# Space physics EF2240


***Tomas Karlsson***

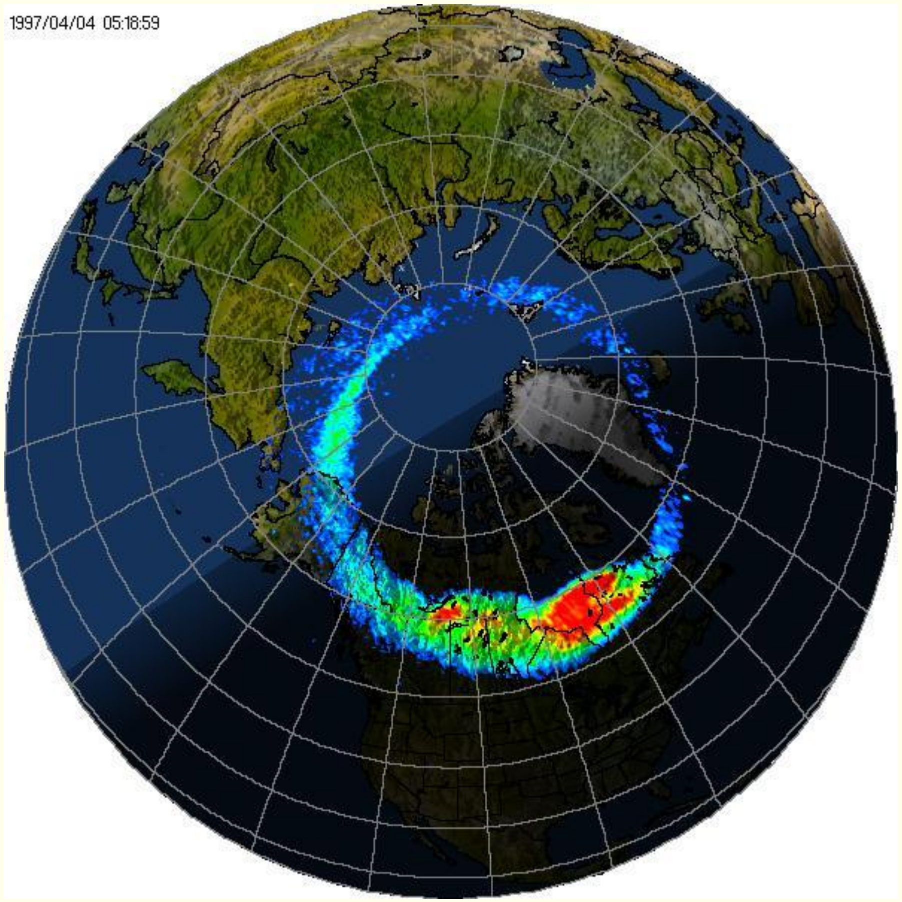
Space and Plasma Physics

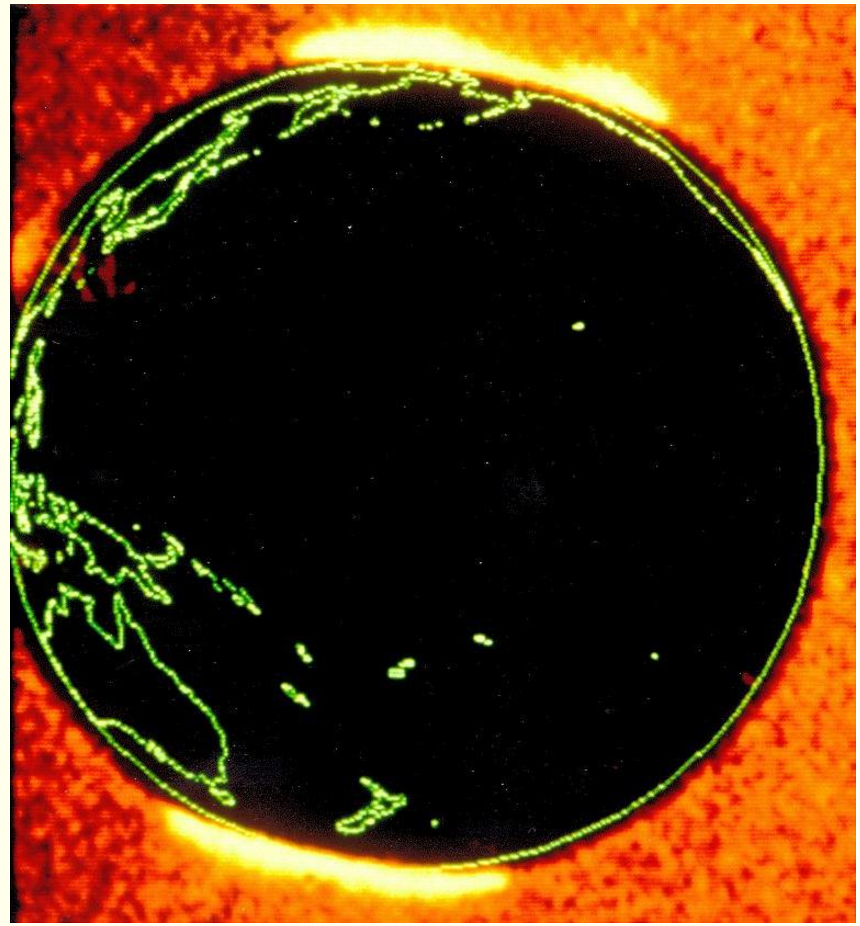
*School of Electrical Engineering*

**What is this?**

# Clue...

# The auroral ovals



# Definition of Space Physics

- **Studies of space in Earth's vicinity with the help of *in situ* measurements (unique for this area, cf. astronomy and astrophysics).**

- **More than 99% of matter in space is in the *plasma* state.**

- **Alternative names:**
  - ***Space plasma physics***
  - ***Solar-terrestrial physics (incl. space weather)***

# Schedule

10×2 h Lectures

6×2 h Tutorials

L = Lecture, T = Tutorial

| Activity | Date | Time | Room | Subject | Litterature |
|---|---|---|---|---|---|
| L1 | 28/8 | 15-17 | Q21 | Course description, Introduction, The Sun 1 | **CGF** Ch 1.1,1.2, 1.4, 5, (p 110-113), 6.3 |
| L2 | 29/8 | 13-15 | Q2 | The Sun 2, Plasma physics 1 | **CGF** Ch 1.3, 5 (p 114-121) |
| L3 | 4/9 | 10-12 | E2 | Solar wind, The ionosphere and atmosphere 1, Plasma physics 2 | **CGF** Ch 6.1, 2, 3.1-3.2, 3.5, **LL** Ch III, Extra material |
| T1 | 6/9 | 8-10 | Q21 | Mini-group work 1 | |
| L4 | 6/9 | 15-17 | Q2 | The ionosphere 2, Plasma physics 3 | **CGF** Ch 3.4, 3.7, 3.8 |
| T2 | 10/9 | 15-17 | Q21 | Mini-group work 2 | |
| L5 | 11/9 | 10-12 | E3 | The Earth's magnetosphere 1, Plasma physics 4 | **CGF** 4-1-4.3, **LL** Ch I, II, IV.A |
| T3 | 17/9 | 8-10 | Q21 | Mini-group work 3 | |
| L6 | 18/9 | 13-15 | Q33 | The Earth's magnetosphere 2, Other magnetospheres | **CGF** Ch 4.6-4.9, **LL** Ch V. |
| L7 | 19/9 | 13-15 | Q2 | Aurora, Measurement methods in space plasmas and data analysis 1 | **CGF** Ch 4.5, 10**,** **LL** Ch VI, Extra material |
| T4 | 24/9 | 8-10 | Q2 | Mini-group work 4 | |
| L8 | 24/9 | 15-17 | V3 | Space weather and geomagnetic storms | **CGF** Ch 4.4, **LL** Ch IV.B-C, VII.A-C |
| T5 | 2/10 | 8-10 | Q31 | Mini-group work 5 | |
| L9 | 2/10 | 13-15 | Q2 | Alfvén waves, Interstellar and intergalactic plasma, Cosmic radiation | **CGF** Ch 7-9, Extra material |
| T6 | 8/10 | 15-17 | Q21 | | |
| L10 | 9/10 | 10-12 | Q2 | Guest Lecture by Swedish astronaut Christer Fuglesang | |
| Written examination | 16/10 | 14-19 | L21, L22, L31 | | |

