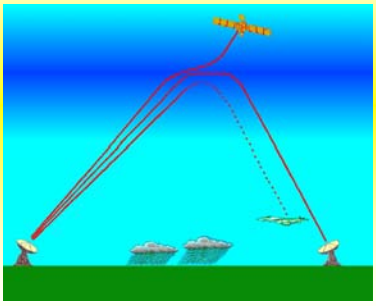
The Earth's electronic atmosphere

Robert Watson-Watt

- Satellite and land-based radio communications are influenced by the Earth's electronic atmosphere, known as the **ionosphere**
  - term coined by Robert Watson-Watt, Brechin born inventor of radar

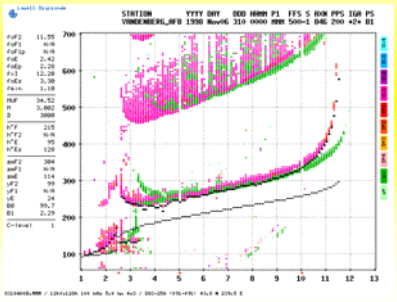


La Mano 5.5 km

http://www.ngdc.noaa.gov/stp/IONO/ionointro.html

Probe the atmosphere from below

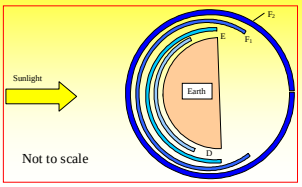
- The Earth is surrounded by layers of ionised matter that reflect radio waves
  - accompanying diagram shows reflection at different frequencies (MHz along the x-axis) changing over a day



http://www.ngdc.noaa.gov/stp/IONO/grams.html

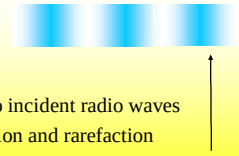
Interpretation of reflections seen

- Several atmospheric layers exist with 'free electrons' and +ve ions, the ingredients of a plasma
  - these layers slow and can reflect low frequency radio waves originating on Earth
  - they transmit high frequencies. Layers labelled:
    - D ~ 70 km
    - E ~ 100 km
    - F_1 ~ 200 km; F_2 ~ 350 km
    - 60 km to 600 km is called the ionosphere
  - lower layers appear mainly during daylight
  - communication with satellites needs to use high frequencies



Plasma oscillations

Schematic electron density



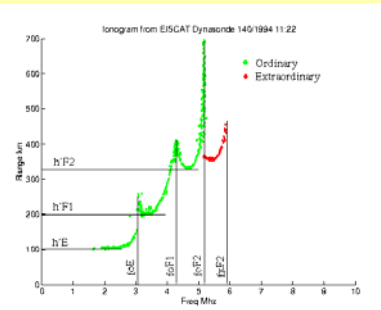
- Electrons in the plasma respond to incident radio waves
- These set up oscillatory compression and rarefaction
- The electrons have a natural response frequency called the 'plasma frequency', ω_p
  - ω_p represents a resonant oscillation of electrons
    - n is the average electron density
    - e is magnitude of the charge of an electron
    - m is mass of an electron
    - ε_o is an electrical constant (= 8.85×10^{-12} F m^{-1})

$$\omega_p^2 = \frac{ne^2}{\varepsilon_o m}$$

- Taking n = 10^{11} electrons m^{-3} gives $\omega_p = 1.78 \times 10^7$ rad s^{-1}
  - equivalent frequency in MHz is 2.8 MHz

Understanding the evidence

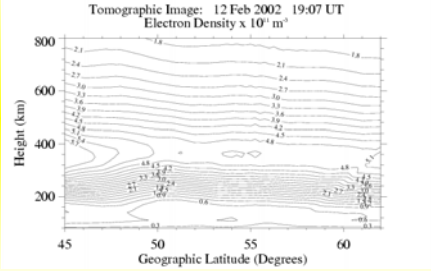
- The range is given by the delay time of the returning signal
- Close to plasma frequency, the speed of the radio waves is slowed a lot
  - this produces the upward spikes on each layer
  - the higher layers reflect at higher frequencies and therefore correspond to increased electron density



http://www.wdc.rl.ac.uk/ionosondes/ionogram_interpretation.html

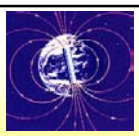
Confirmatory electron densities

- Notice the conspicuous F layer in the evening



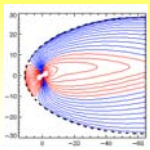
http://www.aber.ac.uk/propag/images/data/feb2002mid/04319_08.hdf.gif

