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Lecture 12:
Heavenly plasmas -- space

Today’s menu

- Earth, our home, and its outer construction
  - Different ‘spheres’
  - Dipole field
  - Earth’s true magnetic field
- Sun, our heater and its construction
  - Solar layers (not called spheres...)
  - Solar wind and other interesting sun-related phenomena
- Geomagnetic effects on us

Mother Earth
-- what is it that surrounds us?

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We have an atmosphere – why?

Rather, atmosphere is the ’reason’ for our existence!

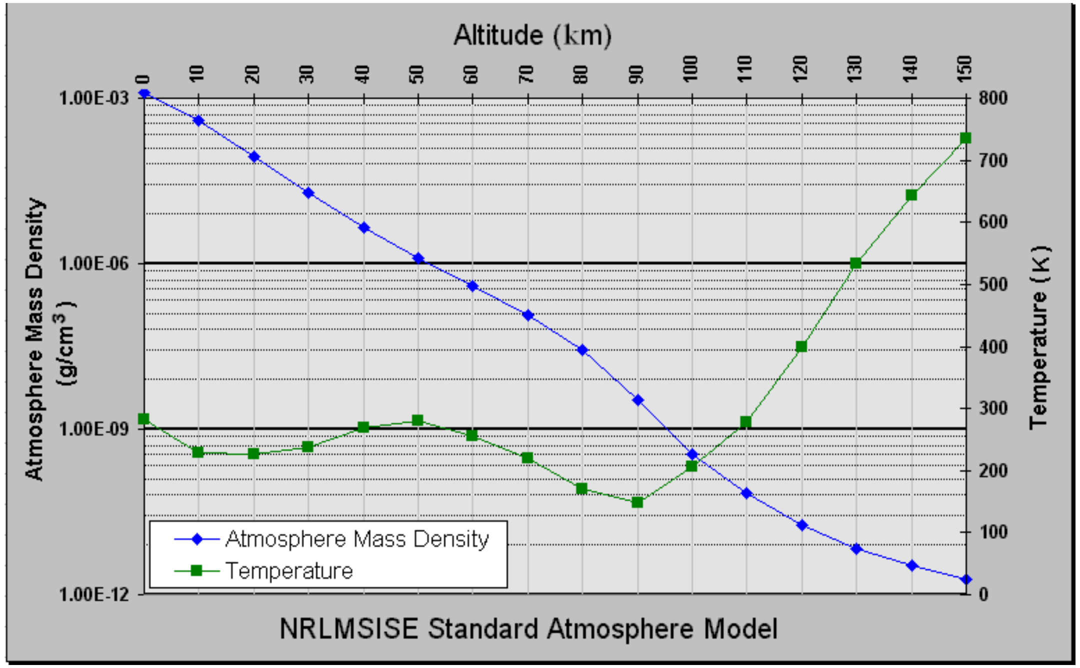
Earth’s atmosphere protects life on Earth by

- creating pressure allowing for liquid water to exist
- absorbing UV radiation from the Sun,
- warming the surface through heat retention (greenhouse effect), and
- reducing temperature extremes between day and night

Our atmosphere

- mass of atmosphere 5×10^{18} kg (10^{-6} M_E)
- Atmospheric pressure = total weight of the air / unit area
- Distribution of the atmospheric mass:
    - 50% below 5.6 km
    - 90% below 16 km
    - 99.99997% below 100 km

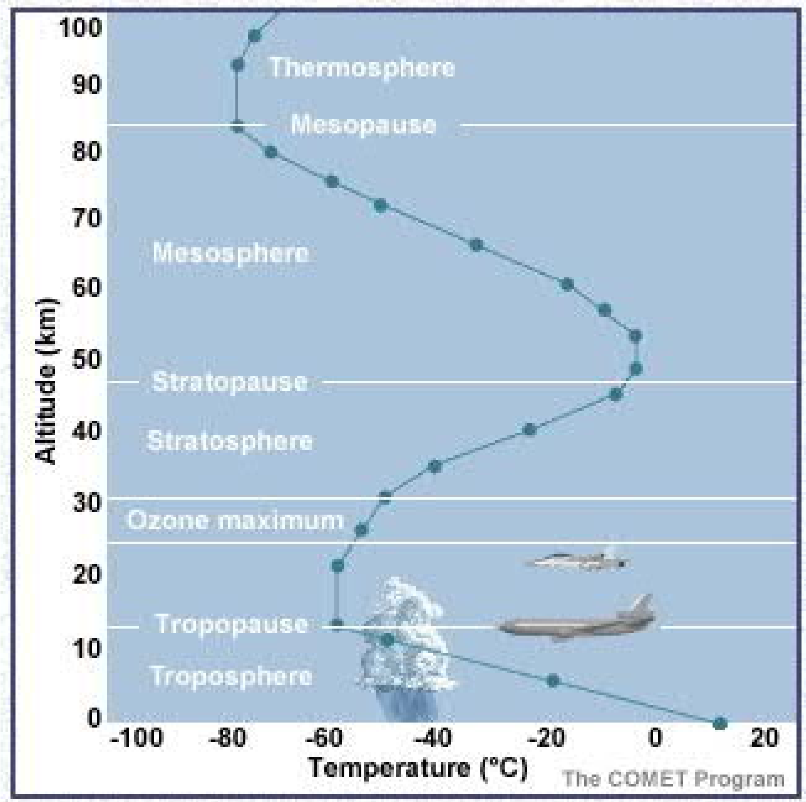
The radius of 100km (0,16 R_E) containing essentially all atmospheric mass is called the Kármán line.



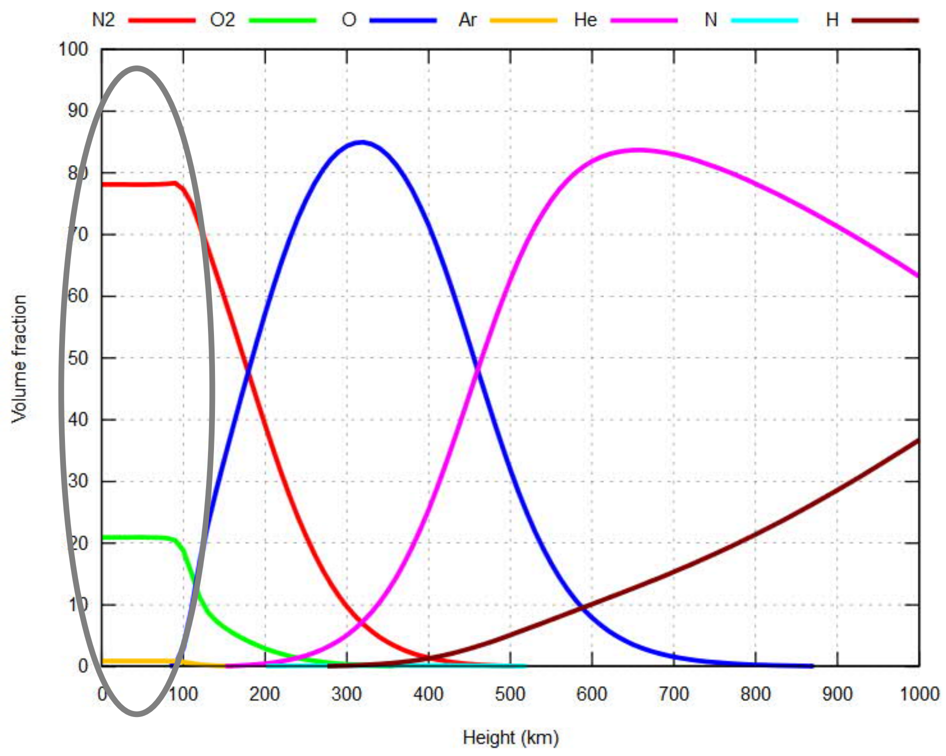
Practical significance of Kármán line?