# Preliminary guest lecturer

## Swedish astronaut Christer Fuglesang
## Lecture 10

# Course goals

At the end of the course you should be able to:

• define what a plasma is, and classify various types of plasma.

• describe the plasma physical properties of various regions of space, with emphasis of the near-earth region.

• explain how some important plasma populations in the solar system (e.g. Earth's ionosphere and magnetosphere) get their basic properties and how these properties can vary between the planets.

• make order of magnitude estimates of some properties of space plasmas and space physics phenomena, for example the power dissipated in the aurora or the magnitude of electric currents floating from the magnetosphere into the ionosphere.

• make simple analyses of measurement data from satellites and ground-based instruments. (E.g. calculate currents in space from magnetometer data.)

• make simple models of some space physics phenomena by applying basic physical laws expressed with simple mathematics. (An example would be to model the basic shape of the magnetosphere or estimate the temperature of a sunspot.)

• describe to interested laymen or "the man in the street" what we can learn from space physics and how it affects our everyday life (for example by various space weather phenomena.)

# Examination

1. Written examination (open book*), 18/10

100 p

2. Continous examination (mini-group works)

25 p

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Grades:

| | |
|---|---|
| A: | 111-125 p |
| B: | 96-110 p |
| C: | 81-95 p |
| D: | 66-80 p |
| E: | 50-65 p |

(Fx)

# Written examination,
# 16/10 2012, 14.00-19.00, L21, L22, L31

(*) You may bring:

- all the course material
- any notes you have made
- pocket calculator
- mathematics and physics formula books or your favourite physics book
- formula sheet

(No computers are allowed, due to the possibility to communicate with the outside world.)

Approx. 5 different problems (which may contain sub-problems).

The character of the problems is such that to get a high score you will have to show that you have obtained a certain course goal, e.g. to make a reasonable order of magnitude estimate or figure out a simple model for some space physics phenomenon.

# Continous examination
# Mini-group works

5 mini-group works
(5×5 p = 25 p)

*Approx. 1 h during Tutorials 1-5*

- *A problem similar to those on the written examination is given*
- *Groups of 3 (randomized).*
- *Elect a secretary!*
- *Write down a solution!*

# Litterature

- C-G. Fälthammar, ”Space Physics” (compendium), 2nd Ed, Third Printing, 2001.
- Larry Lyons, ”Space Plasma Physics”, from *Encyclopedia of Physical Science and Technology, 3rd edition, 2002.*
- Lecture notes and extra material handed out during lectures.

# Course home page

*KTH Social:*

https://www.kth.se/social/course/EF2240/

*At the home page I will post new information continuously. Here you can also find lecture notes, exercises (and some solutions), etc.*

# Last Minute!

**What was the most important thing of today's lecture? Why?**

**What was the most unclear or difficult thing of today's lecture, and why?**

**Other comments:**

# Study the Course Description carefully!

# EF22445 Space Physics II
# 7.5 ECTS credits, P2

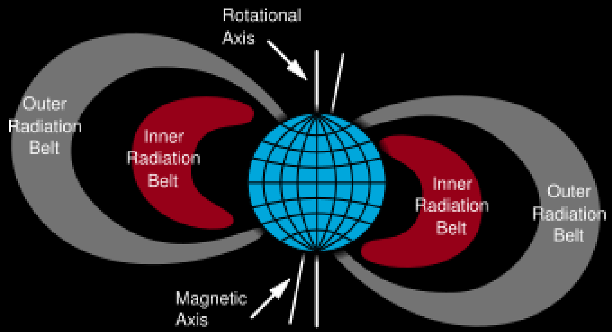
- shocks and boundaries in space
- solar wind interaction with magnetized and unmagnetized bodies
- reconnection
- sources of magnetospheric plasma
- magnetospheric and ionospheric convection
- auroral physics
- storms and substorms
- global oscillations of the magnetosphere

## Courses at the Alfvén Laboratory

# EF2260 SPACE ENVIRONMENT AND SPACECRAFT ENGINEERING , 6 ECTS credits, period 2

- environments spacecraft may encounter in various orbits around the Earth, and the constraints this places on spacecraft design
- basic operation principles underlying the thermal control system and the power systems in spacecraft
- measurements principles in space

*The Astrid-2 satellite*




*Radiation environment in near-earth space*

## Projects:

- Design power supply for spacecraft
- Study of radiation effects on electronics

What is a plasma?

Where in the universe can you find it?

# Plasma

***E.g. Water***

**1 eV ~ 11600 K**

T

| | |
|---|---|
| Plasma | ~$10^5$ K *( H: 13.60 eV, ionization* <br> *O: 13.61 eV, ionization )* |
| | ~$10^4$ K *(5 eV, dissociation)* |
| Gas | |
| | 373 K |
| Liquid | |
| | 273 K |
| Solid | |

***Definition:*** A plasma is an ionized gas, showing collective behaviour.

”Fourth state of matter ”

Somewhat misleading:

- *No phase transition*
- *Ionization can be caused by other mechanisms than heating, e.g. UV radiation.*

# Energy - temperature

Average energy of molecule/atom:

$$E = \frac{3}{2} k_B T \quad \Rightarrow$$

$$T = \frac{2E}{3k_B}$$

1 eV = $1.6 \cdot 10^{-19}$ J $\Rightarrow$

$$T = \frac{2E}{3k_B} = \frac{2 \cdot 1.6 \cdot 10^{-19}\,\mathrm{J}}{3 \cdot 1.38 \cdot 10^{-23}\,\frac{\mathrm{J}}{\mathrm{K}}} = 7729\,\mathrm{K}$$