The magnetosphere



Courtesy: NASA

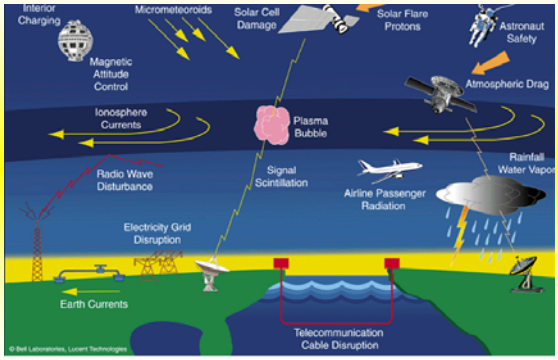
- The Earth's magnetic field inside and close to the Earth is approximately like that of a bar magnet
- Outside the Earth it is distorted and more complex because of the interaction with the solar wind
  - The magnetopause is the boundary between the solar wind plasma and the ionospheric plasma



Units are Earth radii

Courtesy: NASA

Magnetic storm effects

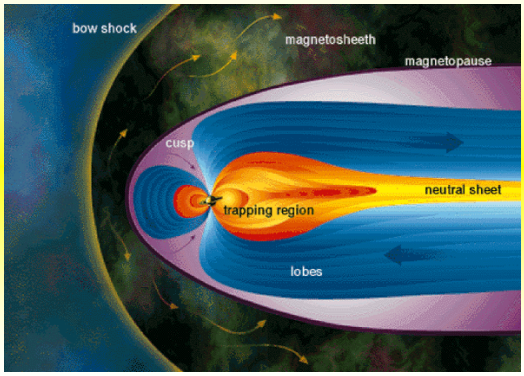


The effects of magnetic storms - what scientists call space weather - extend from the ground to geostationary orbit and beyond. http://pwg.gsfc.nasa.gov/istp/outreach/theretohere.html

What's out there?

- The Earth's outer environment is complex:
  - plasma
  - deformed and stretched out magnetic field lines
  - electrical currents of millions of amps
- This environment is subject to big changes
- Satellites, the ISS and near-Earth space business operate here
  - understanding it is an essential challenge

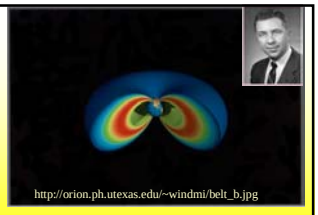
More detail of the magnetosphere



Courtesy: http://pwg.gsfc.nasa.gov/istp/outreach/theretohere.html

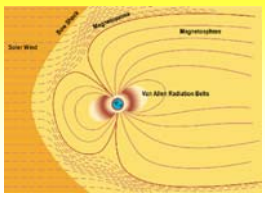
Van Allen radiation belts

- The Van Allen belts were discovered by rocket probe (Explorers 1 and 4) in 1958
- They are doughnut shaped regions of high energy electrons and protons



http://orion.ph.utexas.edu/~windmi/belt_b.jpg

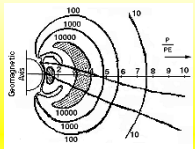
- They extend from about 2 to 5 Earth radii beyond the surface



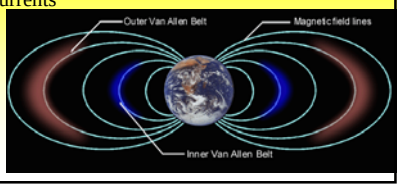
James A.Van Allen (1914-)
http://www-pi.physics.uiowa.edu/java/

Detail of the Van Allen belts

- The inner belt is around 1.5 R_E, mainly protons
- The outer belt at 3 – 9 R_E is trapped magnetospheric plasma
  - contributes a ring current that can induce Earth currents
  - highly fluctuating
  - lower energy protons contribute mostly



http://www-istp.gsfc.nasa.gov/Education/wradbelt.html



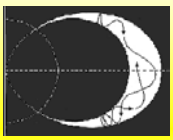
http://www.windows.ucar.edu/glossary/images/radiation_belt.gif

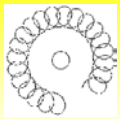
Harmful effects of the belts

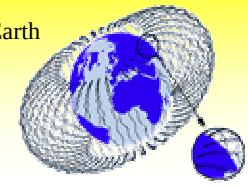
- Degradation of satellite components, notably semiconductor and optical devices
- Generation of spurious background noise in detectors
- Cause of errors in digital circuits
- Production of electrostatic charging within insulators
- A health threat to astronauts

The physics of motion in magnetic and electric fields

- charged particles have 3 motions
  - gyration
    - takes << ms
  - motion along magnetic field lines
    - takes ~0.1 s
  - drift around the Earth
    - takes minutes