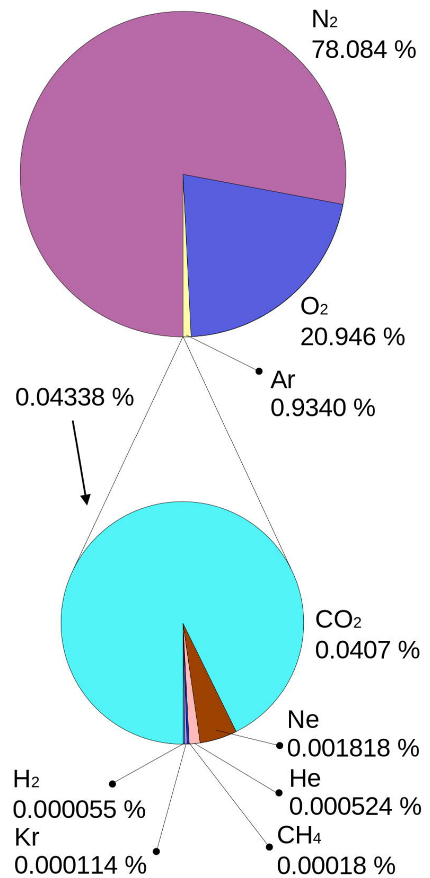
The Kármán line

- the border between the atmosphere and outer space
- marks the beginning of space where human travelers are considered astronauts
- atmospheric drag becomes noticeable during reentry of a spacecraft
- meteors begin to glow



Composition of the ’atmosphere’

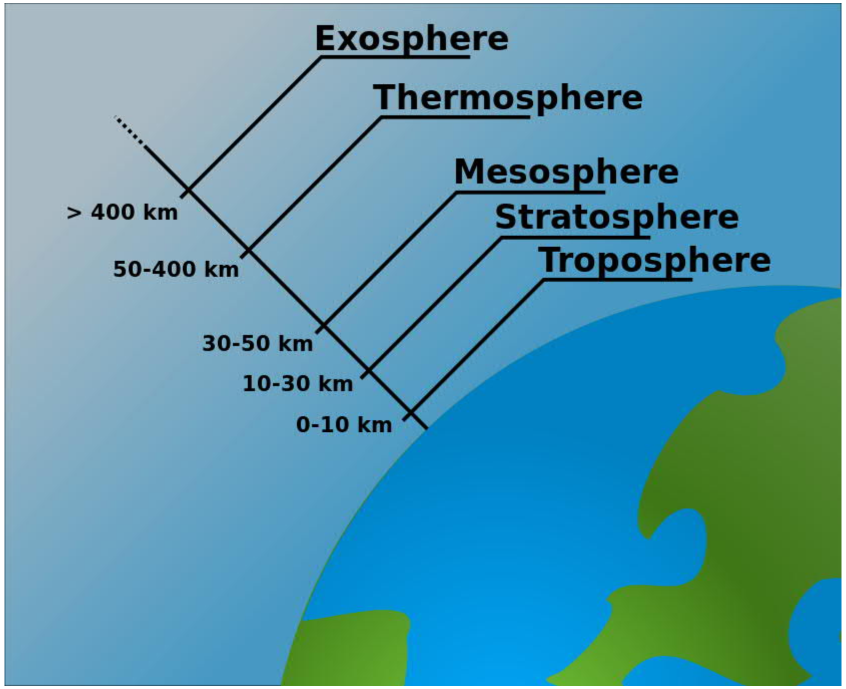




Atmospheric layers = ’spheres’

Five main layers:

- Troposphere (0 – 17km)
  - This is where weather as we know it happens
  - The home of jet streams (affects flight times)
- Stratosphere (17km – 50km)
  - Here is where our ozone layer resides
- Mesosphere (50 – 90km)
- Thermosphere (90 – 400km)
- Exosphere (>400km)
  - Gravitation too weak to confine particles



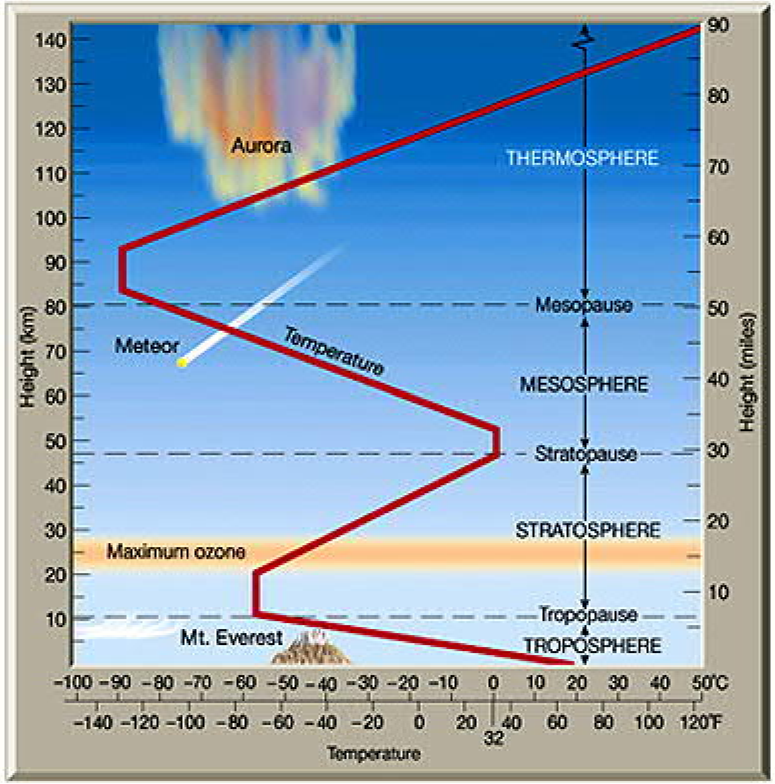
Temperature – not what you would expect

Experience: the higher you go, the colder it gets

But the layers of the Earth's atmosphere affect temperature in complex ways.

- Leave the Troposphere ➔ for 10km T=const
- In Stratosphere, T increases !!
- In Mesosphere, T again begins to drop,
- Enter Thermosphere ➔ T begins to increase, eventually becoming even warmer than the temperature on the surface of the Earth !!!

➔ layer division based on temperature behaviour



Stuff above the Kármán line

Two new, qualitatively different spheres appear:

- Ionosphere:
  - a region where material is partially ionized by solar radiation
  - Extends from ~50km to 500 – 1000km (depending on the time of day...)
- Magnetosphere:
  - Region with fully ionized plasma
  - Region of MHD ...

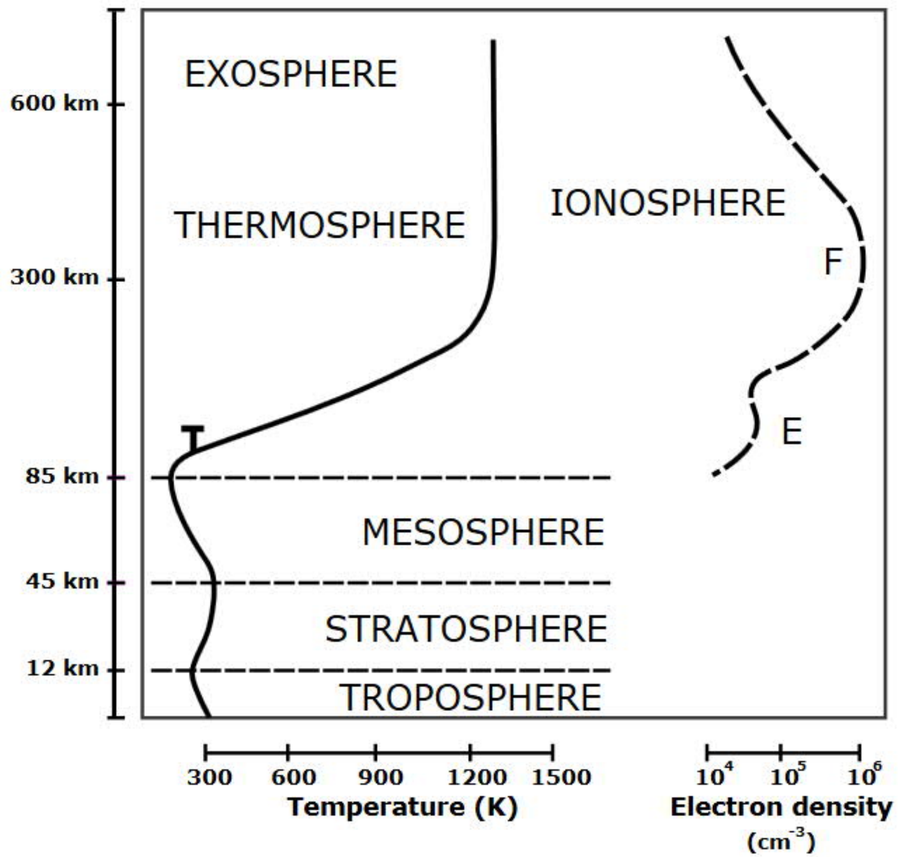
Stuff above the Kármán line

- By comparison, the International Space Station and Space Shuttle typically orbit at 350–400 km, within the F-layer of the ionosphere where they encounter enough atmospheric drag to require reboosts every few months.
- Depending on solar activity, satellites can experience noticeable atmospheric drag at altitudes as high as 700–800 km.

