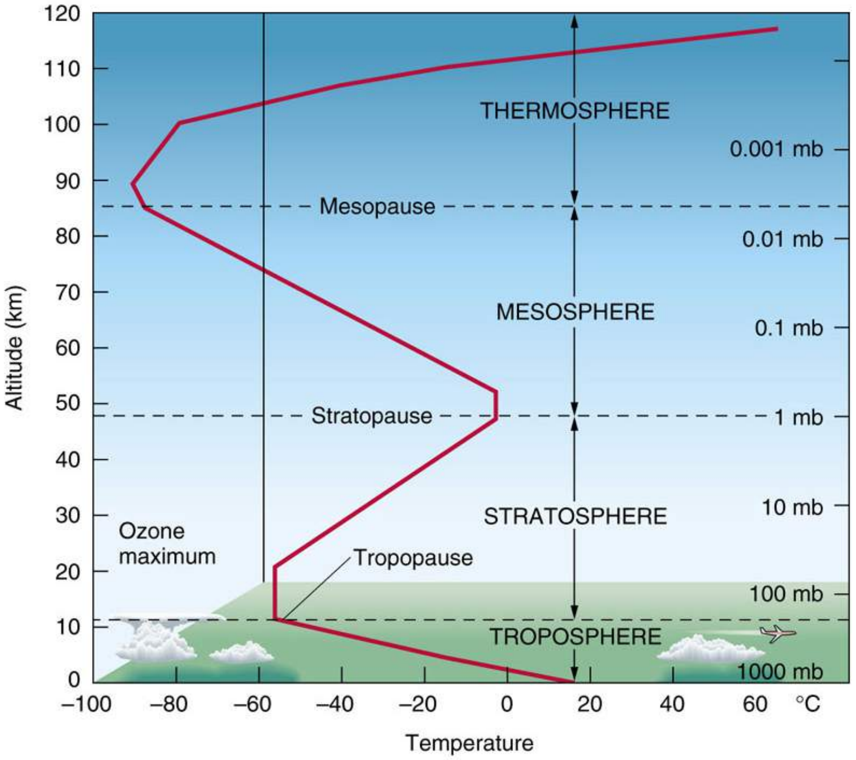
Lecture 7

Upper atmosphere

Revision from Lecture 1: Thermosphere

Thermosphere (~ 90 – 700 km)

- Temperature increases with height
- Region of highest temperature in atmosphere due to absorption of high photon energy radiation
- Very low density: contains very little of atmosphere's mass
- Location of **ionosphere** (mixture of positively charged ions and electrons) that reflects radio waves



- Location of aurora (produced in the **magnetosphere**)
- No clear separation with interplanetary space (**exosphere** extends out to ~10,000km and merges with solar wind)

Ionosphere

Ionosphere

At high altitudes (> 60 km), the relative density of ions and electrons increases as a result of ionisation of air molecules by solar X-ray and UV radiation. High energy cosmic rays also contribute to ionisation.

Charged particles are also produced in the atmosphere by other processes:

- radioactive decay of substances within the earth's crust,
- charge separation within clouds.

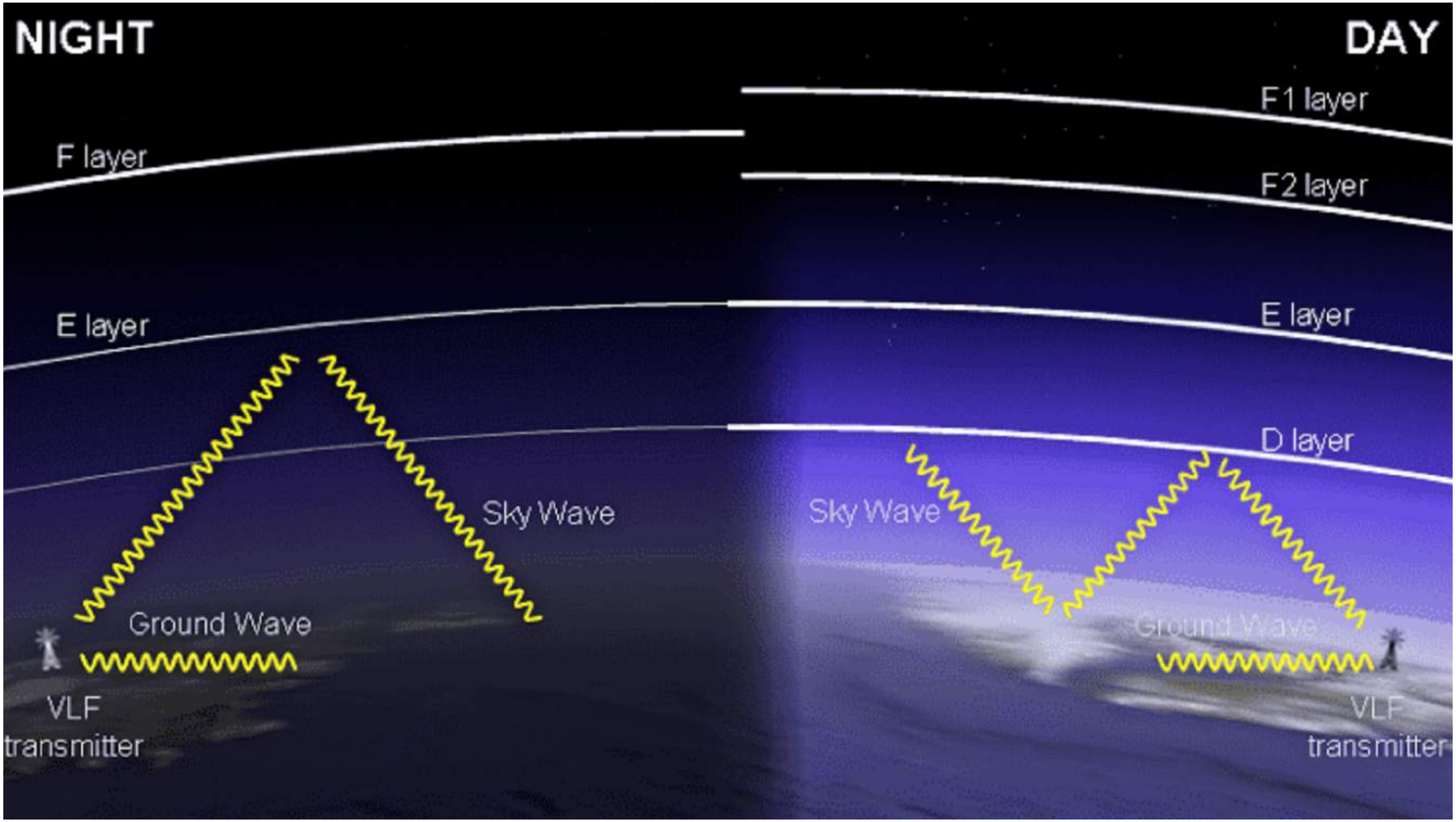
Ionisation increases with altitude as a result of

- increased mean free path => increased life time,
- increased radiation.

The free electrons in the ionosphere have an impact on radio communication by reflecting or absorbing radio waves and also act as a Faraday cage against charged particles.

Ionosphere layers

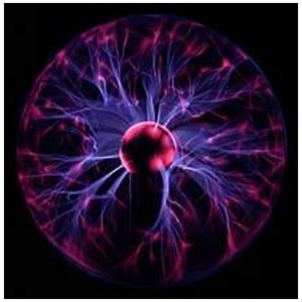
Revision: cut-off frequency from Lecture 6



Ionosphere

The free electrons make the ionosphere conducting, a so-called plasma. For a given electron density we can calculate the **plasma frequency** f, this results in the fact that the plasma becomes a reflector for all electromagnetic waves with frequencies $\mathrm{f} < \mathrm{f_p}$

$$\mathrm{f_p} = \sqrt{\mathrm{N}}\frac{\mathrm{e}}{2\pi}\sqrt{\frac{1}{\varepsilon_0 \mathrm{m}}} = \mathrm{constant} * \sqrt{\mathrm{N}}$$



with the constant $\approx 9\times10^{-3}$, $\mathrm{f_p}$ in [MHz], the electron density N in [cm^{-3}], m the mass of the electron, and ε_0 the permittivity in vacuum.

Therefore for an electron density of $\mathrm{N} = 3\times10^5\mathrm{cm}^{-3}$ we find a plasma frequency $\mathrm{f_p} = 5\mathrm{MHz}$.

The height profile of electron density in the ionosphere can be studied from the ground by sending up radio pulses at different frequencies and measuring the time lag for the reflected signal (ionosonde)

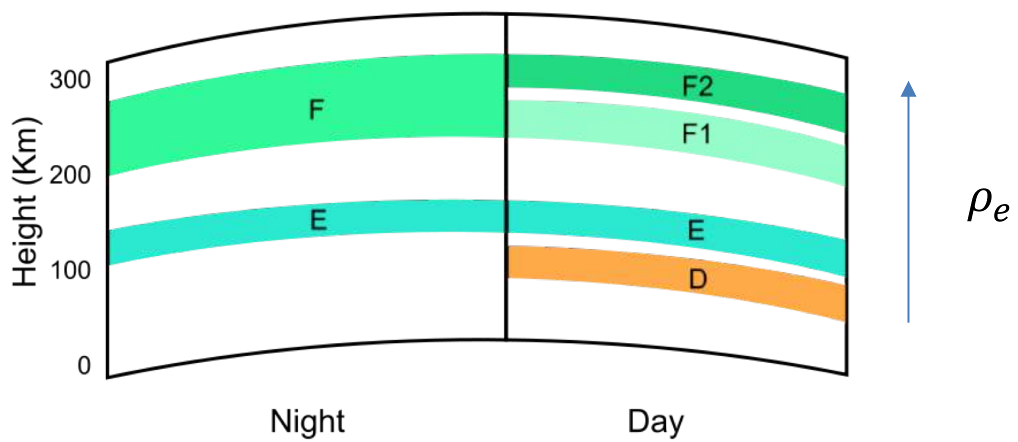
Ionosphere layers

D layer
- Exists only in daytime at ~70km altitude
- $F_p \sim 180$ kHz
- Reflects some VLF and LF, not useful for HF communication

