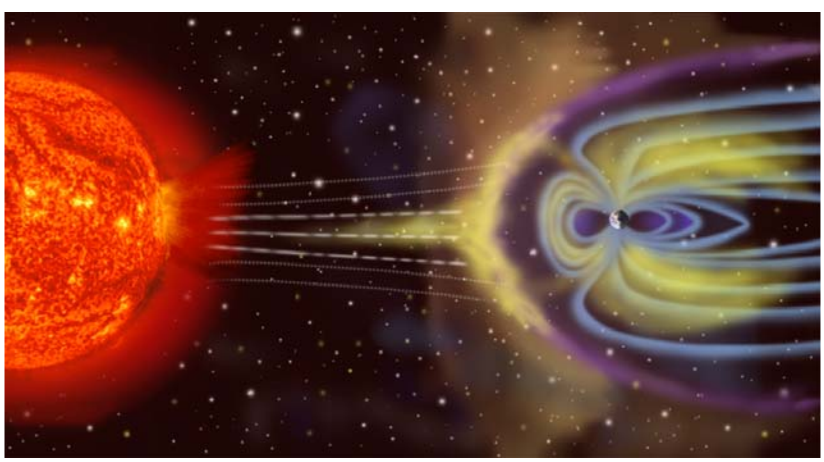
- A complex fluid motion is believed to act as a self sustaining dynamo. Computer simulations of the **geodynamo** can partially explain the observed spatial and secular field variations, including reversals. These models include convection, Coriolis forces and magnetohydrodynamics. However many details remain unanswered.



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

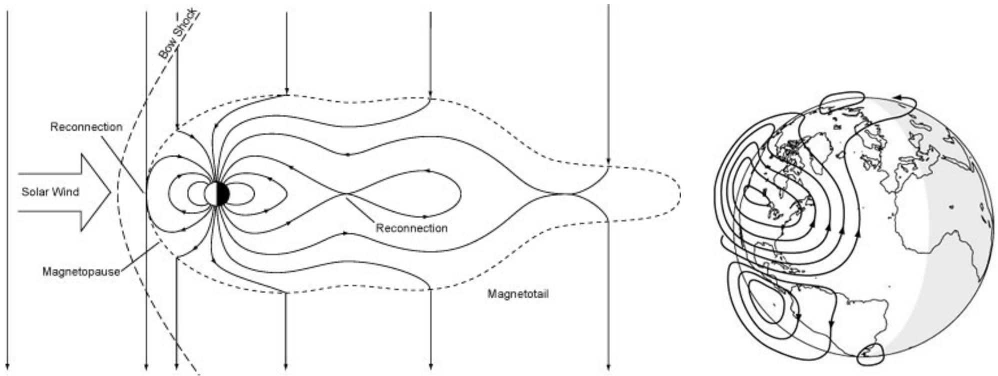
D2.2 External component of the Earth's magnetic field

The magnetic field measured at the surface of the Earth is due to sources **inside** and **outside** the Earth. The external component is generated in the atmosphere and magnetosphere.



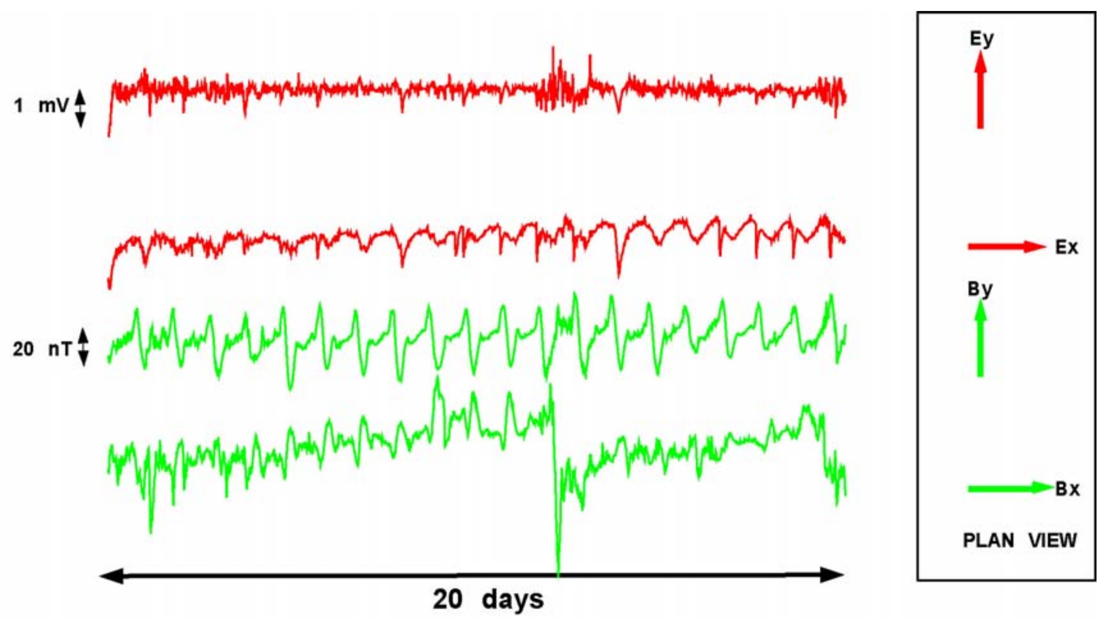
- The solar wind (a stream of *H* and *He* ions) is deflected by the Earths internal magnetic field to create the magnetosphere.

●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.

● Large currents flow in specific locations including:
-equatorial electrojet flows on magnetic equator on side facing sun
-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**

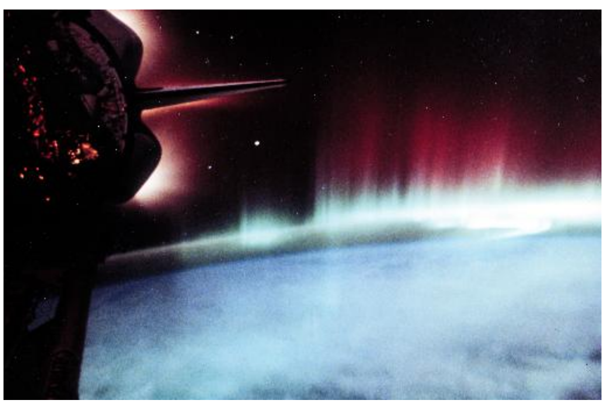
variation (S_q). The amplitude is typical 10-20 nT and varies with latitude. Clearly seen in time series above.

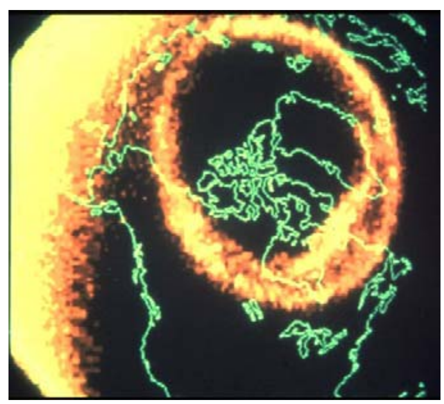
● A much smaller variation is seen every 25 days and is caused by the orbit of the moon.

● 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.





References

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

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.

D2.3 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}