Ionosphere

Includes

- thermosphere
- parts of mesosphere
- parts of exosphere
- Important for HF radio communication
  - atmosphere is thin ➔ free electrons can exist for short times ➔ cut-offs ...
- This is where auroras take place
  - Since also neutrals exist



Ionospheric layers
-- sublayers to atmospheric ones

D layer:

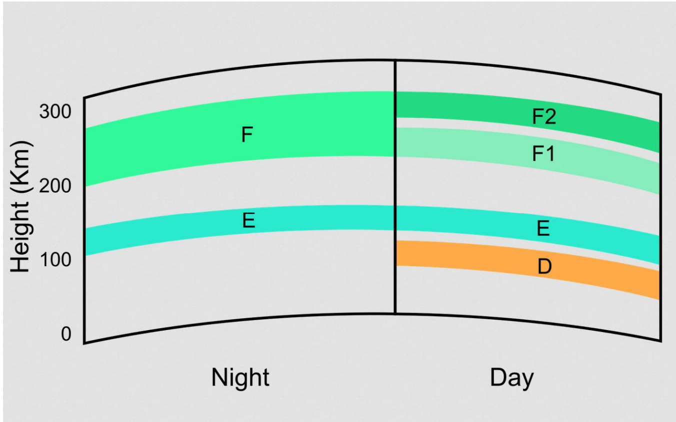
- 60 – 90km ➔ more neutral molecules than ions
- MF radio waves significantly attenuated

E layer:

- 90 – 150km
- reflect radio waves w/ f < 10 MHz

F layer:

- 150 – 500km
- At night, only one layer (F2), during day also F1.
- Responsible for HF radio communication



Holding on to our ionosphere

But wait …

Exosphere started at 400km

Now we have a big part of ionosphere extending up to 1000km

Who is holding on to our particles in the outer *ion*osphere ???

Well, no-one as far as neutral particle are concerned.

So let’s focus on charged particles, i.e., *ionospheric plasma*

Earth’s magnetic field

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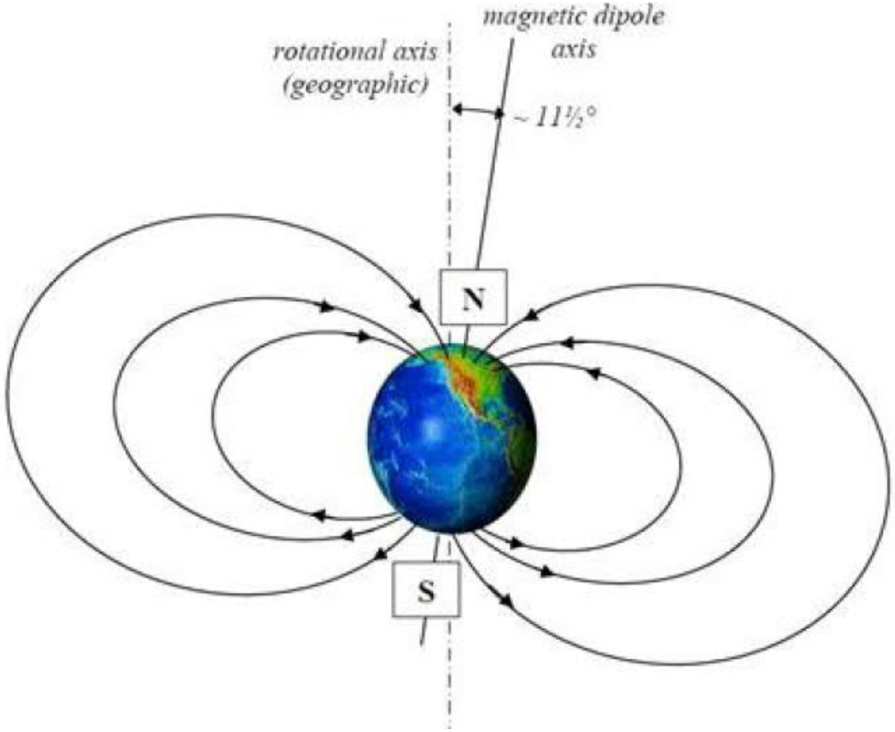
Dipole approximation

- If you have ever used a compass, you know that there is a magnetic field around and among us.
- The needle of your compass always (if held horizontal, that is) points to 'north' – roughly (*)
- 'Near' the surface of the Earth, the magnetic field can be closely approximated by a dipole field
- This dipolar field accounts for 80–90% of the field *in most locations*

(*) Two definitions of 'north':

- Due to axis of Earth's rotation
- Due to the 'north pole' of the magnetic dipole



Dipole magnetic field mathematically

As HW you will show that the components of Earth's dipole field in *almost* spherical coordinates are

$$B_r = \frac{-2k_0}{r^3}\sin\lambda$$

$$B_\lambda = \frac{k_0}{r^3}\cos\lambda$$

$$B_\varphi = 0$$

and the magnitude is $B = \frac{k_0}{r^3}\sqrt{1+3\sin^2\lambda}$

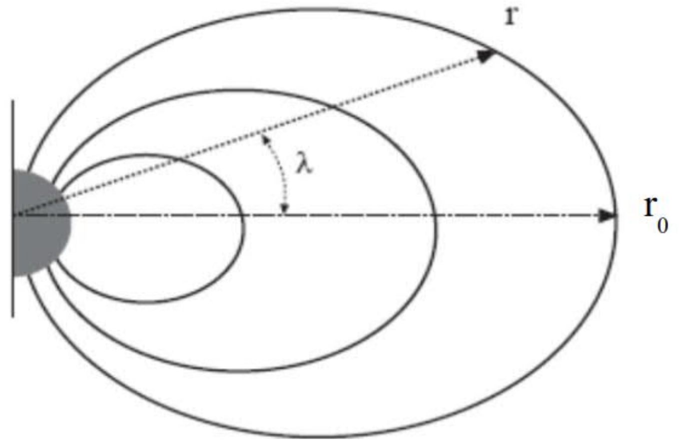
Here: $k_0 = \frac{\mu_0 M}{4\pi} \approx 8 \cdot 10^{15} Tm^3$

Minimum strength at the equator, $\lambda = 0$:

$$B_{min} = B_\lambda = \frac{k_0}{R_E^3} \approx 30\mu T$$

Maximum strength at the poles, $\lambda = \pm\frac{\pi}{2}$:

$$B_{max} = B_r = \frac{2k_0}{R_E^3} \approx 60\mu T$$



Parametric representation

Let us now take the magnetic field value at the equator as the reference value for each field line: $B_0 \equiv k_0/r^3$, where r is the distance of the field line from Earth at the equator.

Then we can express the magnetic field along a field line as

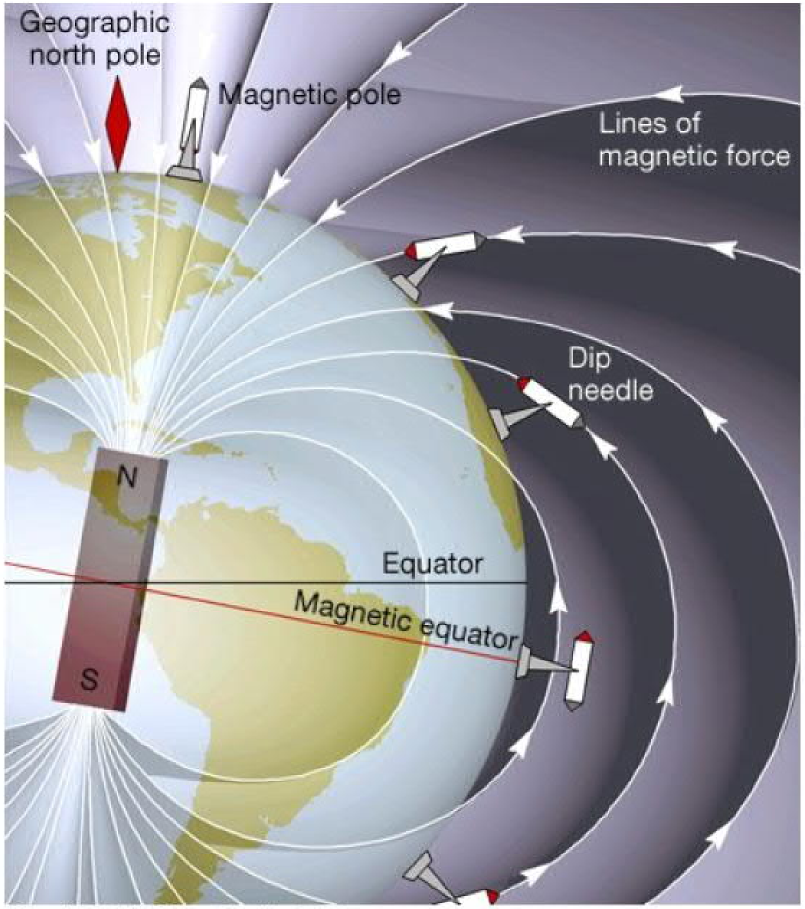
$$B_r = -2 B_0 \sin\lambda$$
$$B_\lambda = B_0 \cos\lambda$$
$$B = B_0 \sqrt{1+3\sin^2\lambda}$$

And we can find the distance of the field line as a function of λ:

$$\frac{dr}{r d\lambda} = \frac{B_r}{B_\lambda} \rightarrow r = r_0 \cos^2\lambda \;\; (HW)$$

How about the magnetic dipole?