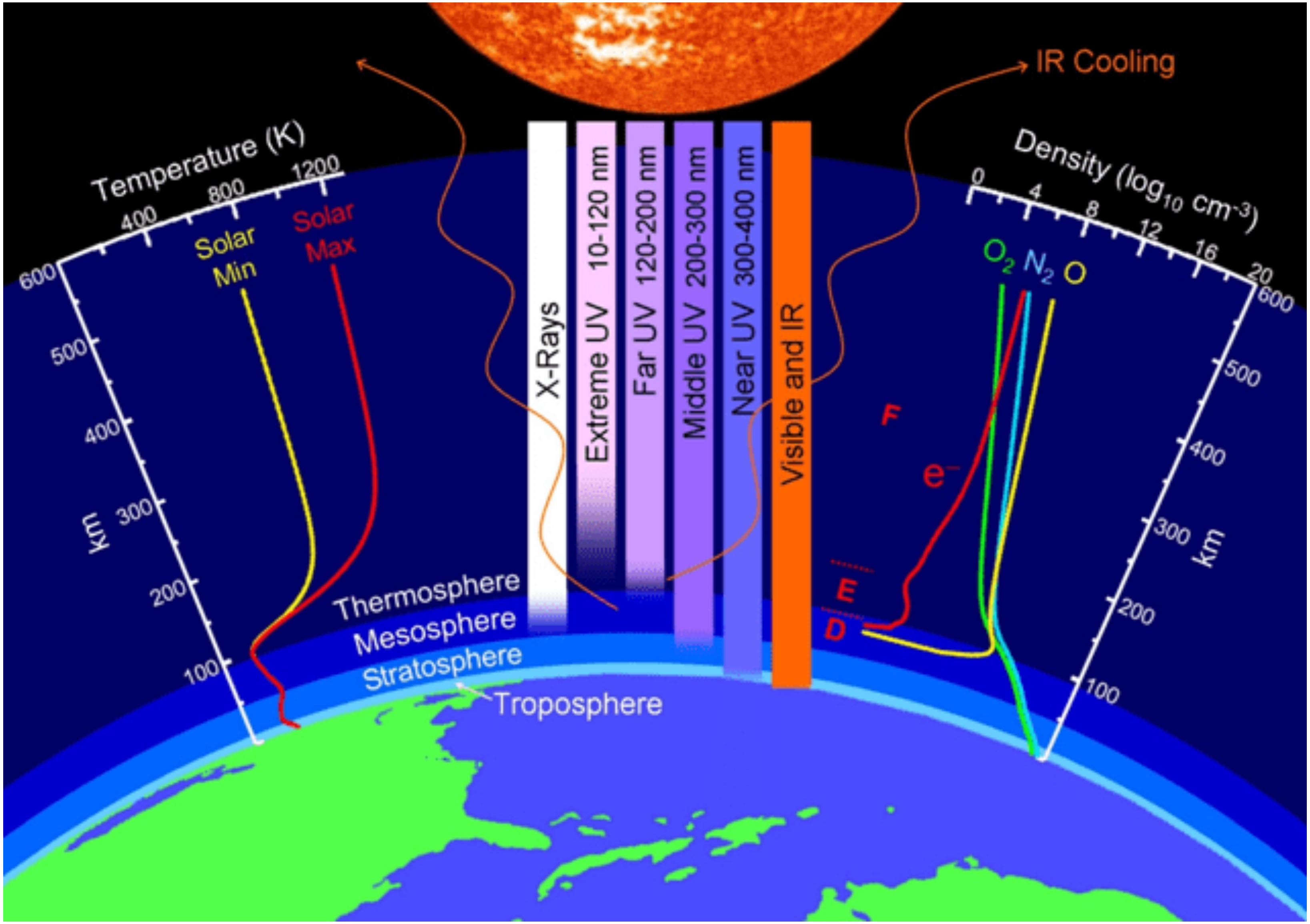
E
- ~ 100km daytime
- $F_p \sim 4$ Mhz
- Reflects some HF

F1
- ~180km daytime
- Combines with F2 at night
- $F_p \sim 5$ Mhz

F2
- ~ 325 km daytime
- $F_p \sim 8$ Mhz
- Most important layer for HF communications

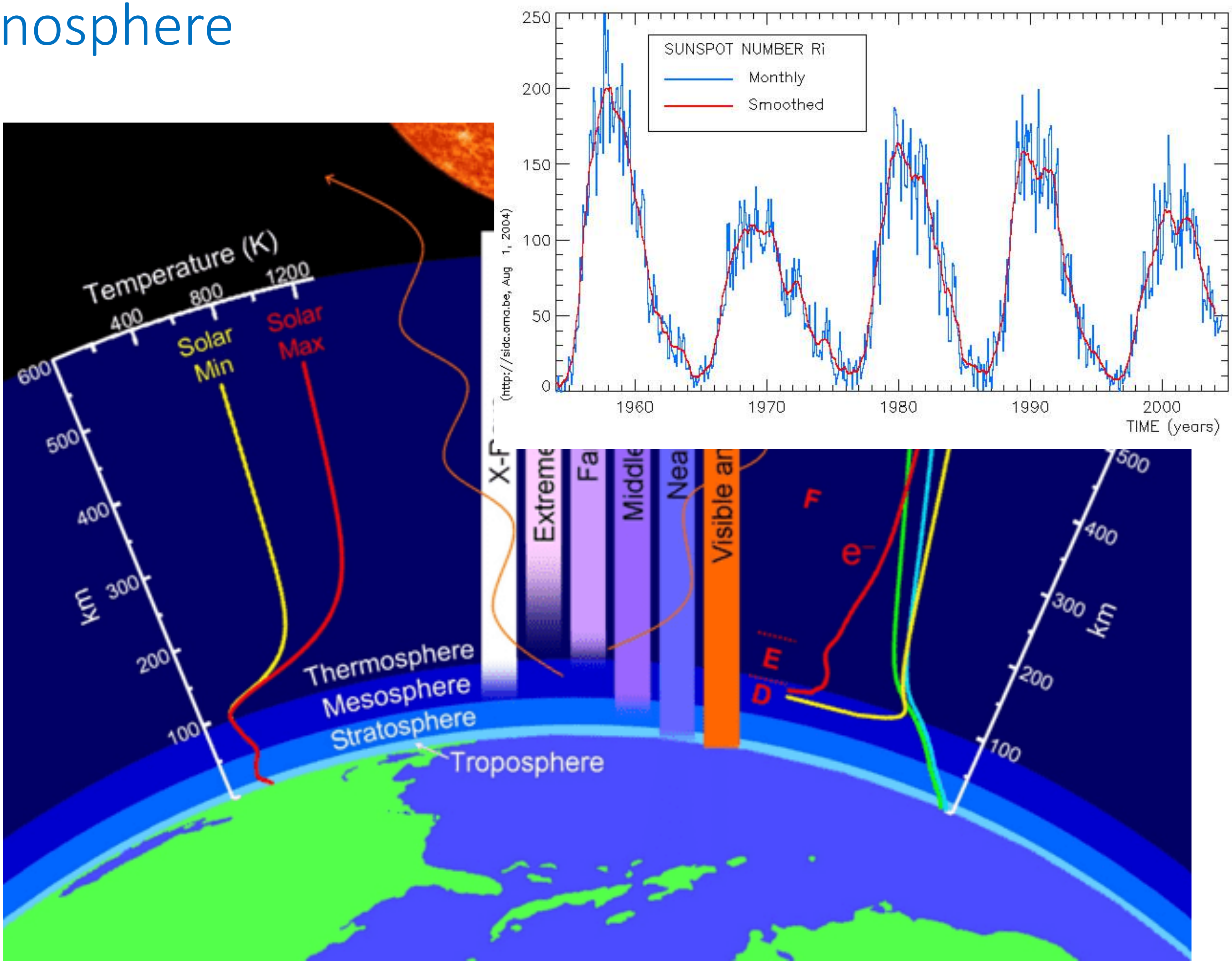


Ionosphere



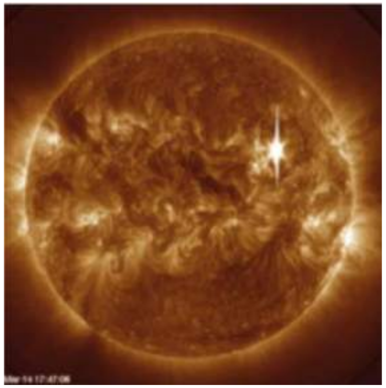
IR Cooling
Temperature (K)
400
800
1200
Solar Min
Solar Max
600
500
400
300
200
100
km
X-Rays
Extreme UV 10-120 nm
Far UV 120-200 nm
Middle UV 200-300 nm
Near UV 300-400 nm
Visible and IR
Thermosphere
Mesosphere
Stratosphere
Troposphere
Density ($\log_{10}$ cm^{-3})
0
4
8
12
16
20
O_2 N_2 O
F
e⁻
E
D

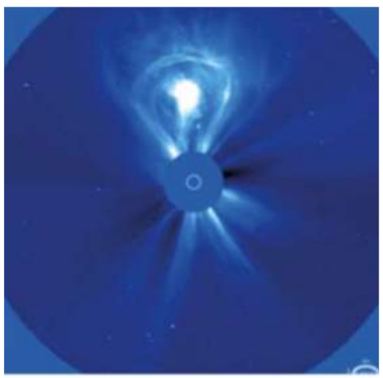
Ionosphere

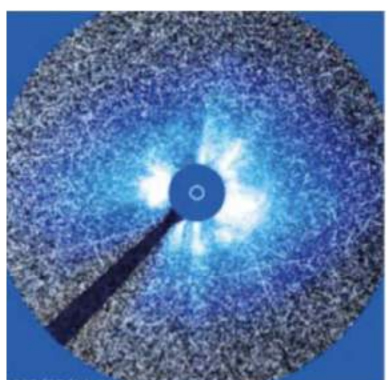


SUNSPOT NUMBER Ri
Monthly
Smoothed
250
200
150
100
50
0
1960
1970
1980
1990
2000
TIME (years)
(http://sidc.oma.be, Aug 1, 2004)
Temperature (K)
400
800
1200
600
500
400
300
200
100
km
Solar Min
Solar Max
Thermosphere
Mesosphere
Stratosphere
Troposphere
F
e⁻
E
D