# But beware!

## In plasma physics, usually:

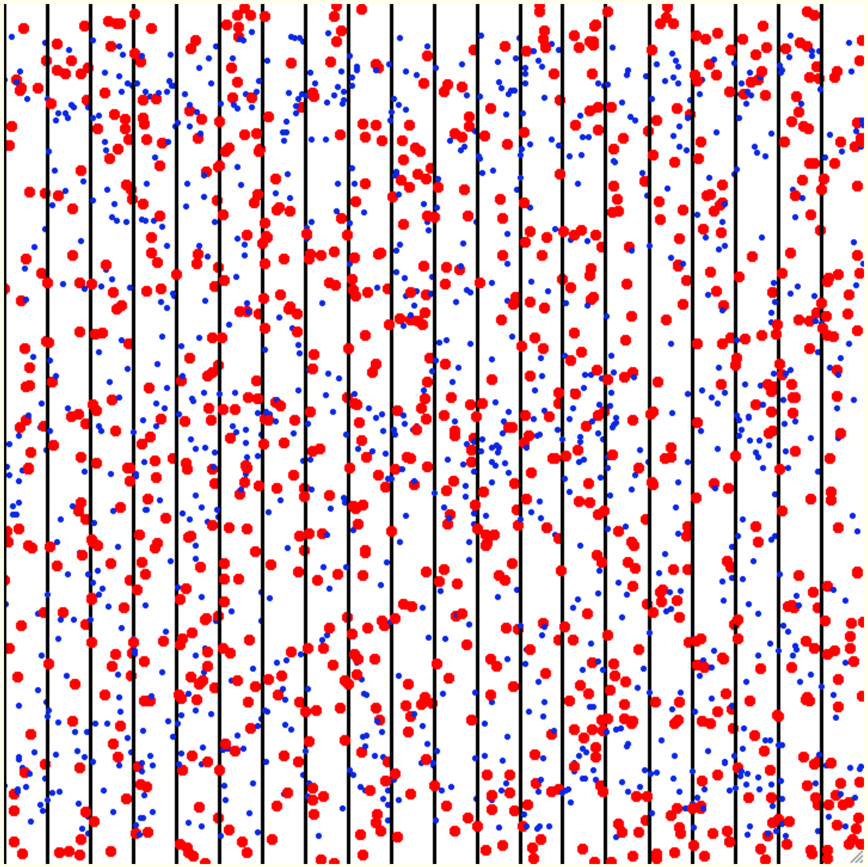
$$E = \cancel{\frac{3}{2}} k_B T \quad \Rightarrow$$

$$T = \frac{E}{k_B}$$

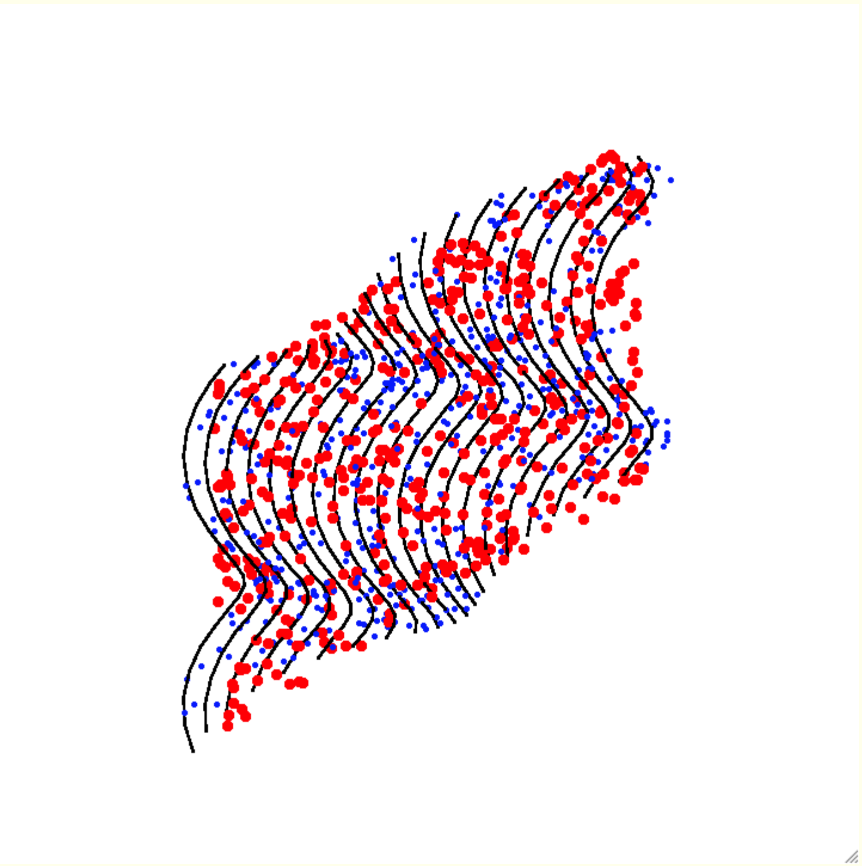
1 eV = 1.6·10$^{-19}$ J $\Rightarrow$

$$E = k_B T = \frac{1.6 \cdot 10^{-19}\,\mathrm{J}}{1.38 \cdot 10^{-23}\,\dfrac{\mathrm{J}}{\mathrm{K}}} = 11594\,\mathrm{K}$$