- The dipole is roughly equivalent to a powerful bar magnet
- This magnetic dipole would be positioned at the center of the Earth and tilted at an angle of about 11 degrees with respect to the rotational axis of the Earth



So where is the Earth’s permanent magnet?

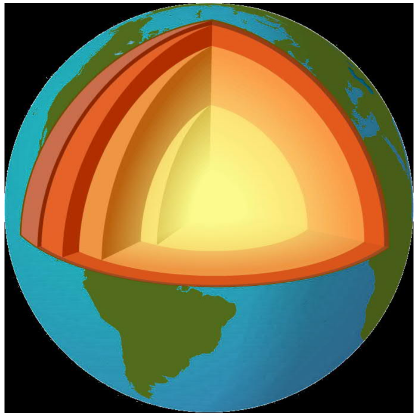
Nowhere.

Magnetic field is not due to permanent magnetization of the materials.

The Earth’s magnetic field is sustained by the *dynamo effect*.

A requirement for the *induction* of a field is a rotating conducting fluid.

In the case of the Earth, the magnetic field is induced and constantly maintained by the convection of liquid iron in the outer core.

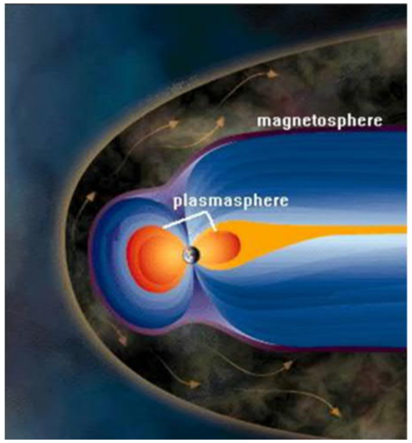


Combine Faraday’s law, Ampere’s law and Ohm’s law ➔

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{V} \times \boldsymbol{B}) + \eta \nabla^2 \boldsymbol{B} \ ,$$

where $\eta = 1/\mu_0 \sigma$ is the magnetic diffusivity

Back to spheres: *magnetosphere*



It is now clear that the earth's magnetic field has an important role in holding the outer parts of our atmosphere together

➔ Earth is surrounded by *magnetosphere:*

- "A magnetosphere is a region of space surrounding an astronomical object in which charged particles are manipulated or affected by that object's magnetic field."

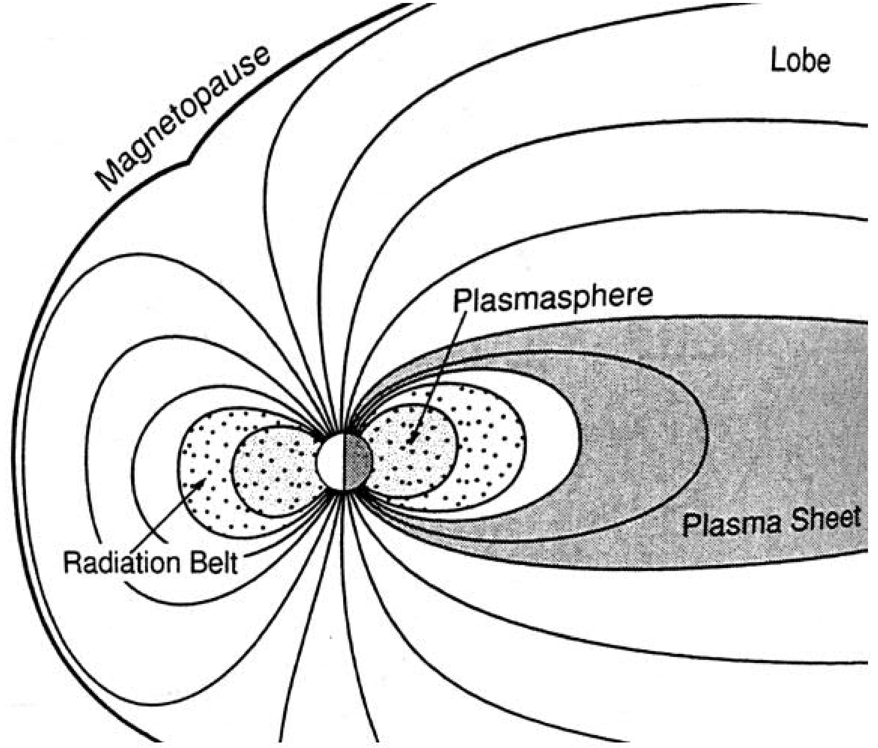
The inner part of the magnetosphere is called the *plasmasphere*

- Plasmasphere protects us from ultrarelativistic electrons (cosmic or solar)

But there is an issue… these spheres are far from a sphere …

Earth’s magnetosphere

Day side

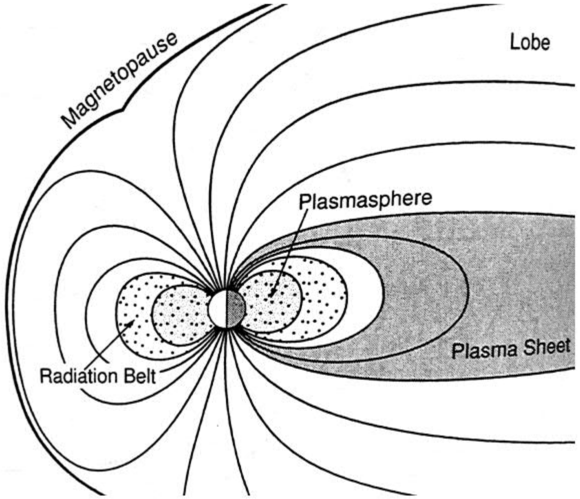


Night side

➔ Far enough from Earth, the magnetosphere becomes very asymmetric

Our magnetosphere has a complicated structure …

- Bow shock
- Magnetopause
- Magnetosheath
- Magnetotail
- …



But to understand the structure, we have to understand why the dipole field is not enough.

We have to have a look at the ***Sun*** !