Space weather







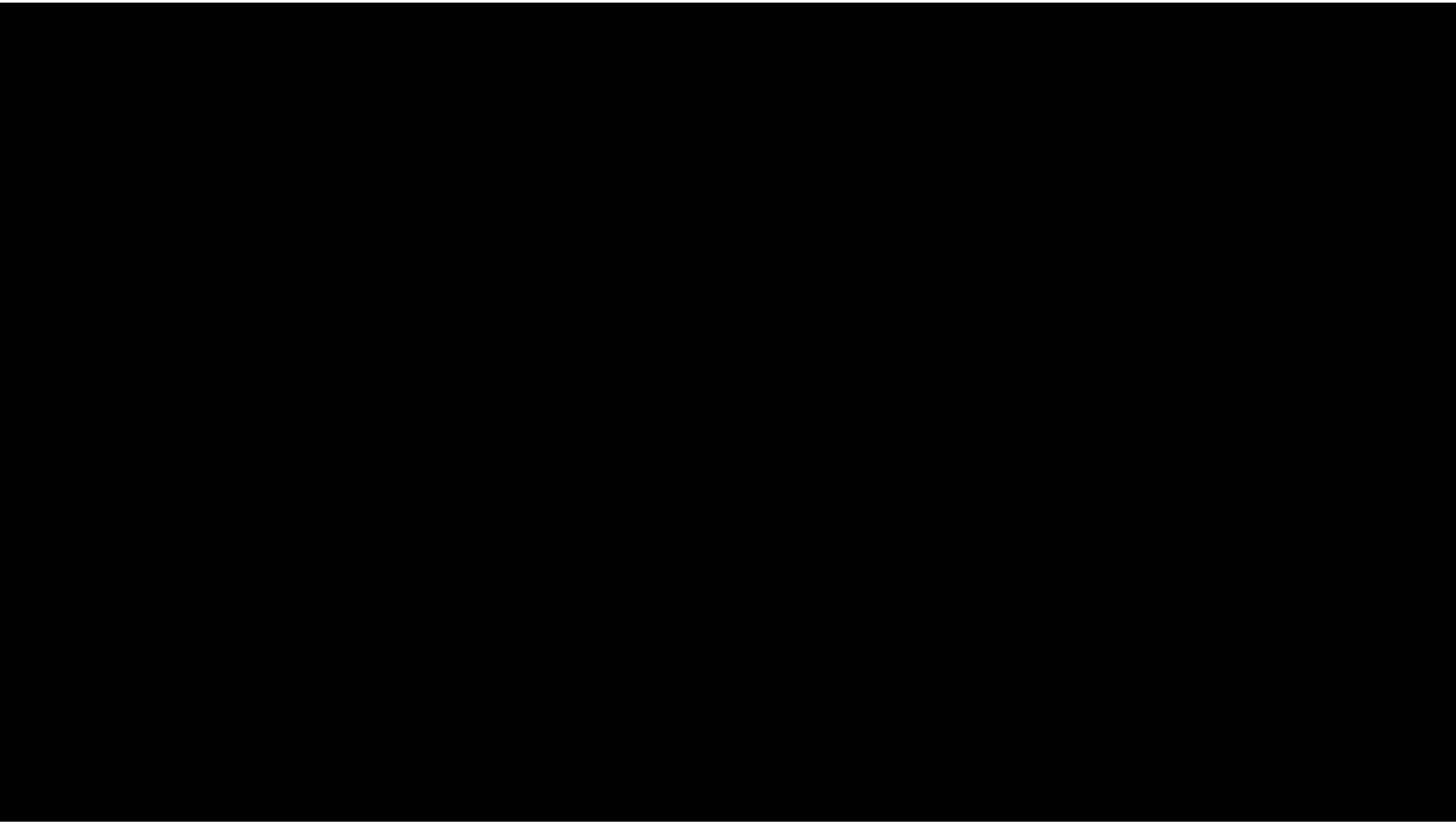
Space weather keywords

- **Solar flare:**
  a sudden burst of radiation including X-rays and UV from a localised region in the Sun's atmosphere.
- **Solar wind:**
  a constant but gusty outward flow of material into the Solar System.
- **Coronal mass ejection:**
  an ejection of electrically charged gas and magnetic field.
- **Solar energetic particles:**
  high-energy electrically charged particles that can travel with speeds close to the speed of light.
- **Geomagnetic storm:**
  temporary disturbance to the Earth's magnetic field.
- **Solar cycle:**
  the rise and fall of solar activity levels over an (approximately) 11-year timescale. Large space weather events can occur at any phase of the cycle.

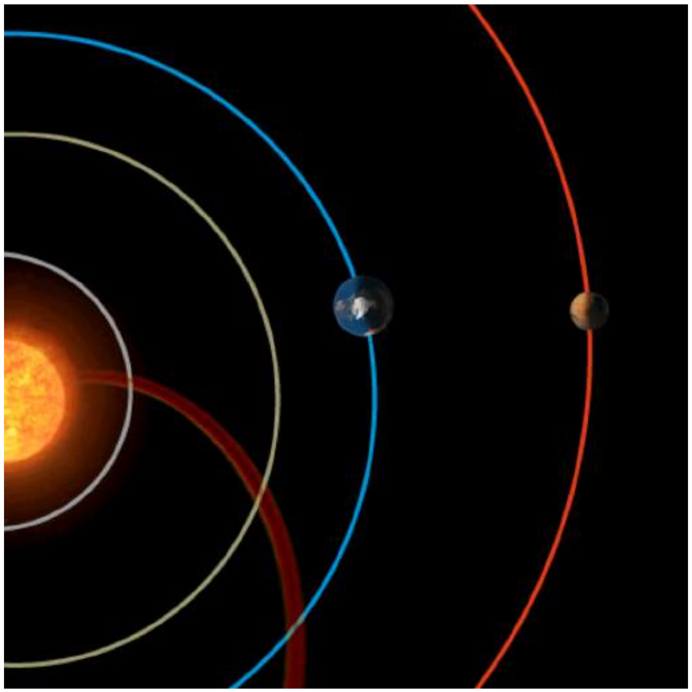
http://luciegreen.com/wp-content/uploads/2016/08/space_weather_and_finance.pdf

Ionosphere

The ionosphere responds strongly to solar eruptions.



Space weather



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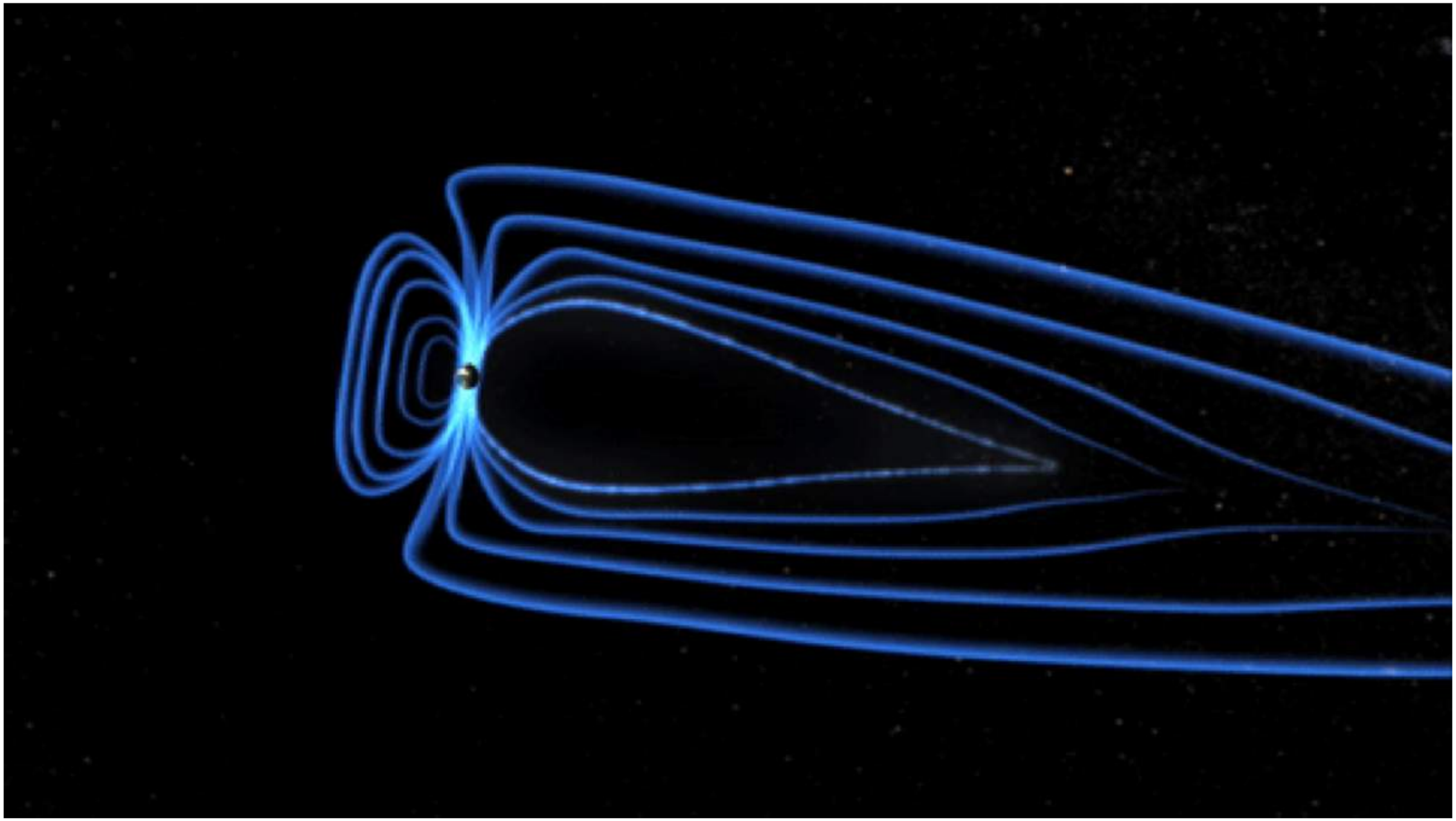
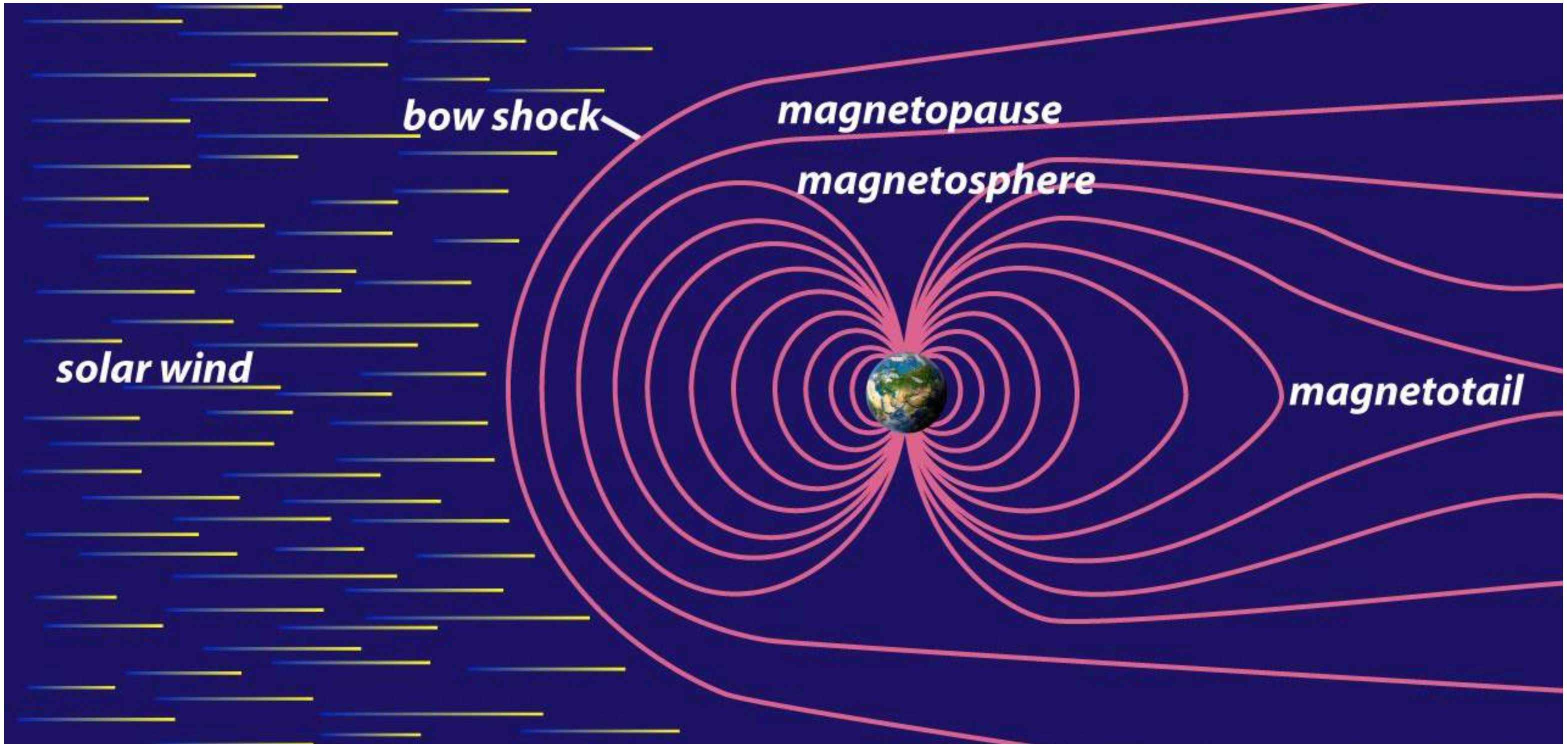
Magnetosphere