# Example of collective behaviour: Plasma waves

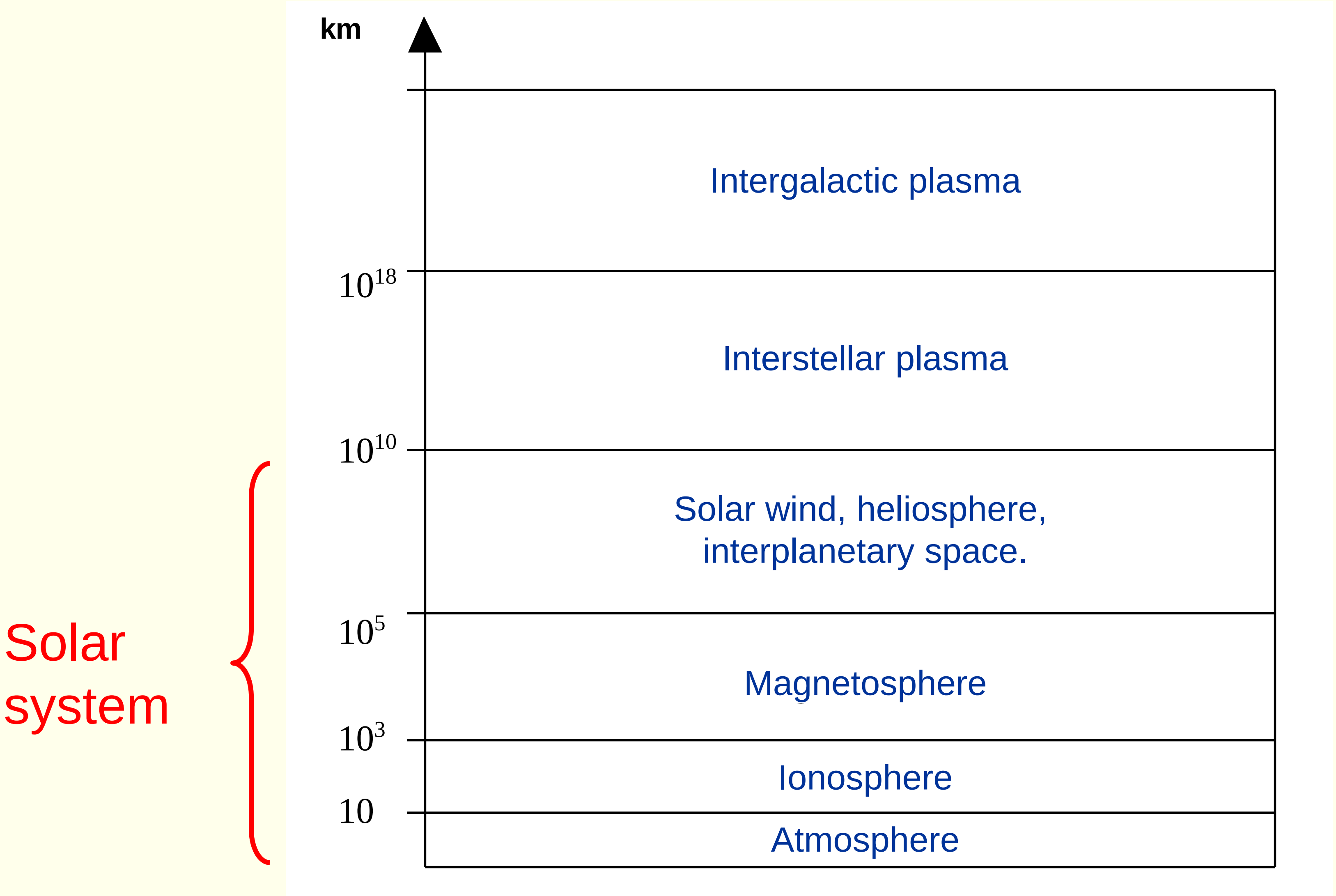


Electron plasma waves

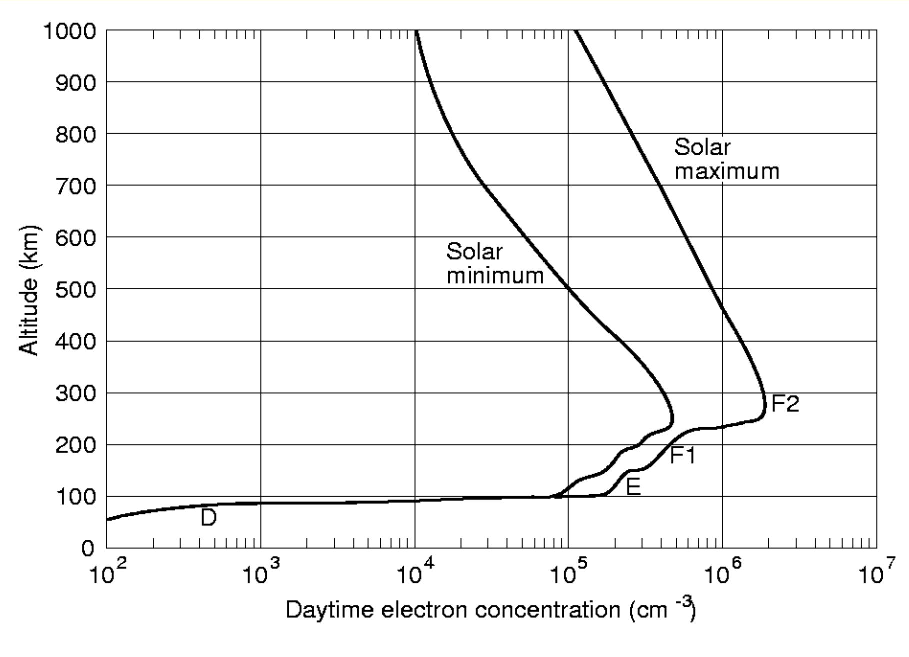


Whistler waves

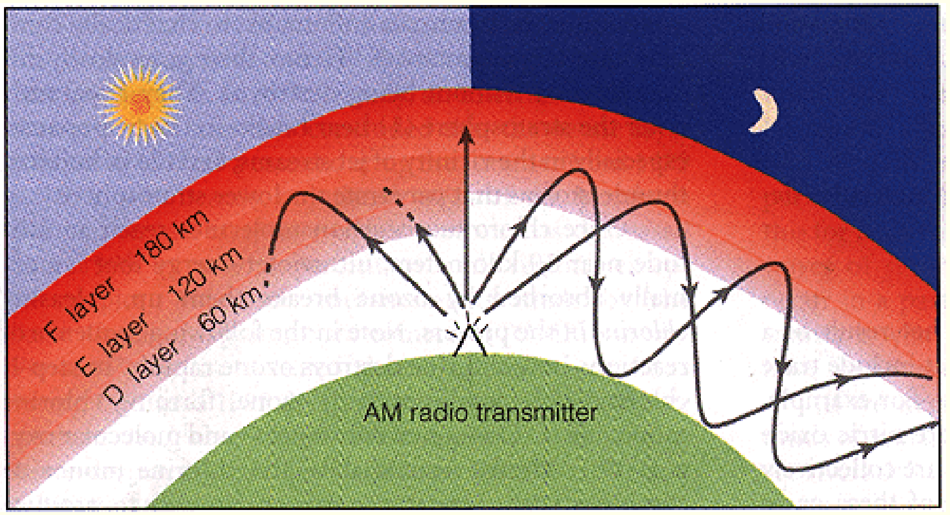
# From atmosphere to intergalactic plasma!