Solar physics

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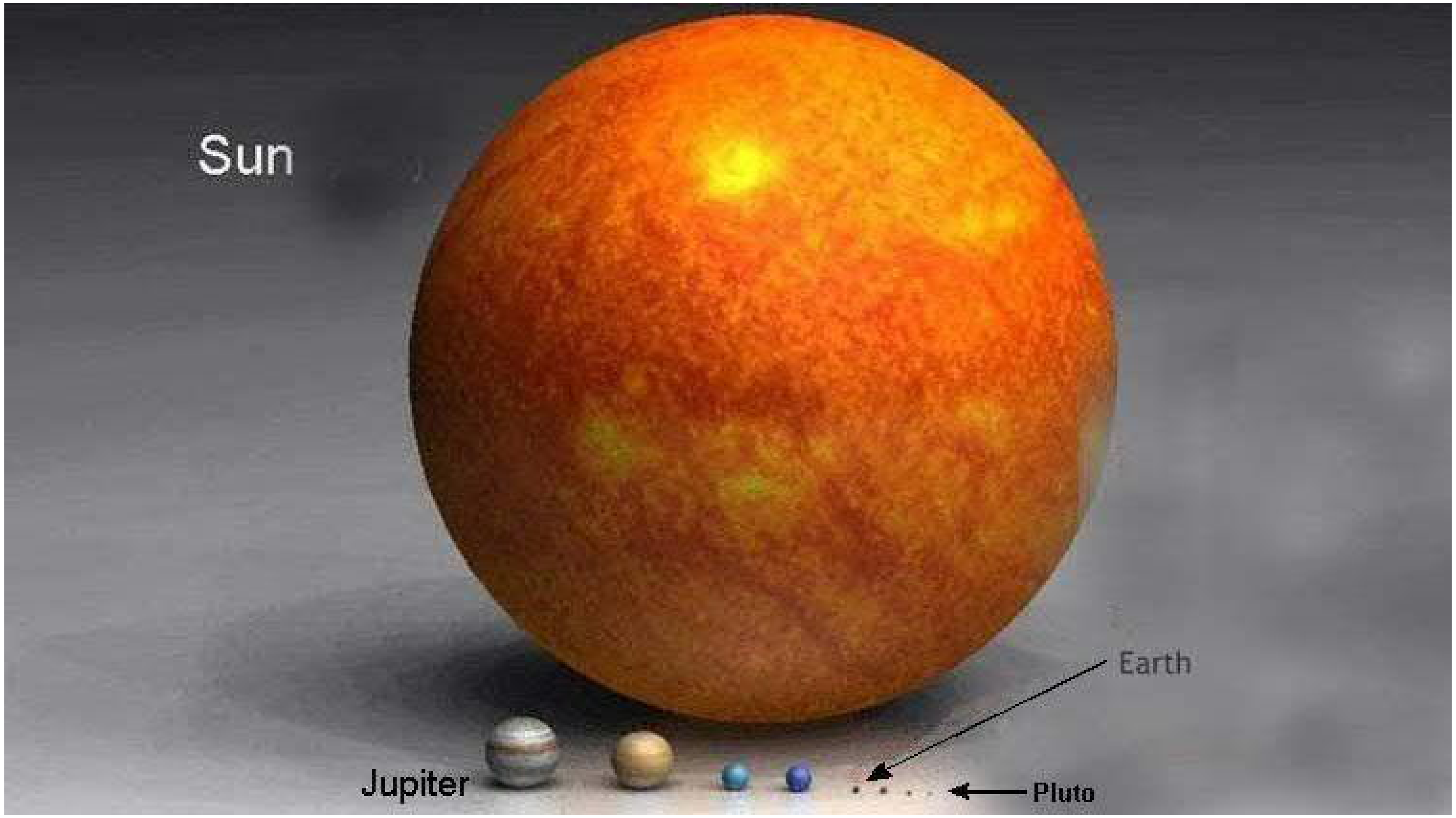
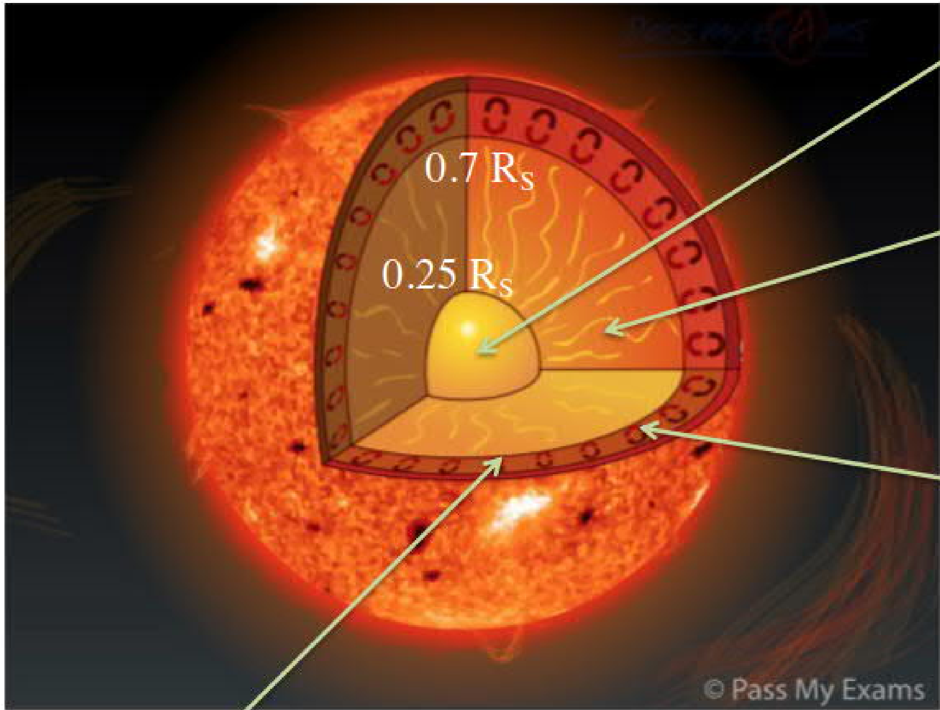


http://www.physast.uga.edu

The structure of the Sun



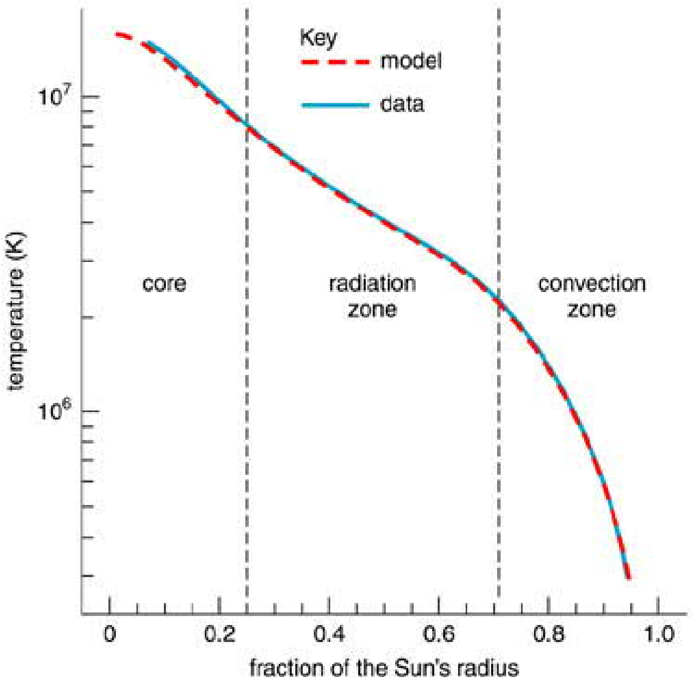
Core: the ’engine’ of Sun
This is where fusion reactions convert hydrogen to helium

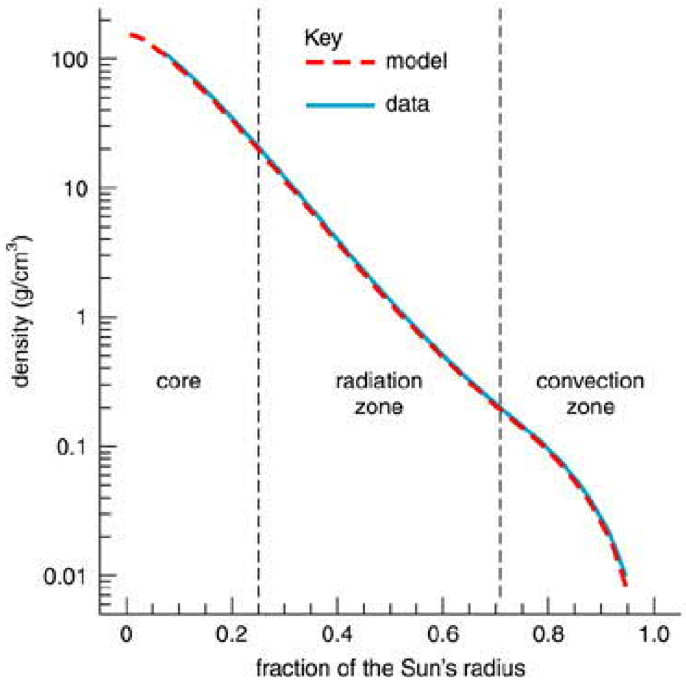
Radiation zone:
Small opacity ➔ energy tranferred via radiation

Convection zone:
Large opacity ➔ energy transferred via convection ➔ hot outer layer