Magnetosphere

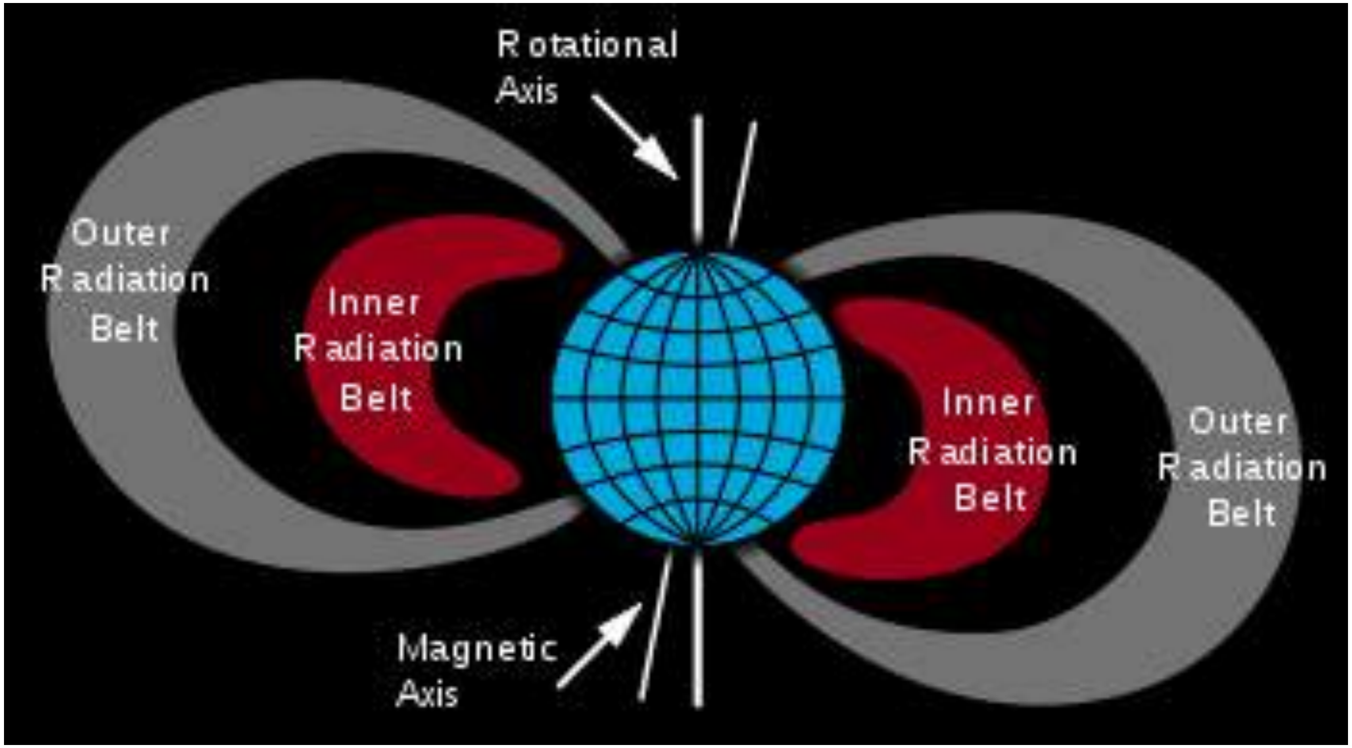
- Above 500 km collisions are infrequent and the Earth's magnetic field governs the motion of charged particles.
- The magnetic field provides a shield against the solar wind, which distorts the magnetic field.
- Solar outbursts impact the magnetic field and inject particles into the lower ionosphere, which produce auroral displays.



Van Allen Belts

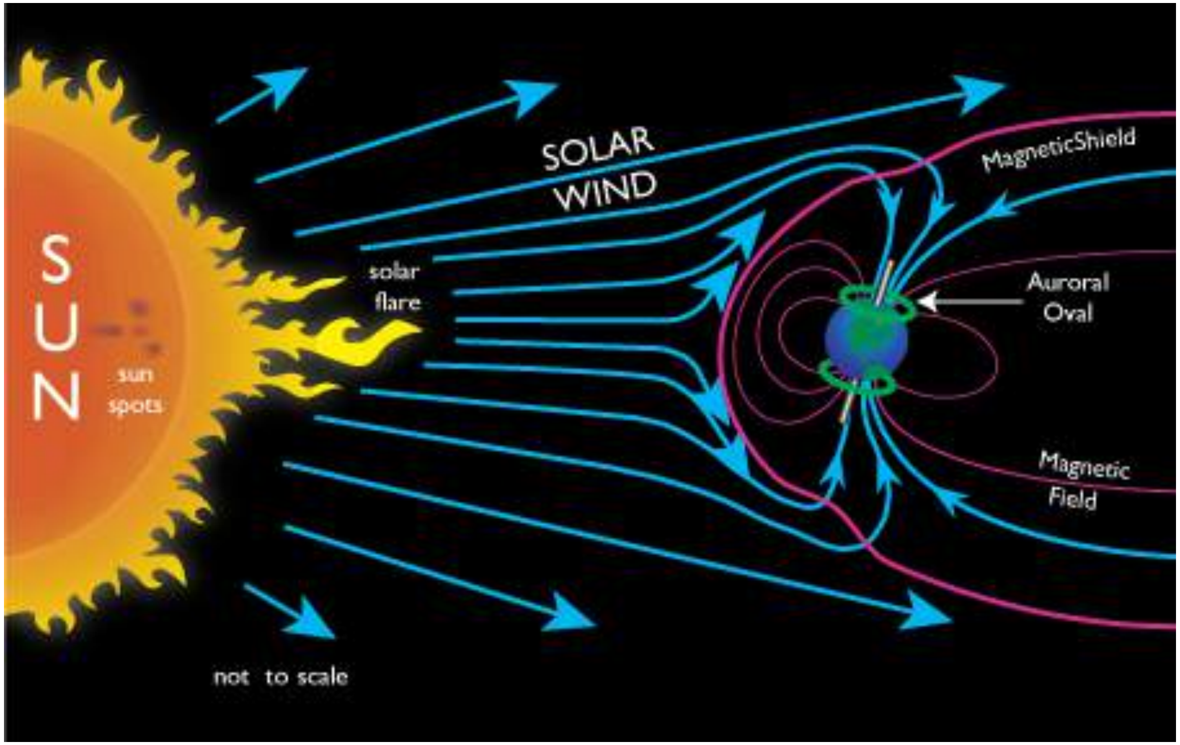
Charged particles that enter the magnetosphere experience a force perpendicular to their velocity and the magnetic field and travel around magnetic field lines from pole to pole (1s) and rotate around the earth.

- Inner belt: energetic protons (H^+) up to 100 MeV
- Outer belt: Mainly electrons 0.2 – 10 MeV and some ions O^+, He^+

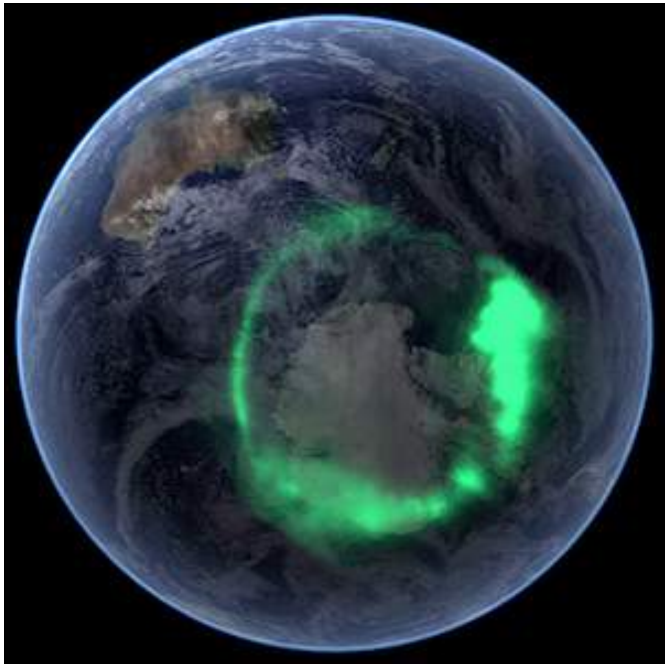


Aurorae

- Coloured lights in the sky at night in polar latitudes, mostly in an oval between 15° and 30° from the magnetic poles.
  - Aurora borealis = aurora in the Arctic
  - Aurora australis = aurora in the Antarctic
- Source: Atomic and molecular emissions from oxygen and nitrogen caused by ionisation by fast charged particles in the ionosphere. The particles do not originate from the solar wind but are produced by it.