# Ionosphere

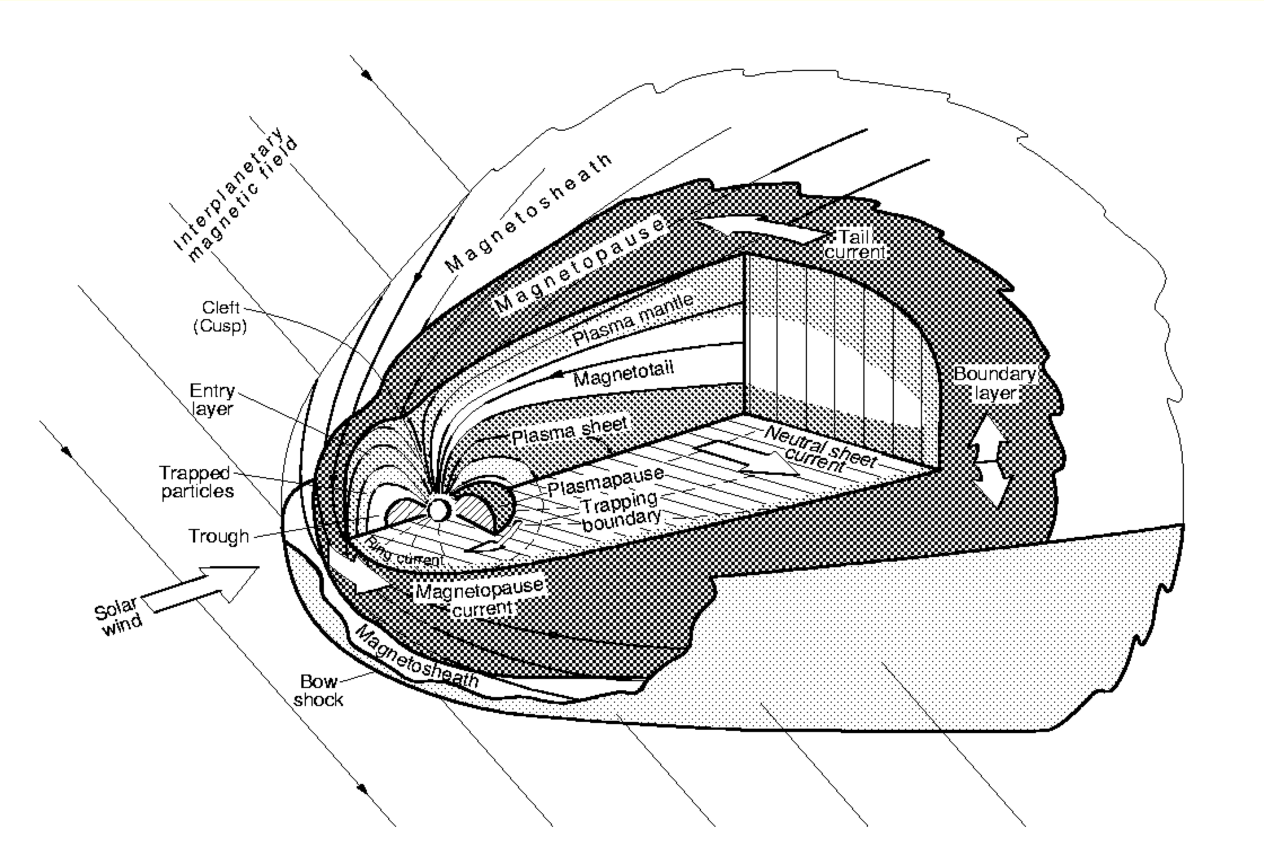


1000
900
800
700
600
500
400
300
200
100
0
Altitude (km)
$10^2$
$10^3$
$10^4$
$10^5$
$10^6$
$10^7$
Daytime electron concentration ($cm^{-3}$)
Solar maximum
Solar minimum
F2
F1
E
D

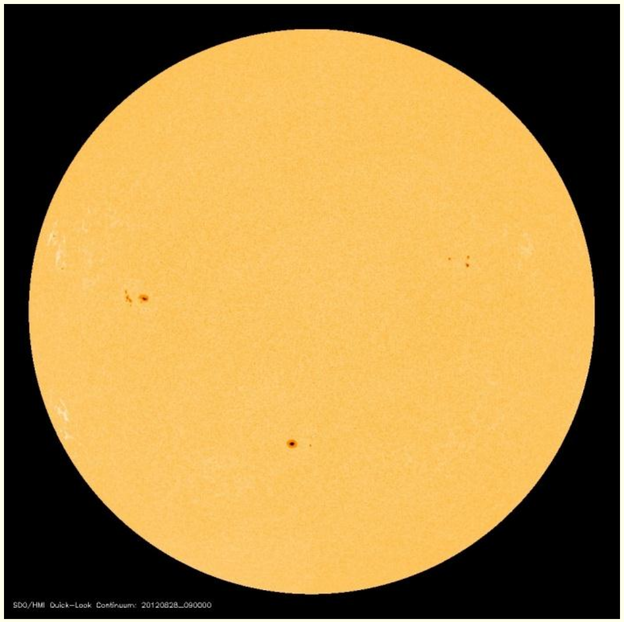
F layer 180 km
E layer 120 km
D layer 60 km
AM radio transmitter

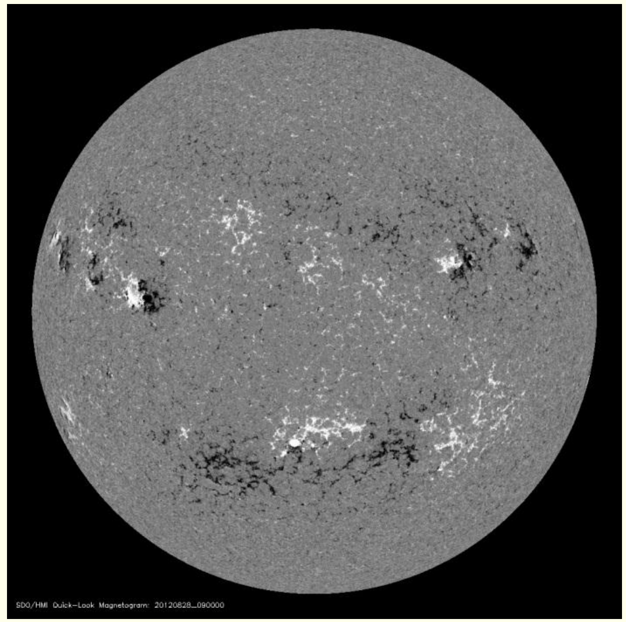
# Magnetosphere

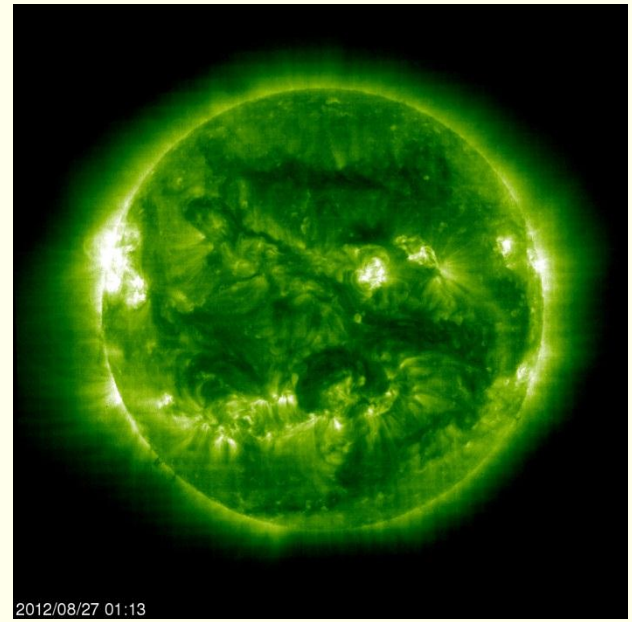



**Definition:** *That region in space where the geomagnetic field is the dominating magnetic field.*

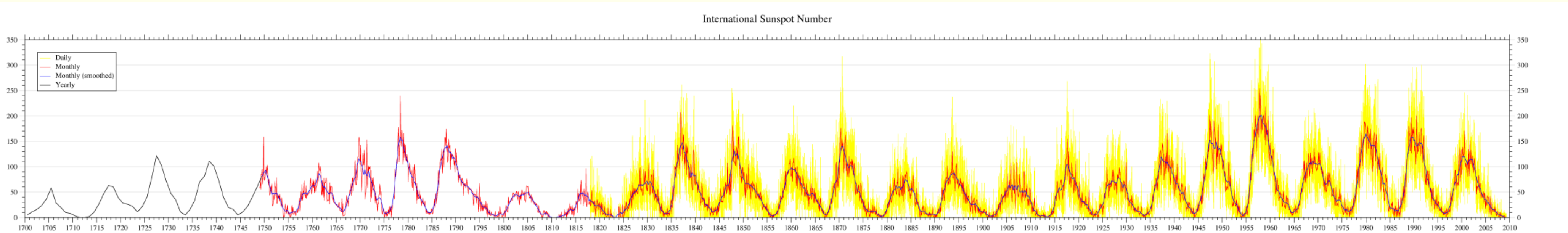
# The sun (2012-08-23)
## SOHO observations