Tachocline – bottom of the convection zone

The structure of the Sun



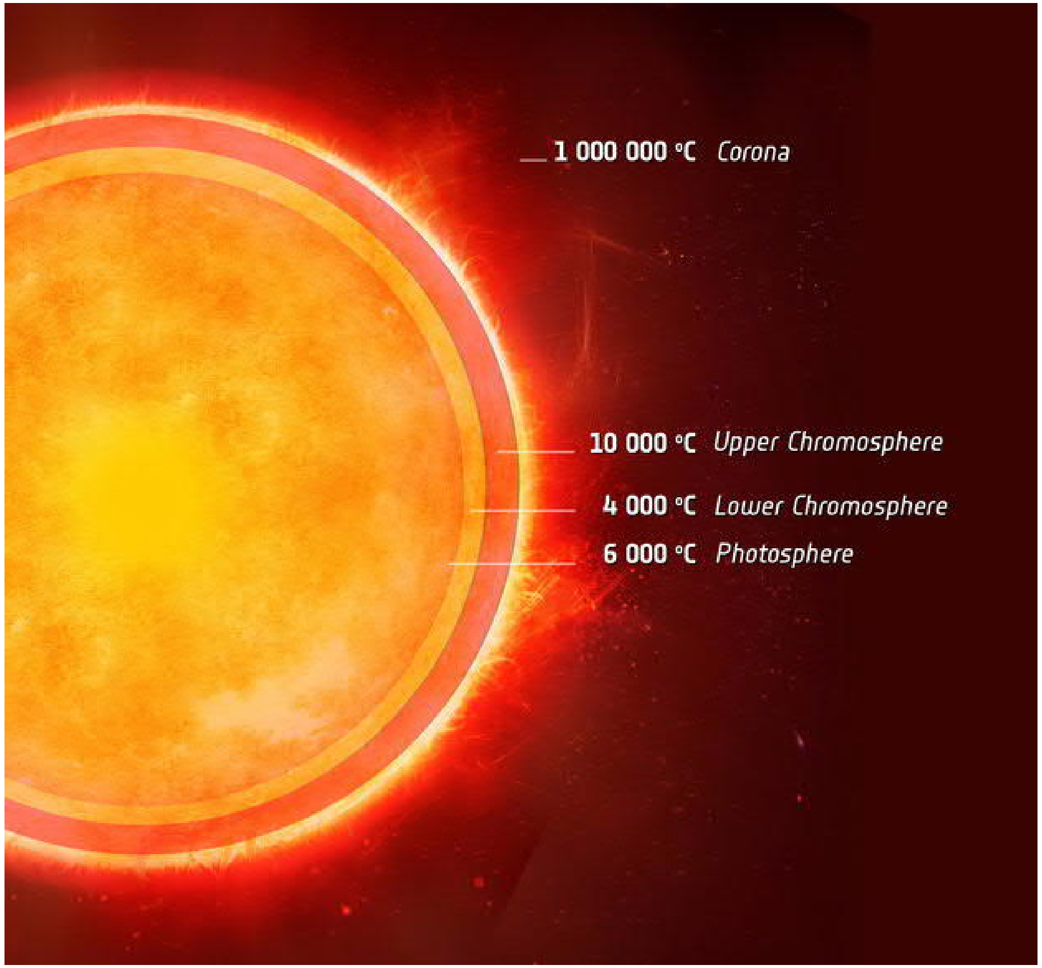


Pearson education, publishing Addison Wesley
http://www.physast.uga.edu

Solar atmosphere

- Photosphere:
  - visible surface of the Sun
  - 10 000—100 000km thick
  - Ionization degree ~3%
- Chromosphere:
  - seen red during a solar eclipse
  - About 2000km thick
- Solar corona:
  - Extends to millions of km
  - The second hottest part of Sun

The strange temperature behavior of Sun’s atmosphere is yet to be fully understood = ‘coronal heating problem’



Also Sun has a magnetic field !

Today's understanding:

Even the solar magnetic field is generated via dynamo effect:

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{V} \times \boldsymbol{B}) + \eta \nabla^2 \boldsymbol{B}$$

Here the rotation is in the *convection zone*.

During quiescent periods, Sun's magnetic field is almost a dipole field, with two large cusps at the poles.

But most of the time, things are a lot more complicated

Solar wind

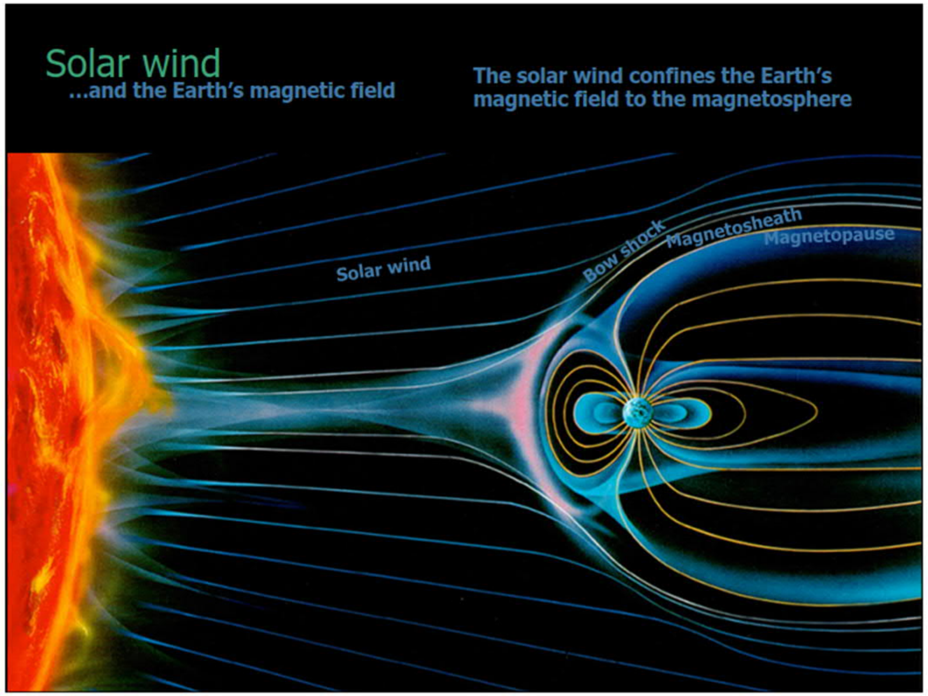
- The outer layers of solar atmosphere are eroded and plasma expelled along open field lines via *coronal* holes

➔ *solar 'wind'*

- The magnetic field *frozen* to the plasma

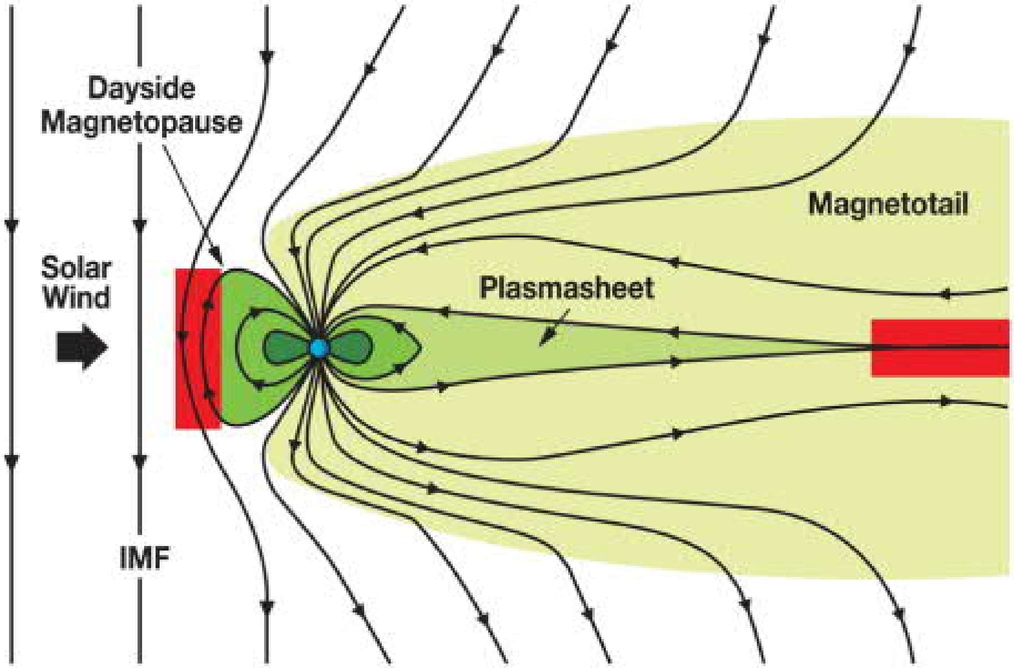
  ➔ field lines move embedded in the solar wind

➔ IMF = Interstellar Magnetic Field



Earth’s magnetosphere

- By the time the solar wind reaches Earth, its ’curvature’ is so large that the field lines appear straight when encountering Earth’s dipole field
- IMF and dipole field get mixed up via reconnection



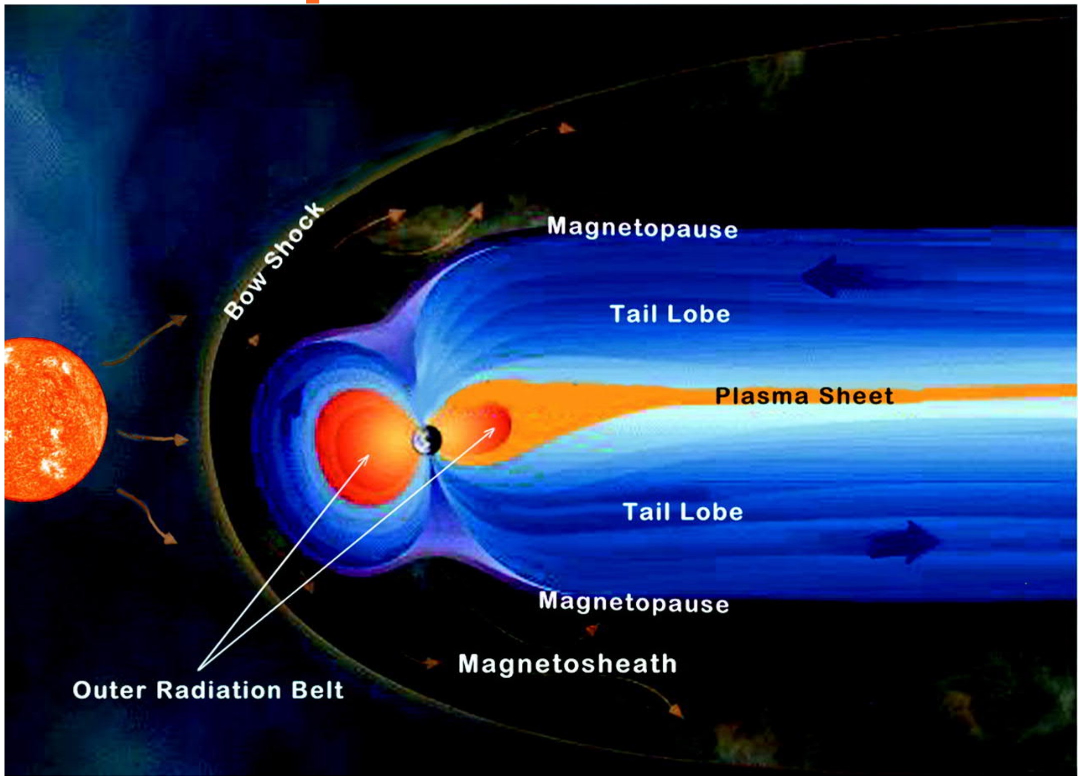
Earth's magnetic field = dipole + solar wind