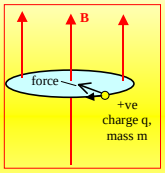




Courtesy: NASA

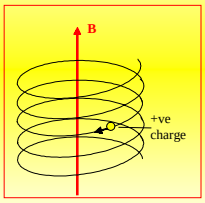
Charged particles and a uniform magnetic field - 1

- Charged particles circulate around magnetic field lines, **B**
- The magnetic force on them is at right angles to their velocity and to **B**
  - this force maintains their motion in a circle
  - this force doesn't change the energy of the particle
  - gyration frequency f is $f = \frac{qB}{2\pi m}$
  - for electrons with B = 10^{-5} T, $f = 2.8\times10^{5}$ Hz
  - Circle radius ∝ (perpendicular speed)/f



Charged particles and a uniform magnetic field - 2

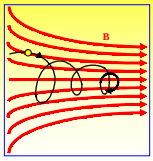
- If the particles also have a motion parallel to the magnetic field lines, they spiral up or down the field lines
  - the motion parallel to the line is unaffected by **B**
  - again, there is no change in the energy of the particle



+ve charge spiralling down a field line

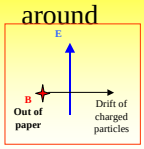
Charged particles spiralling down converging field lines

- The lines of the Earth's field converge at the magnetic poles
- Particles spiralling polewards do so in faster, tighter circles
- Their progress towards the poles becomes slower (because their kinetic energy is conserved)
- They are eventually reflected back up the field line
- The magnetic poles create **magnetic mirrors** for charged particles



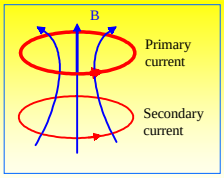
Add an electric field **E** perpendicular to the magnetic field B

- Charged particles drift at right angles to both fields
  - drift doesn't depend on particle charge or mass
    - +ve and negative particles drift in the same direction
    - speed of drift is E/B
- This drift causes a ring current around the Earth



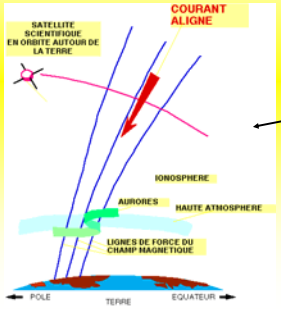
The transformer principle

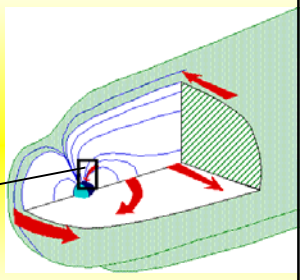
- Induction was discovered by Michael Faraday in the 1830s
- A **changing current** in one coil (the *primary*) sets up (*induces*) a changing current in a parallel neighbouring coil (the *secondary*)
- Magnetic flux links the two coils



Motion of electrons in the magnetosphere

- strong electric currents

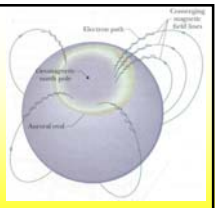


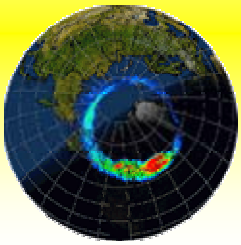


Nous remercions:
http://www.cetp.ipsl.fr/~rezeau/BclDir/Francais/ObjScientifiques.html

Permanent auroral oval around both poles

- Electrons spiral down field lines towards poles to height of 300 – 80 km
  - incident energy ~6 KV
  - aurora is emission from excited upper- atmosphere molecules





http://tide.gsfc.nasa.gov/studies/GILES/bridgman/Auroral%20Oval/

HST image

Auroral colours

- Emission lines from N_2 and O
- Lowest emission < 100 km
  - blue & red from N_2 and N_2^+
- Medium height 100 – 200 km
  - Green (557.7 nm) from O
- High > 200 km
  - red (630 nm) from O
- Colour mixing of blue, green and red can produce a huge range of colours

http://lasp.colorado.edu/tour/science_research/atmospheric/images/aurora-lasp.gif

Example Auroras

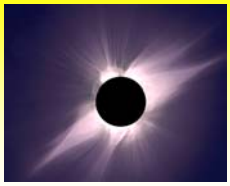
- Notice how the colours correspond to the details on the previous slide