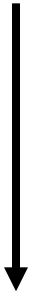
Aurorae



Red:
- 630 nm emission; oxygen

Green:
- 557.7 nm; atomic oxygen and nitrogen

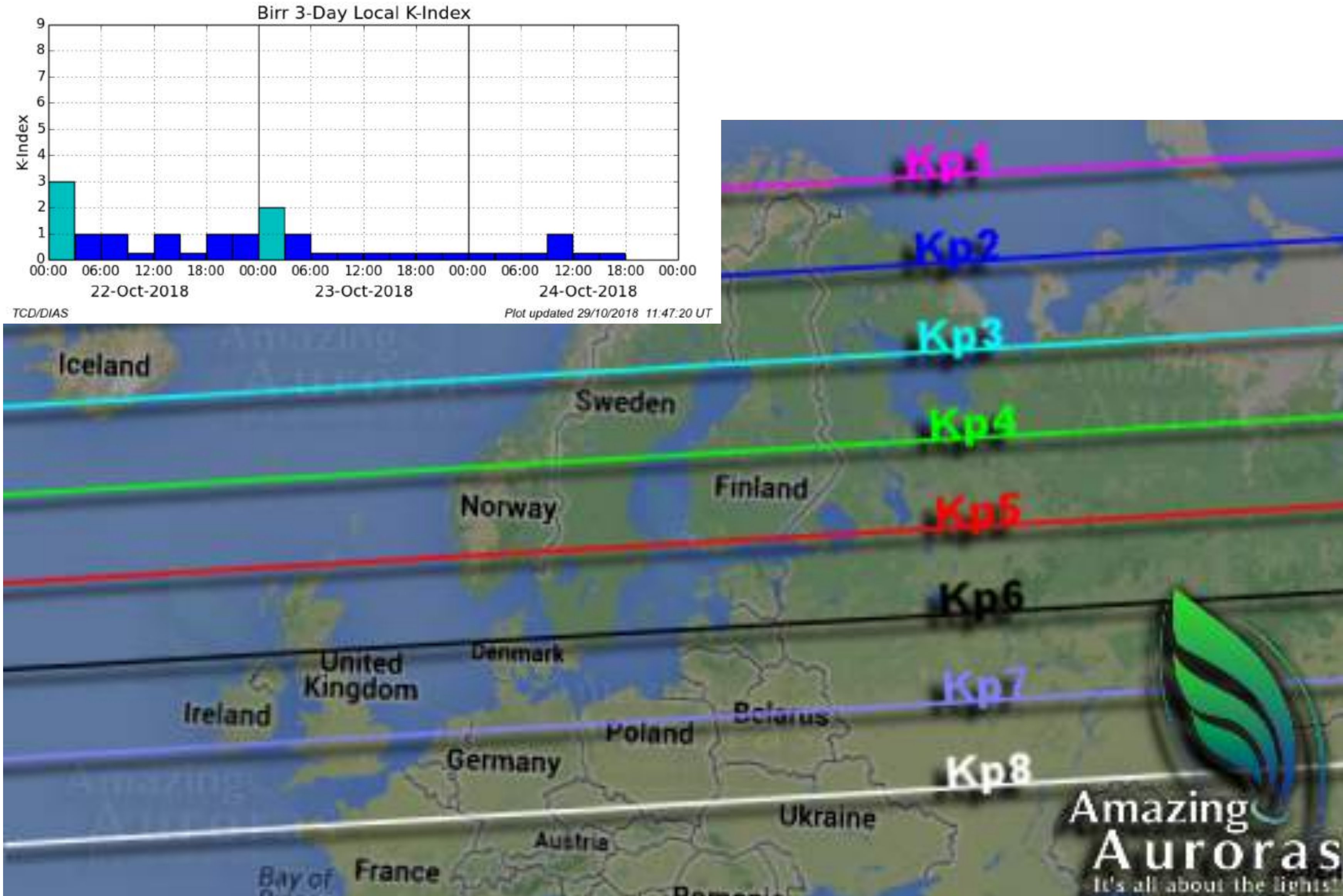
Blue:
- 428 nm; molecular and ionised nitrogen



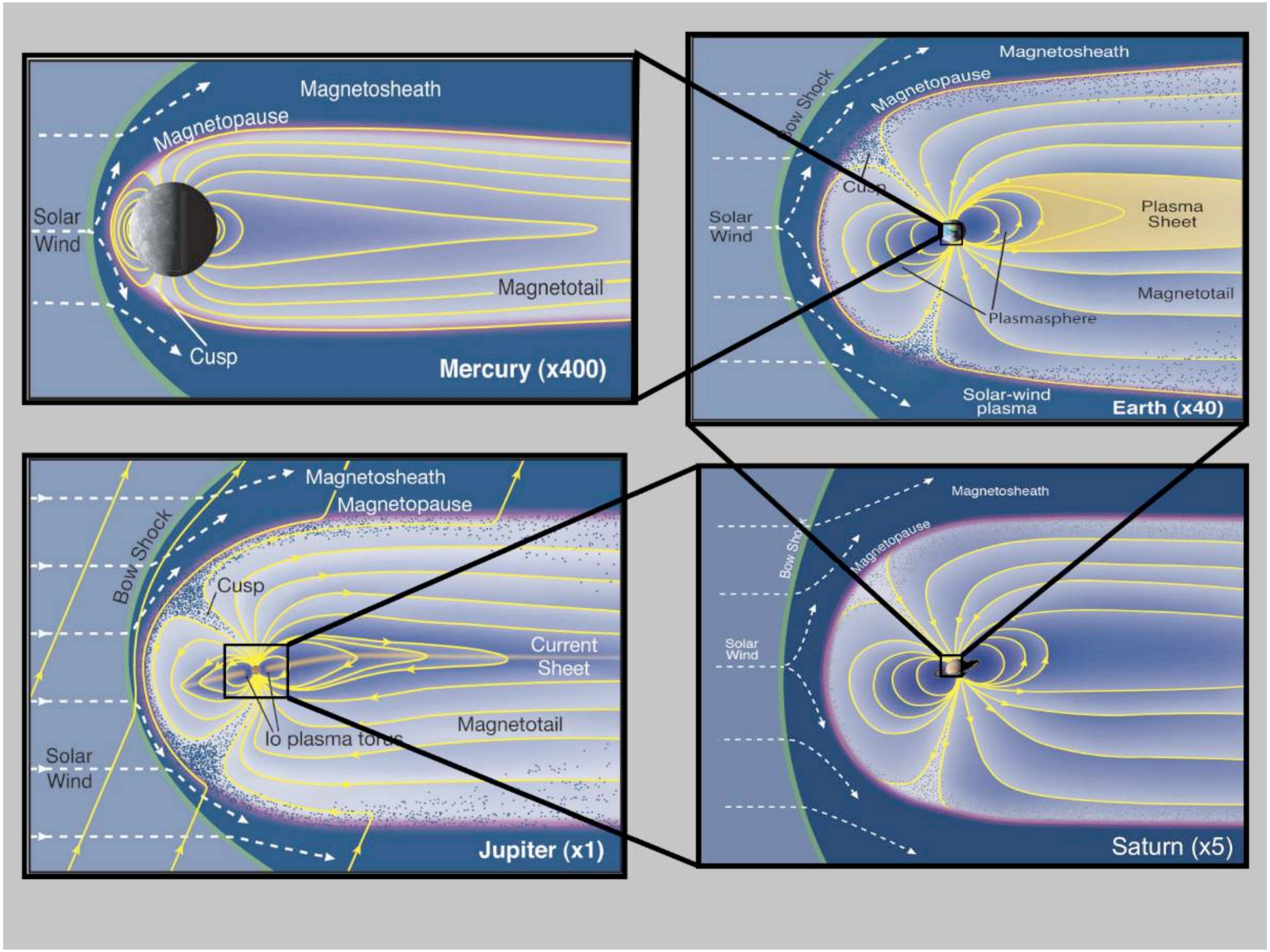
January 2012
Inishowen, Donegal
Adam Porter