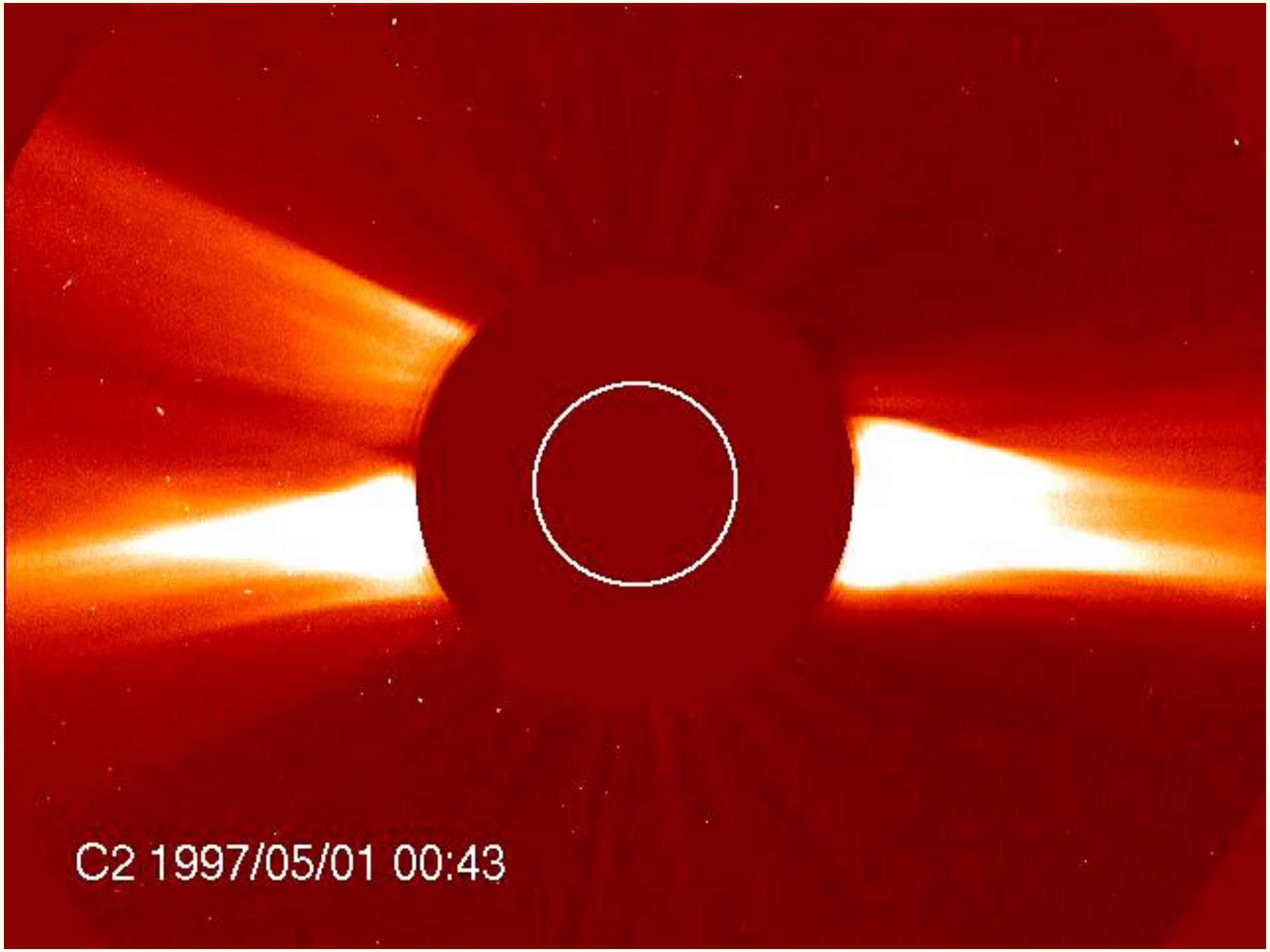




*Visible light* *Magnetogram* *SOHO EUV (Fe XV)*

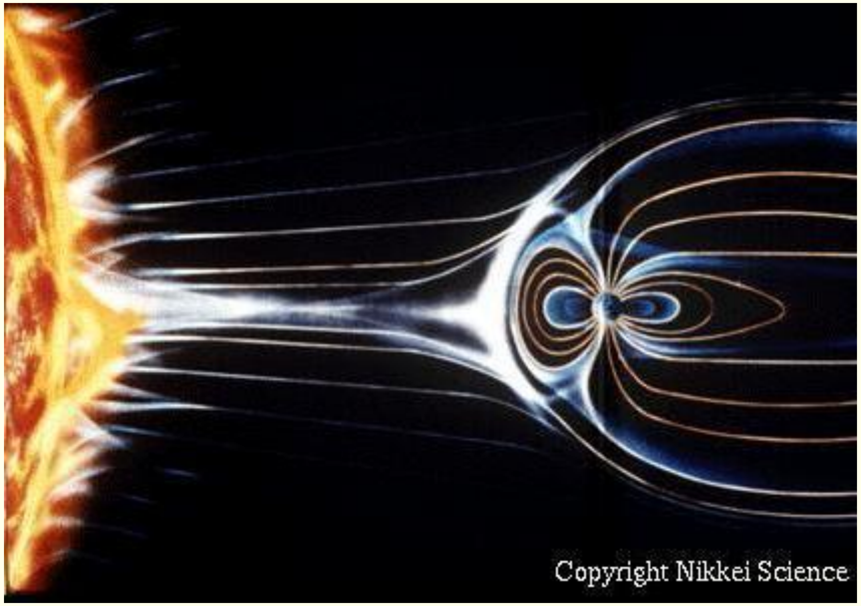


# The sun, solar wind

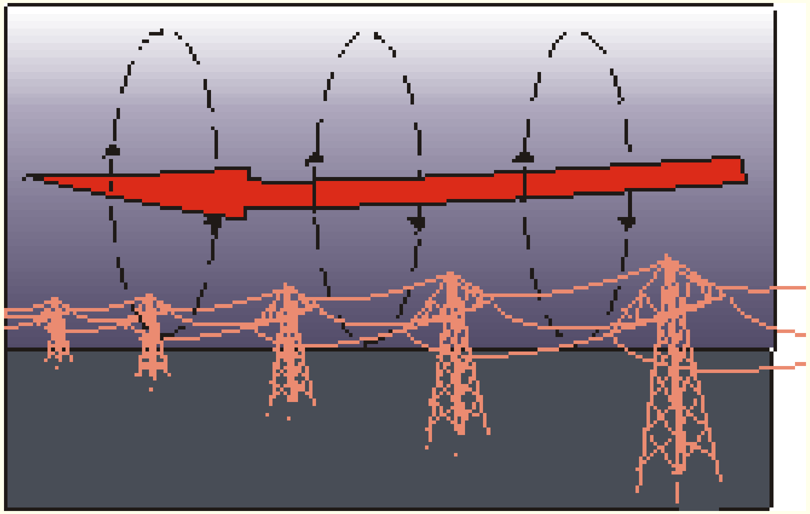


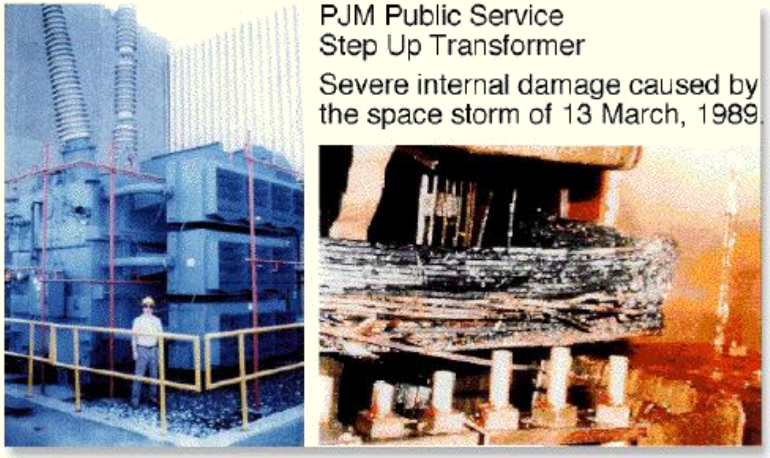

**Solar and Heliospheric Observatory (SOHO),**
***LASCO C2 Coronagraph Movie***

# Solar-terrestrial interaction

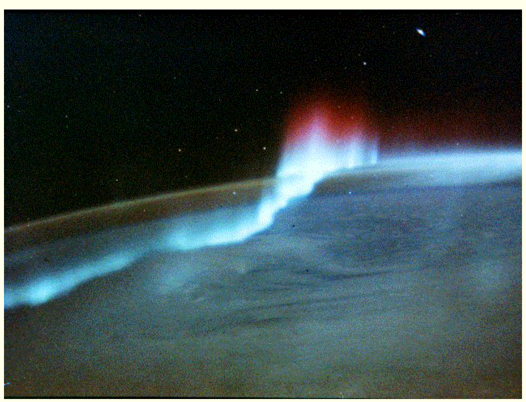



## **Space weather:** Geomagnetically induced currents (GIC)

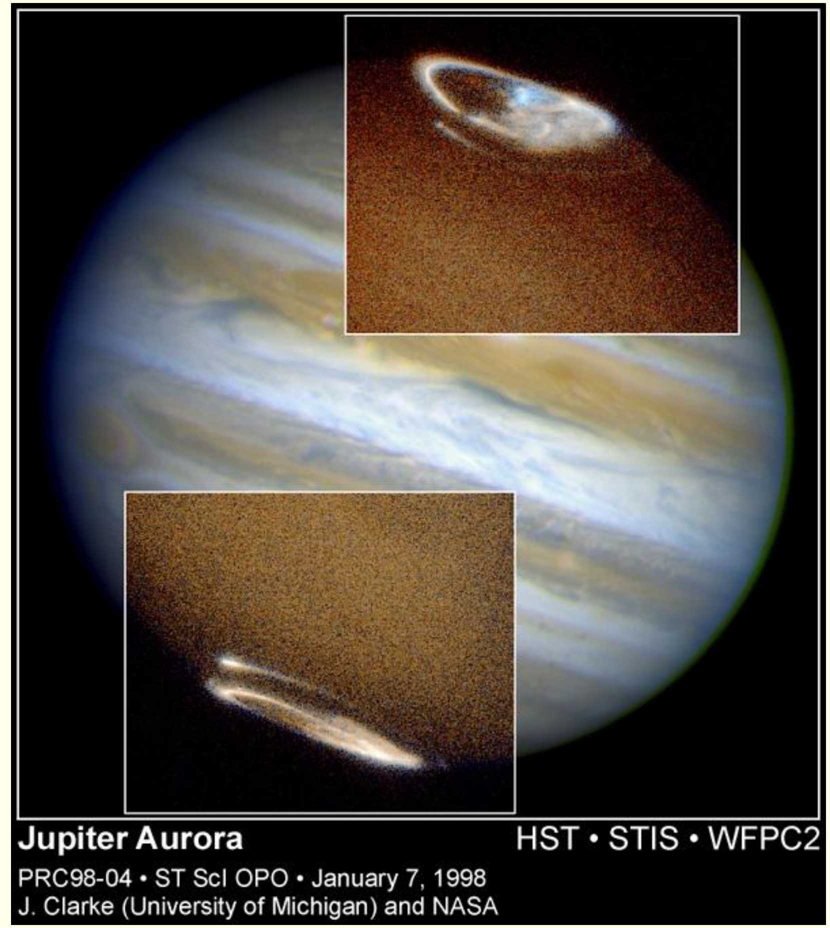