The magnetosphere now has two different kinds of field lines:

- Open field lines
- Closed field lines

The night side is more interesting:

- Reconnection !
- accelerated particles



John G. Lyon Science 2000;288:1987-1991

The solar wind, magnetosphere, and ionosphere form a single system driven by the transfer of energy and momentum from the solar wind to the magnetosphere and ionosphere

Activities of our Sun

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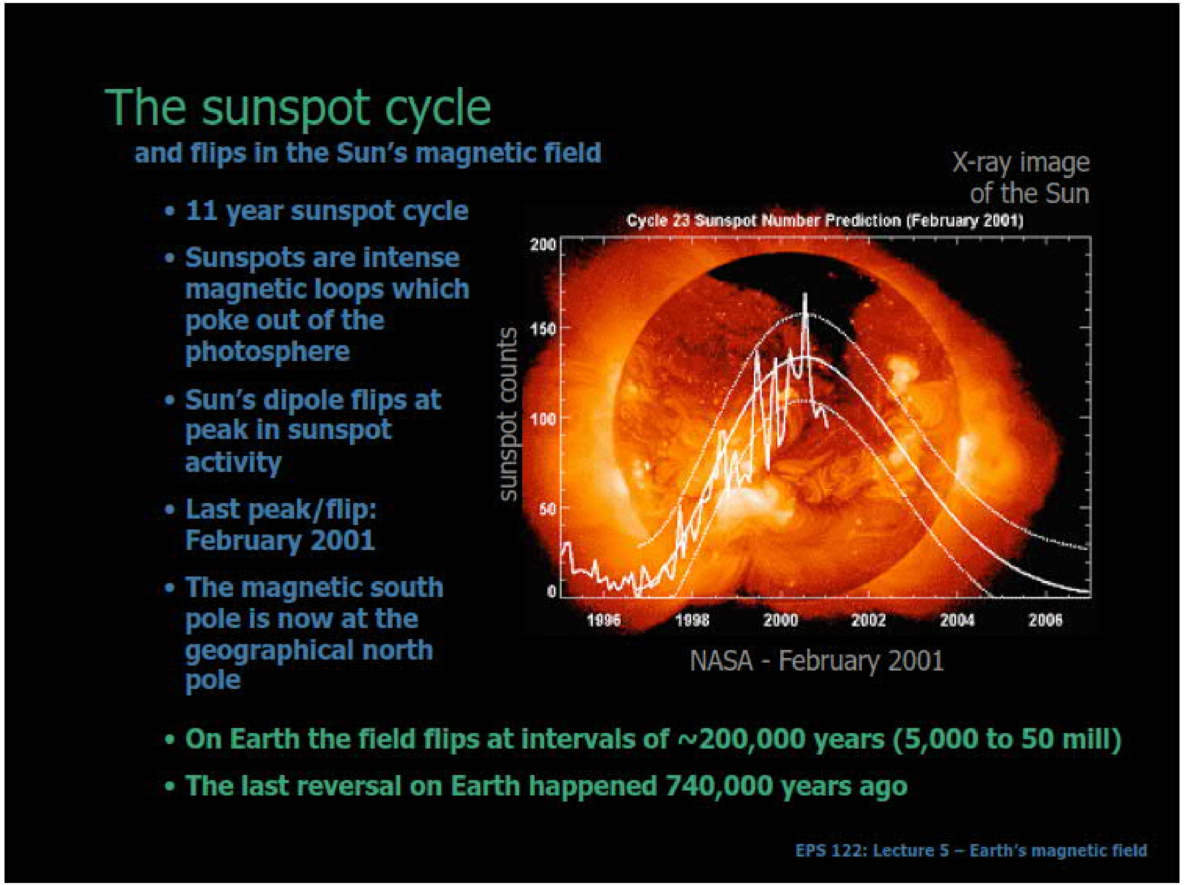
Sun spots & Sun ’flipping’

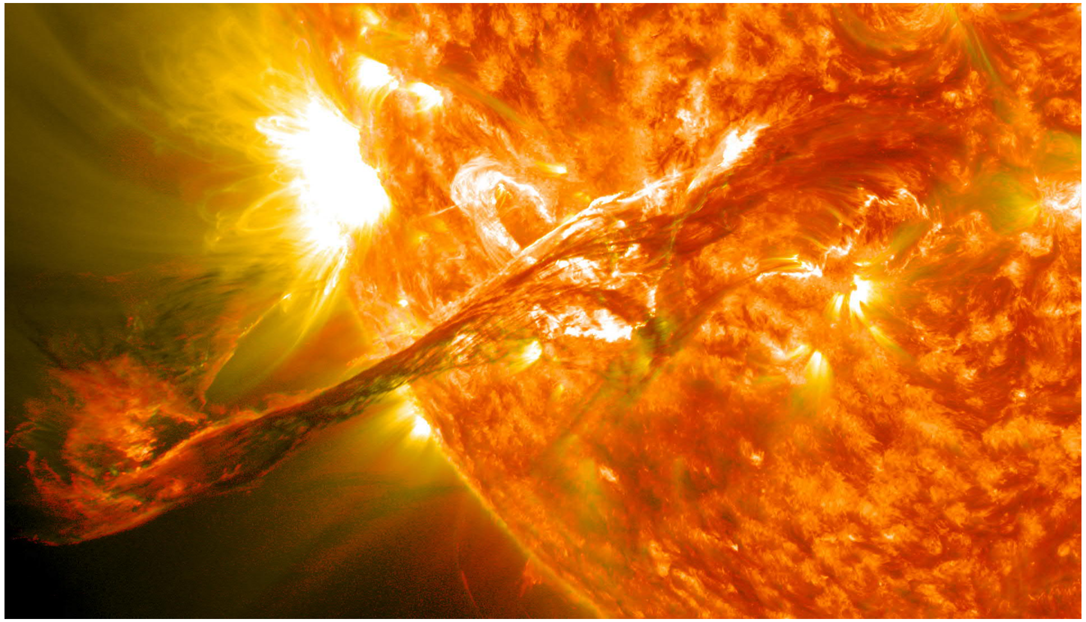
As promised, the magnetic field of Sun is not simple dipole field but exhibits dramatic features that are responsible for most of the interesting solar phenomena.

- *Sun spots*: probably the most familiar
- *Solar magnetic field flipping polarity* (see also HW)



Solar flares

- occur around sunspots, where the magnetic field penetrates the photosphere, linking the corona to the solar interior.
- powered by sudden release of magnetic energy stored in corona.
- affect all layers of solar atmosphere
- most energy outside the visual range
- X-rays & UV radiation by solar flares can disrupt long-range radio communications



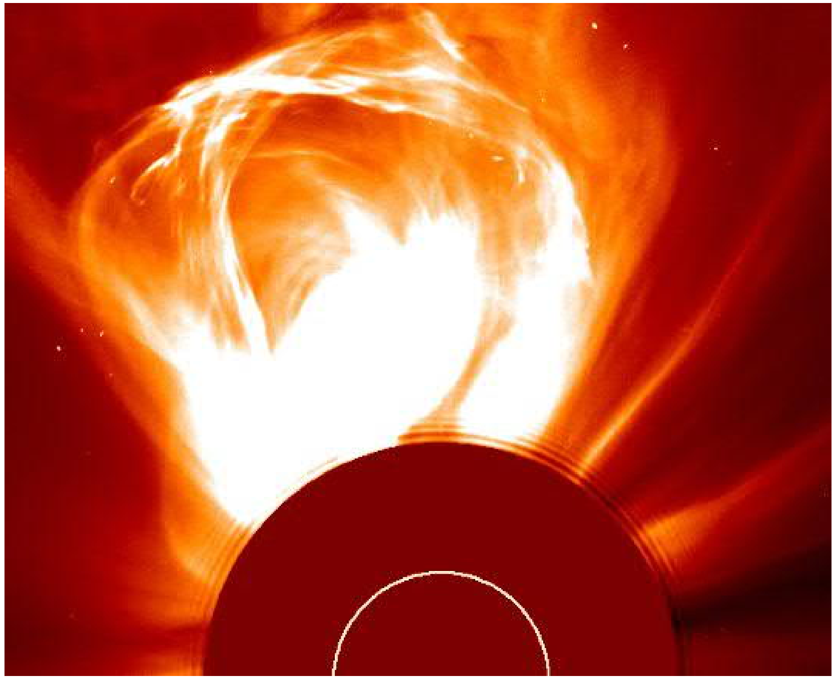
31.8.2012: a long *prominence*/filament of solar material hovering the corona, erupted out = solar flare, causing auroras on Earth 3.9.2012.