Aurorae

http://www.rosseobservatory.ie/data



Magnetospheres of other planets



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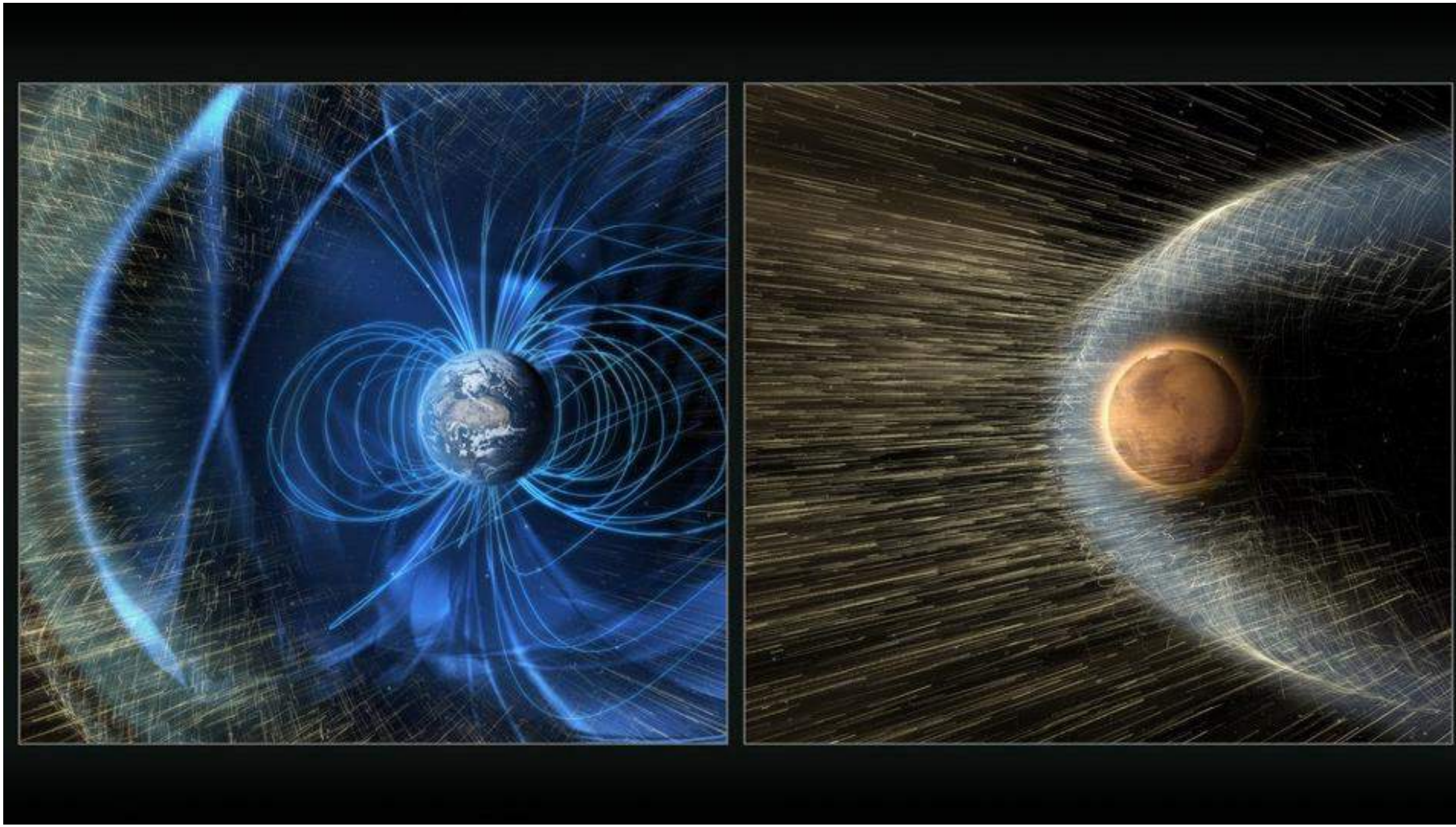


Escape velocity

Earth's atmosphere is only 1/1,200,000 the mass of Earth itself. So it is a very thin skin surrounding our planet.

How does Earth hold on to this thin skin of atmosphere?
Gravity – the same force that keeps us anchored to Earth keeps the atmosphere from flying off into space.

And yet the Earth does continually lose some of its atmosphere to space. This loss occurs in the upper atmosphere, over billion-year time scales.

Molecules in our atmosphere are constantly moving, spurred on by energizing sunlight. Some move quickly enough to escape the grip of Earth's gravity.

Escape velocity and molecule collisions

mgh

A moving body (a molecule in this case) can leave the Earth's gravitational field if its kinetic energy is larger than the potential energy needed to overcome the gravitational field. It depends only on altitude and at 500 km is of the order of 11 km s^{-1}.

If the speed of a molecule is high enough, and at the same time the mean free path is long enough, it may leave the atmosphere.
The speed depends on temperature and mass, and the mean free path on density.

Typical values for mean free path are

- 200 km: 200 m
- 100 km: 15 cm
- 0 km: 0.06 µm

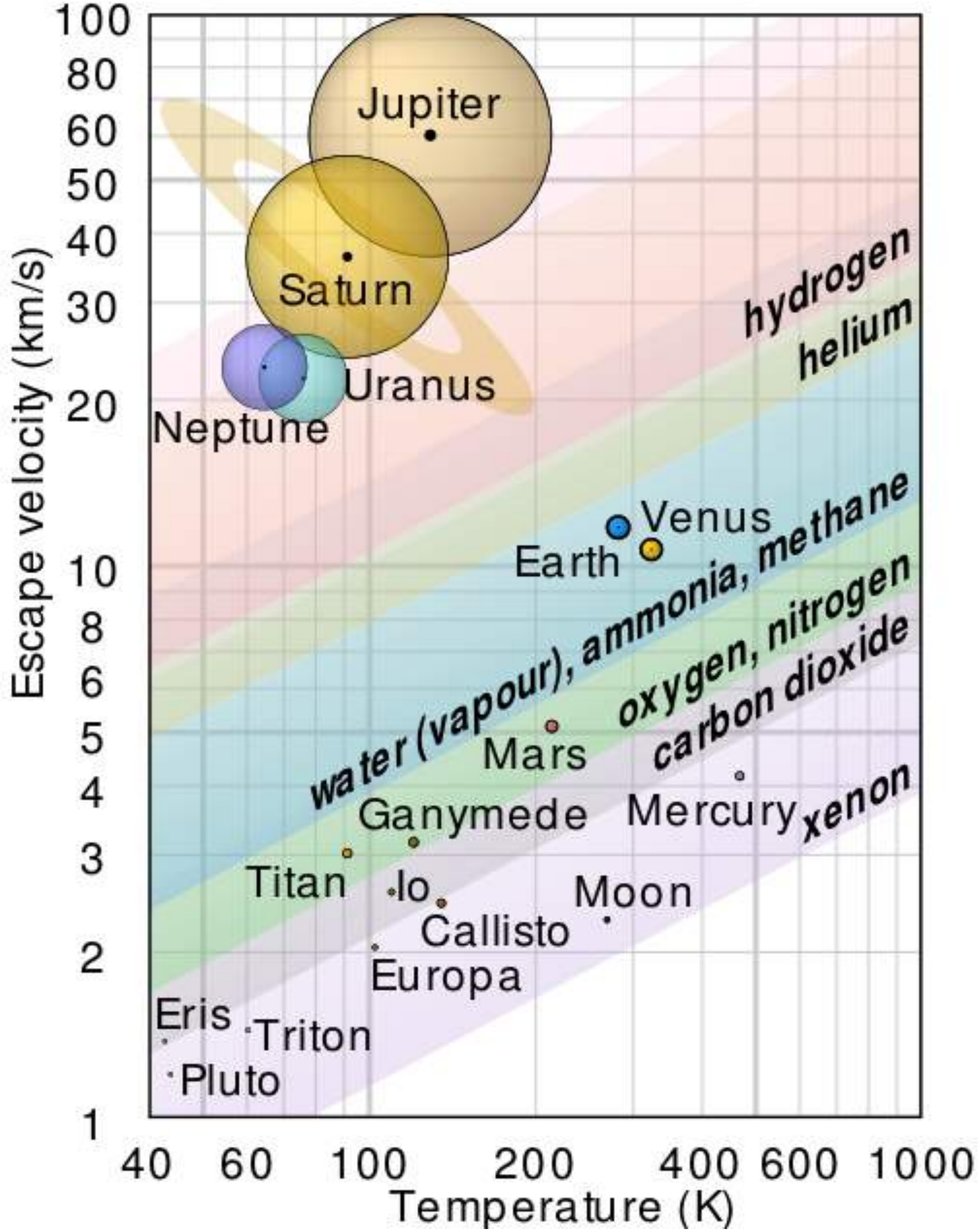
Escape velocity and molecule collisions

Below 100 km (**homosphere**), collisions between molecules are so frequent that all constituents are well mixed and no separation is possible. Above that altitude, the different scale heights come into effect (**heterosphere**).

Lecture 2

From the Maxwell-Boltzmann velocity distribution, there is a probability of about 10^{-6} for each collision that atomic hydrogen is faster than 11 km s^{-1}, and thus can escape the atmosphere. For O_2, the probability is of the order of 10^{-84}, and thus escape is negligible.

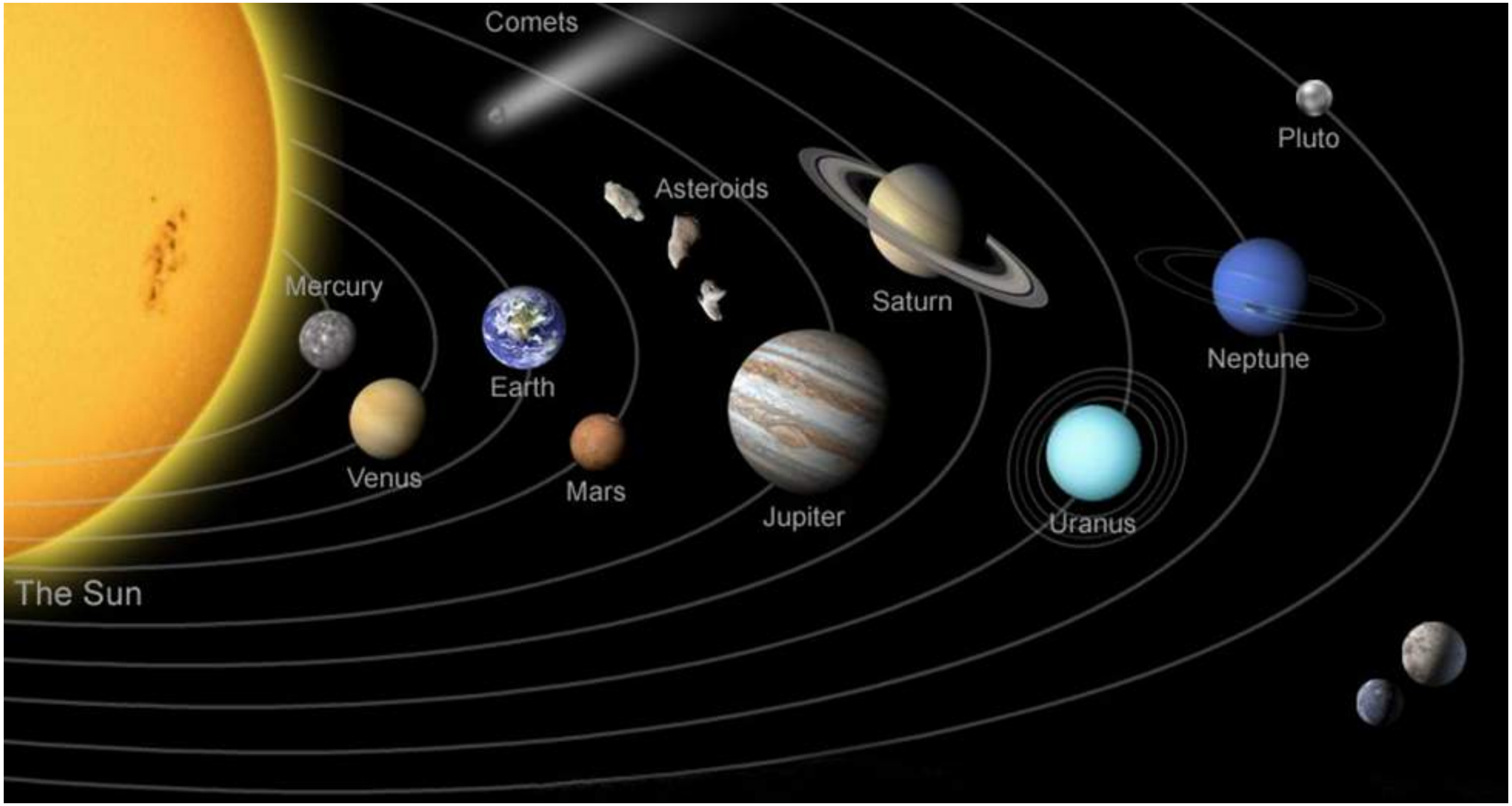
Light elements, like hydrogen and helium, typically move faster than heavier ones, like oxygen and nitrogen. The light atoms are more likely to reach escape velocity and escape to space, hence why light molecules are rare in our atmosphere (in contrast to their abundance in the universe at large).