## Aurora on Earth

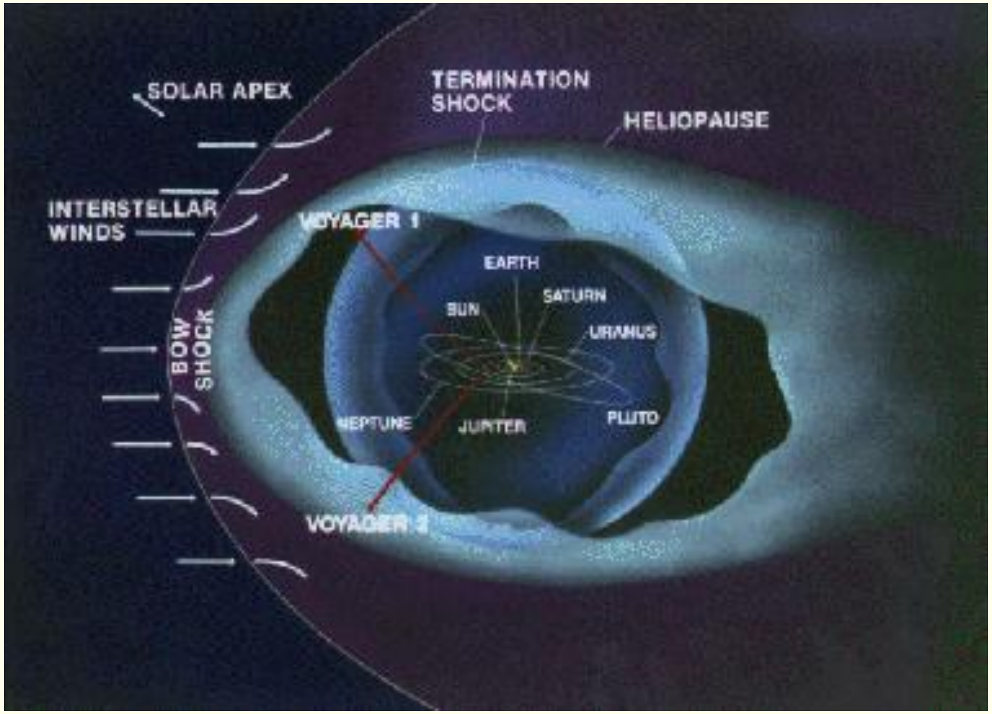


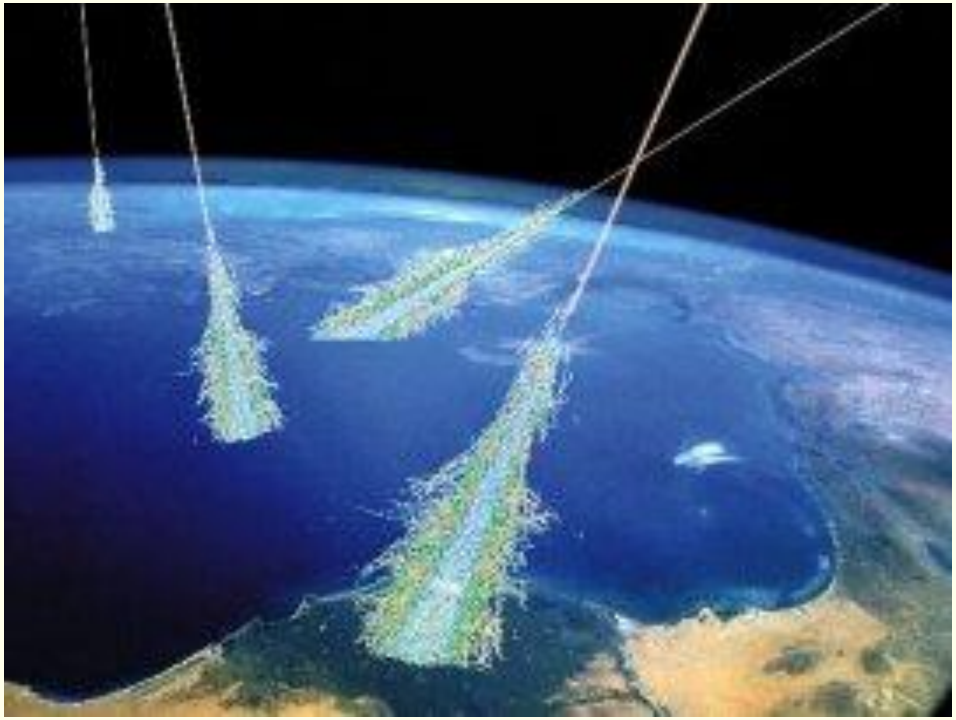
## Aurora on other planets



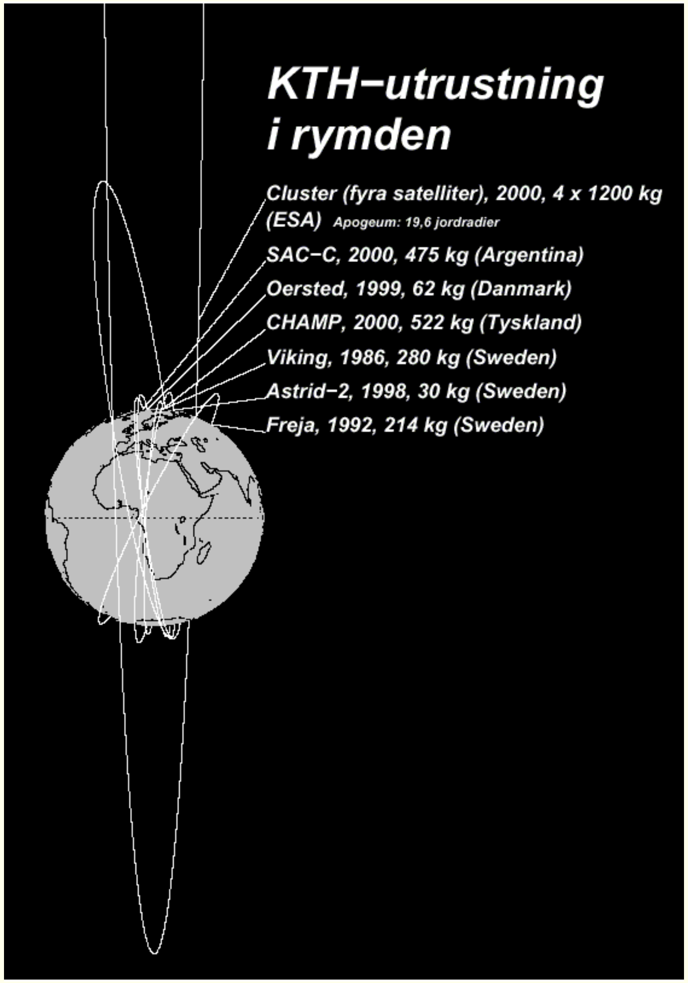
# Interstellar and intergalactic plasma

# Cosmic radiation

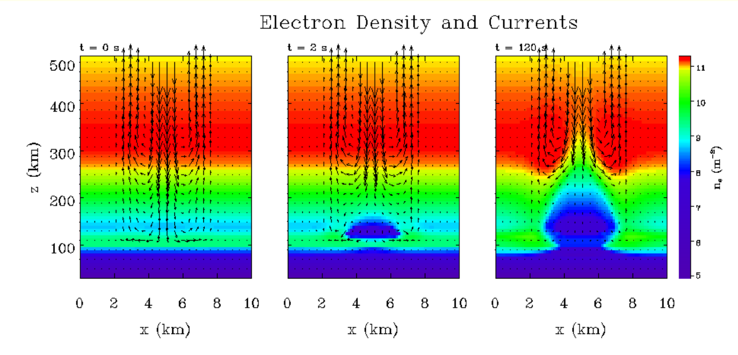


# Swedish and international space physics research

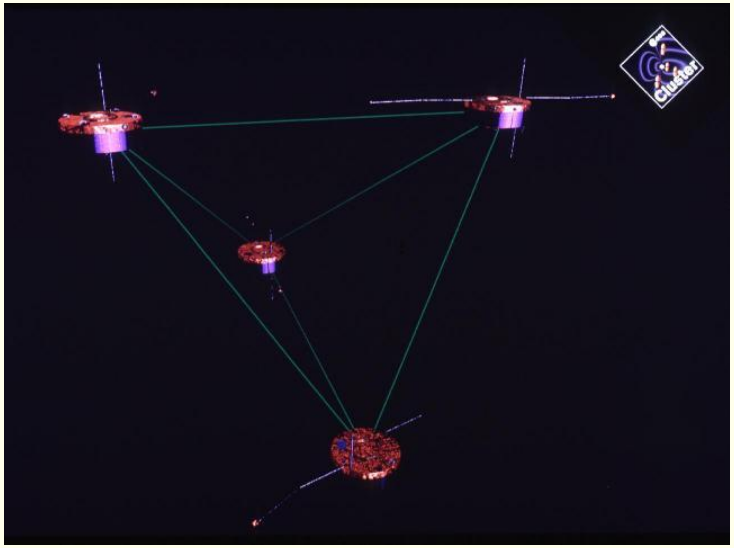



*Micro satellite Astrid-2*




*Simulations*