Courtesy Alistair Skene, Orkney 29th Oct. 2003

http://www.psiaz.com/Schur/astro/aurora3-01.html

Solar wind and space weather is crucial to the origin of the aurora

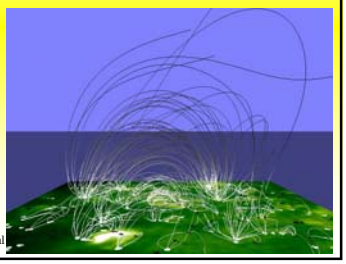
- Solar wind originates outside the visible Sun
  - it represents a streaming away of coronal material



The Sun's corona seen during the total eclipses of 1991 and 1980 courtesy *High Altitude Observatory/ National Center for Atmospheric Research* & http://umbra.nascom.nasa.gov/ssu/magnetic_carpet.html

Why is the Corona a few million degrees?

- Coronal material is heated from below by the effects of unstable and constantly changing magnetic fields



Computer simulation of part of solar surface
http://umbra.nascom.nasa.gov/ssu/magnetic_carpet.html

We live in the Sun

- Solar wind always blows
- It has a slow and a fast component
  - fast component (~750 km s^{-1}) is steadier and comes from coronal holes nearer the solar poles
    - reaches full speed in <10 solar radii
  - slow component (~300 km s^{-1}) is less steady and has a more equatorial origin
    - reaches full speed at ~25 solar radii
- Solar wind varies with the 11 year sunspot cycle

Magnetic fields and plasma

http://www.gsfc.nasa.gov/gsfc/spacesci/sunearth/tracecl.htm

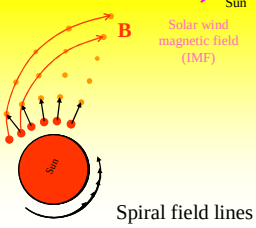
- Close to the Sun, the strong magnetic field controls the motion of the plasma
  - as the field lines loop round, so the plasma in the inner corona follows the field lines
- Far from the main body of the Sun, the magnetic field is comparatively weak and is controlled by the plasma
  - this is the case in the solar wind

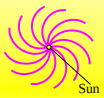
'Frozen' or 'trapped' magnetic field

- In a plasma like the solar wind there is virtually no electrical resistance to the motion of charge
- Maxwell's equations of E&M predict that magnetic field in such a plasma is trapped and carried along unchanged by the plasma in motion
- Hence magnetic field generated on the Sun reaches the Earth

The Sun's spiral magnetic field

- As the hot solar wind is ejected, it drags out its accompanying magnetic field
- The resulting field lines spiral out from the Sun
  - try building up diagram

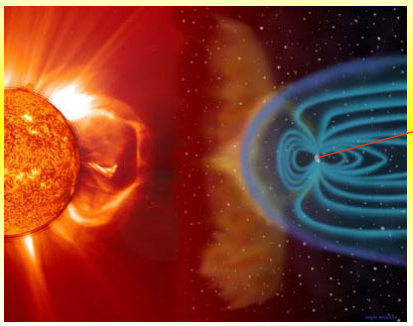




Spiral field lines

When fields collide

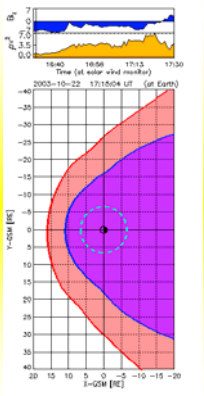
- The Earth's field acts like an umbrella



Courtesy: SOHO/LASCO/EIT (ESA & NASA)

The fluctuating magnetosphere

- The web-page quoted here evaluates the magnetopause from ACE data on a minute by minute basis
  - the gif shows one hour of data
  - note how variable it is

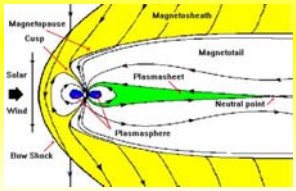


Animated gif

http://muir.spasci.com/DynMod/

Within the magnetopause

- Sun side
  - Earth's field is compressed to within about 10 R_E (Earth radii)
  - note the cusps
- Night side
  - tail stretches > 200 R_E
  - plasma sheet
  - Van Allen belts



http://www.spaceweather.com/glossary/images/mgsphere.gif

Coronal mass ejections (CMEs)

- Coronal mass ejections are now considered the source of major geomagnetic storms
  - not solar flares
  - frequency ~1 per day
  - total mass in one ejection could be ~10^{10} tonnes
  - energy ~10^{24} J (>> 10^8 megatons)
  - speeds of leading edge at the Sun ~ 1000 km s^{-1}
    - Earth's magnetosphere is hit hard