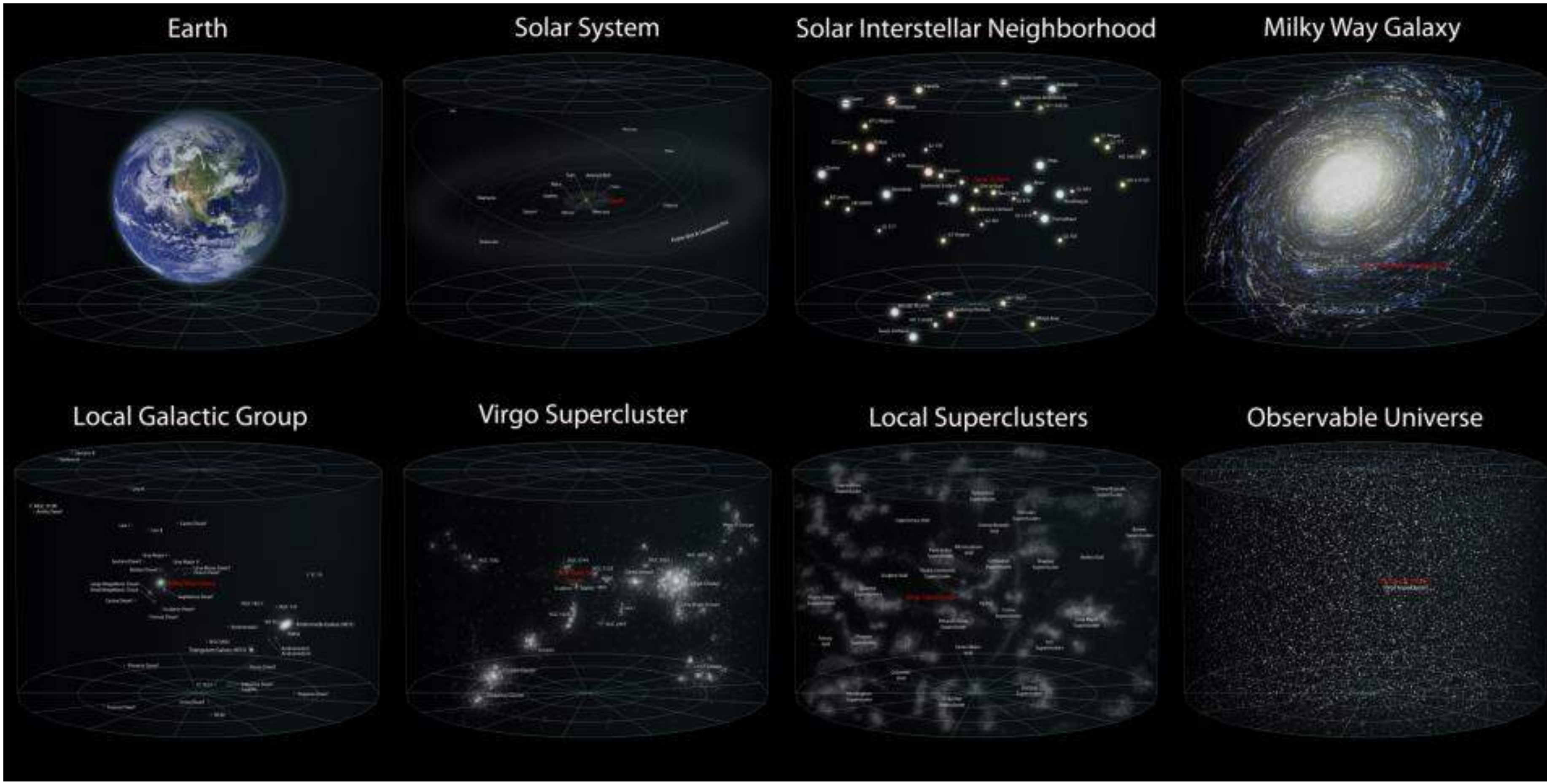
Atmospheric escape mechanisms:

https://en.wikipedia.org/wiki/Atmospheric_escape

Earth in Space

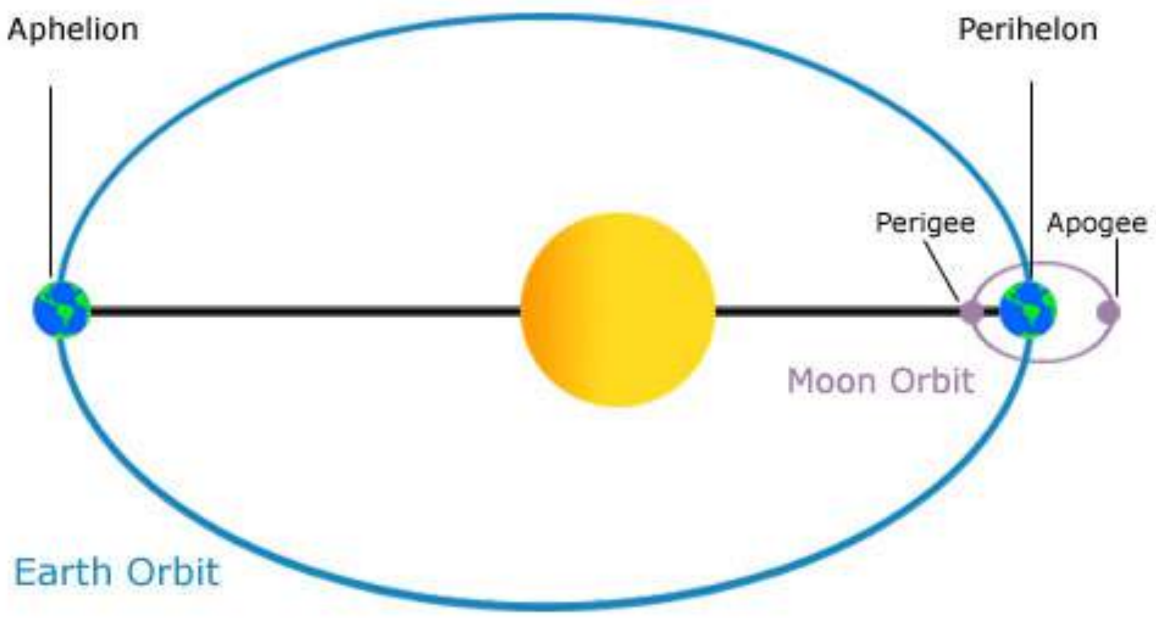


Earth in Space



Earth in Space

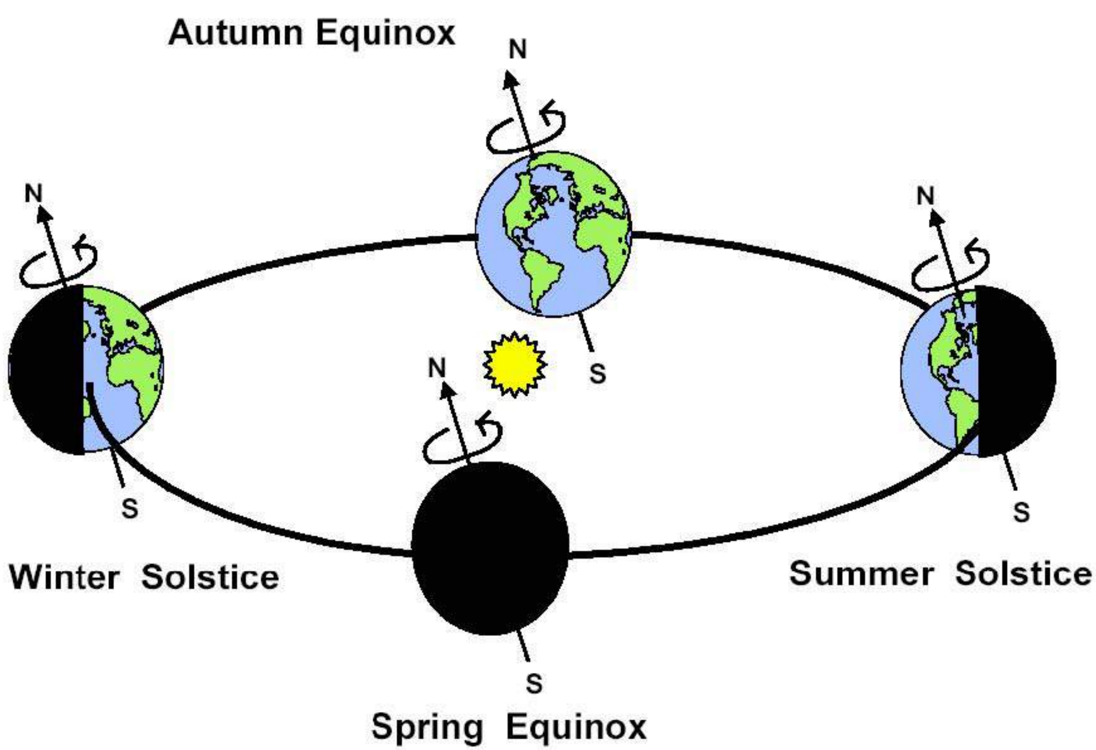
Earth's orbit around the Sun is slightly elliptical (149.6 x 10^8 – 152 x 10^8 km).



Earth in Space

Earth's axis of rotation is tilted at 23.5° to ecliptic plane (plane of Earth orbit around Sun).