Coronal Mass Ejections (CME)

Enormous bubbles of superheated plasma ejected from the sun

- Powerful eruptions near Sun's surface
  - driven by kinks in the solar magnetic field ?
- several times a day when Sun is most active. Quieter periods ➔ CMEs about once every five days
- A major hic-up of the sun:
  - a billion tons of material are lifted off and accelerated to speeds of 10^6 km/h
  - with the power of 20 million nuclear bombs

Analogous to ELMs in tokamaks…



Coronal mass ejection 27.2.2000.
A disk is being used to block out the light of the sun.
The white circle indicates the sun's surface.
Image via NASA (SOHO)

‘Interesting’ phenomena in atmosphere

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CME and geomagnetic storms

every so often, a CME eruption is aimed right at us.

When the plasma cloud hits our planet, a geomagnetic storm follows:

- The plasma shock wave
  - compresses the Earth's dayside magnetic field
  - the nightside gets stretched out.

➔ Nightside magnetic field eventually reconnects = snaps back with the same amount of energy.

Spectacular geomagnetic storms

In 1989, Sun aimed a CME at us ➔

- a geomagnetic storm collapsed the Hydro-Québec power grid
- Six million people were without power for nine hours

In 1859, the *Carrington Event*

- the most powerful geomagnetic storm ever recorded
- Auroras observed as far south as Hawai'i and the Caribbean
- at higher latitudes, newspapers read by the light of the aurora alone
- Telegraph networks around globe catastrophically failed:
    - operators received shocks
    - telegraph paper caught on fire.

Protons: polar cap absorption (PCA)

Energetic protons released by a CME or solar flares

- Protons reach the Earth within 15 minutes to 2 hours
- protons spiral around and down the field lines into the atmosphere near the magnetic poles increasing the ionization of particularly D layer

➔ increase in the number of free electrons in the ionosphere, especially in the high-latitude polar regions

➔ Enhancement in radio wave absorption, especially within the D-region of the ionosphere

= Polar Cap Absorption (PCA) event

  - PCA's last anywhere from an hour to several days

X-rays: sudden ionospheric disturbances (SID)

Particularly strong solar flares can hit the dayside Earth with hard X-rays.

➔ X-rays penetrate to the D-region,

➔ released electrons rapidly increase absorption

➔ a high frequency (3–30 MHz) radio blackout.

This is called a *sudden ionospheric disturbance*, SID

Aurora Borealis -- colors

- Plasma sheet electrons precipitate along field lines which map to ionospheric altitudes
- Excite atmospheric atoms within the *auroral oval* (cusps in the magnetic field)
- De-excitation
- ➔ auroras!

230 km: Red auroras at 630 nm
Electron collisions with atomic O

110 km: Green auroras at 557.7 nm
Electron collisions with atomic O

90 km: Purple auroras at 427.8 nm
Electron collisions with N_2 molecules

Consequences of the ‘interesting’ phenomena

Risks to (modern) society

Strong solar events temporarily increase the radiation levels, but our atmosphere still does a very good job of protecting living organisms .

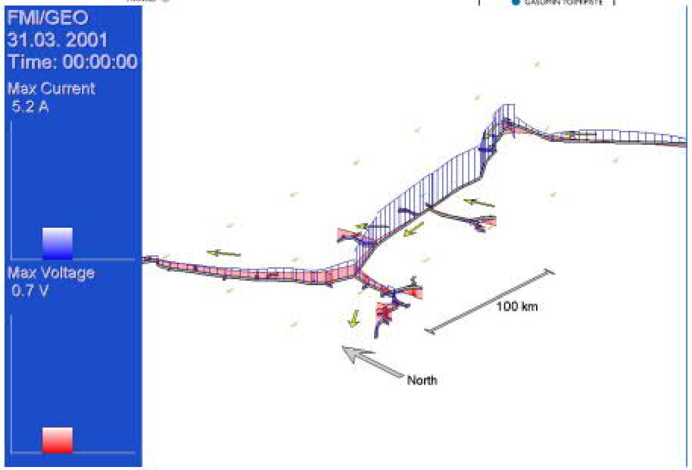
The real danger comes from the storm’s effect on technology.

Strong changes in geomagnetic field induces electric currents and thus can severely disrupt

- power grids
- Satellites ➔ anything using GPS positioning
- communication networks
- anything that uses electricity.

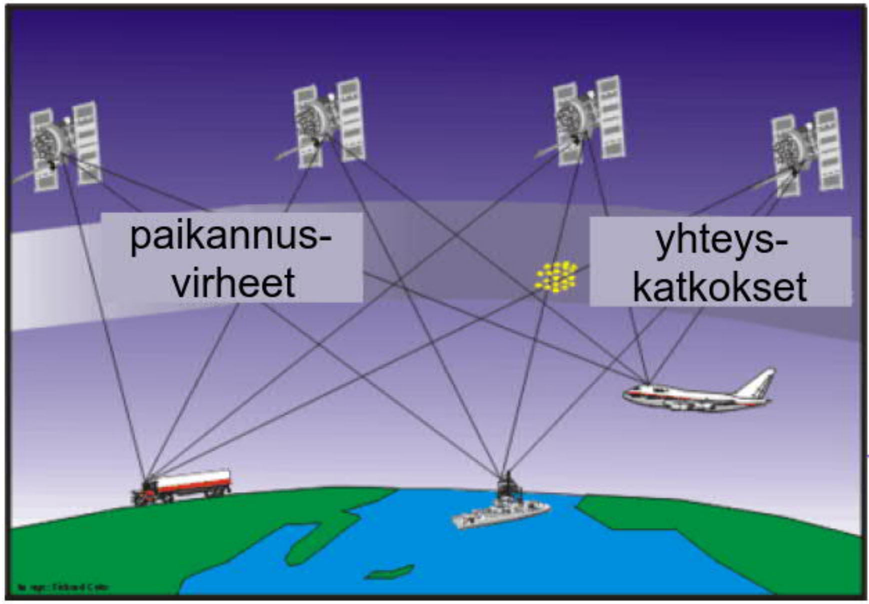
Geomagnetically Induced Currents

Currents and voltages may cause problems in natural gas pipelines and power transmission networks

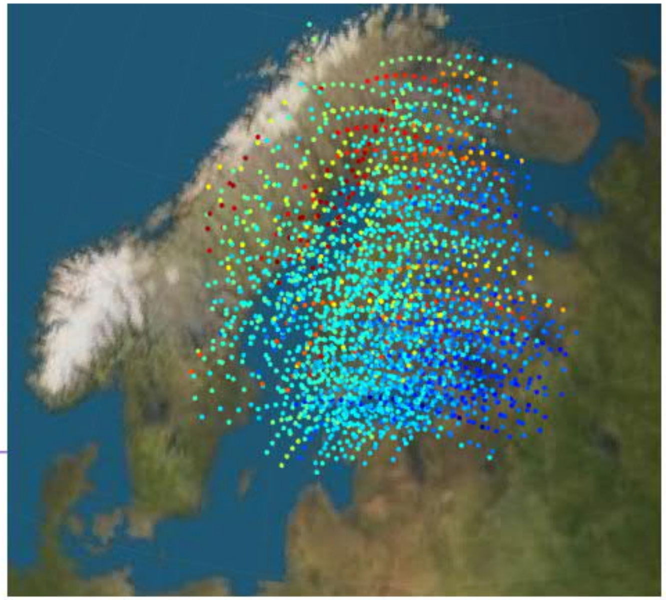


Space weather effects

Auroral currents disturb signal propagation in radio communications and in telecommunications between satellite and ground link



Local GPS measurements give an estimate of communications disturbances



But this was not all that there is …

In this lecture we have been able to get only as far as our Sun.

We should also consider

- *astrophysical* plasmas, and
- plasmas in *early universe*

These plasmas, however, would include material with interactions that we do not have necessary competence for in this course:

The quark-gluon plasmas …