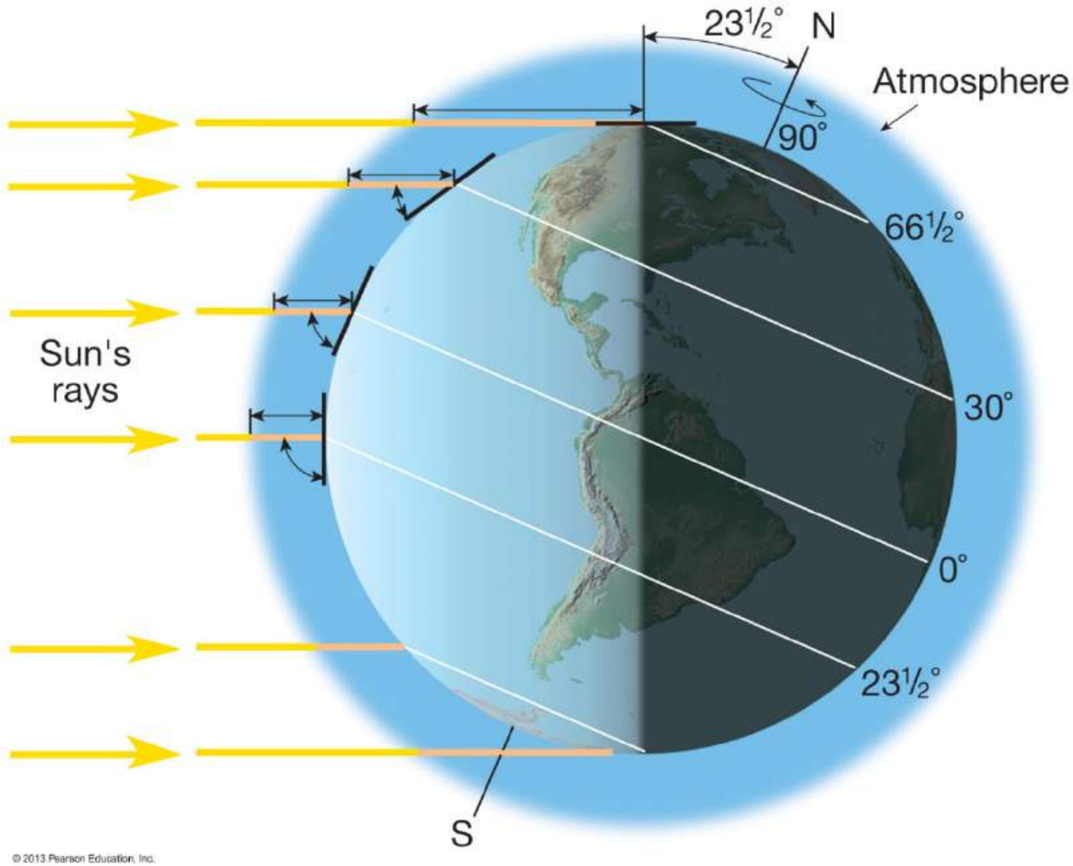
- Seasons due to tilt of rotation axis relative to ecliptic, not elliptical orbit.
- During summer, there is 24 hour daylight in regions North of the arctic cycle, depending on date. During winter, the pole is without solar illumination. Two equinoxes (21 March and 23 December).



Earth in Space

The solar power per unit area reaching the Earth varies with latitude and during the year due to

- variation of the angle at which the sunlight strikes the surface,
- variation in the length of daylight.

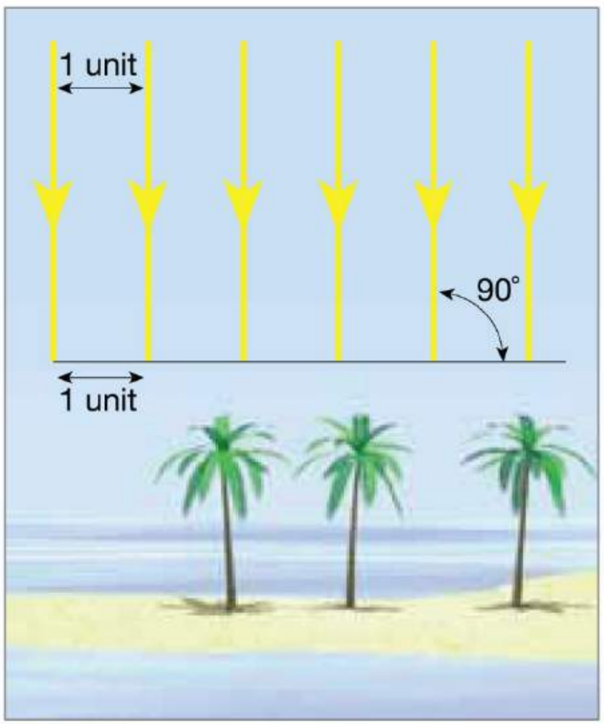


December solstice

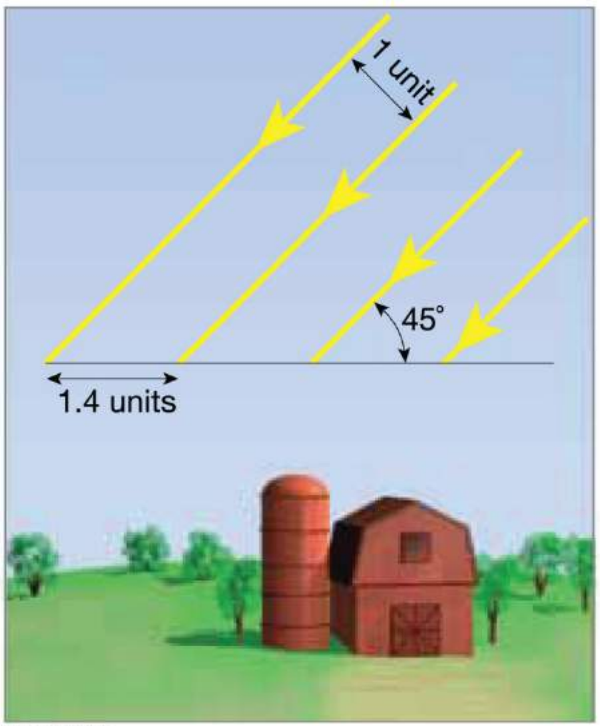
Earth in Space

Variation of the angle at which the sunlight strikes the surface

When sunlight falls on the Earth's surface the power input varies as sin θ, where θ is the angle between the Sun's rays and the surface



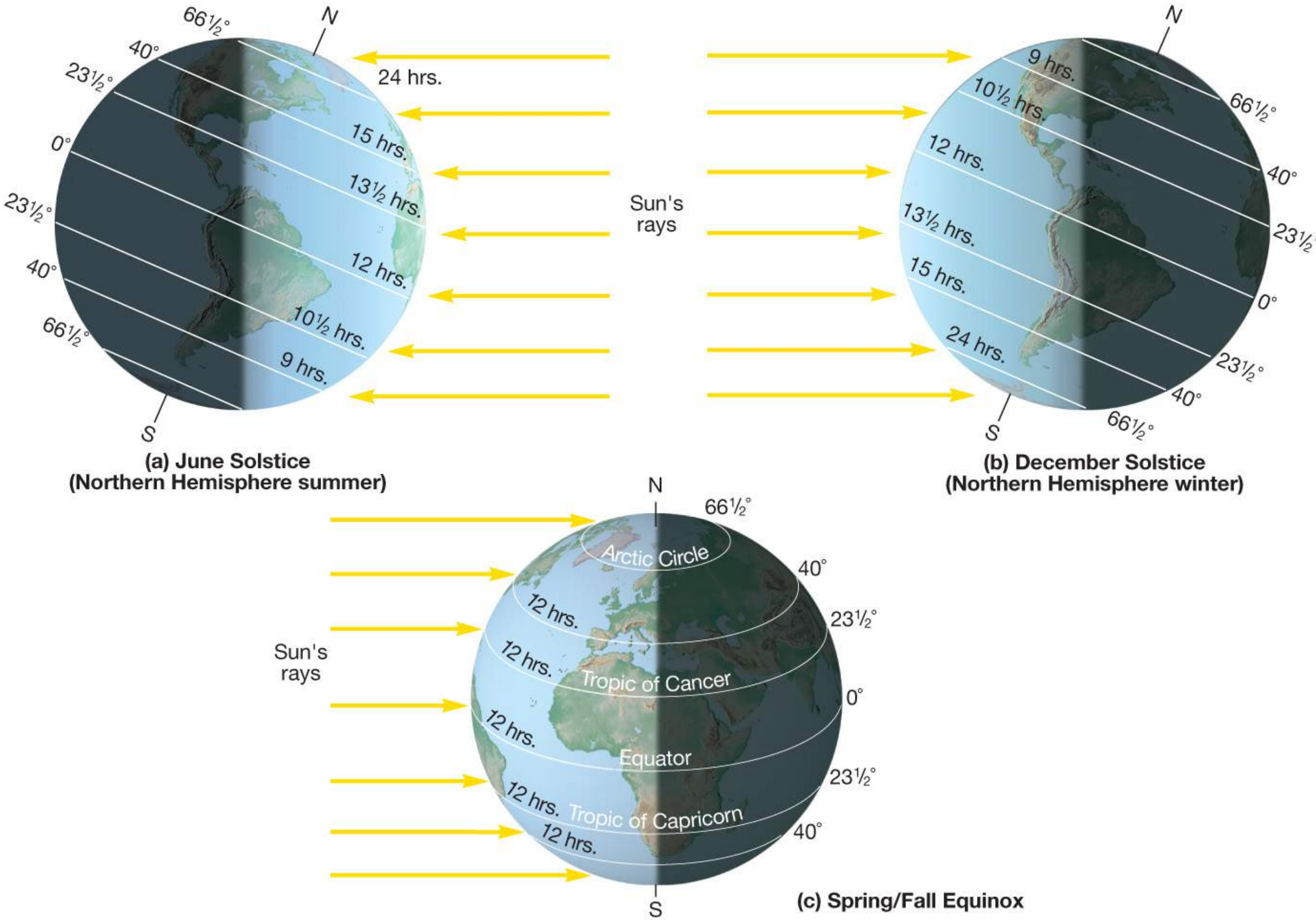
$\sin(90^o) = 1$



$\sin(45^o) = 0.7$

Earth in Space

Variation in the length of daylight



(a) June Solstice (Northern Hemisphere summer)

(b) December Solstice (Northern Hemisphere winter)

(c) Spring/Fall Equinox

Summary

Ionosphere
- Layers
- Plasma frequency
- Impact from the Sun

Magnetosphere on Earth and other planets
- Impact frpm the Sun

Atmospheric escape

Earth in space
- How days, seasons, etc work

Next week (November 12):
Radiation, Tutorial # 1, and handouts for problem sheet #2