*Cassini & Huygens at Saturn*



*Cluster satellites*

# Today

| Activity | Date | Time | Room | Subject | Litterature |
|---|---|---|---|---|---|
| L1 | 28/8 | 15-17 | Q21 | Course description, Introduction, The Sun 1 | **CGF** Ch 1.1,1.2, 1.4, 5, (p 110-113), 6.3 |
| L2 | 29/8 | 13-15 | Q2 | The Sun 2, Plasma physics 1 | **CGF** Ch 1.3, 5 (p 114-121) |
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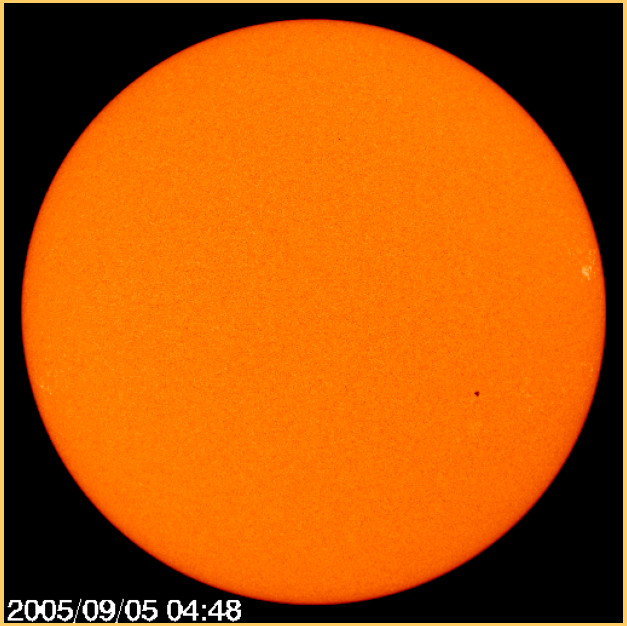
| T1 | 6/9 | 8-10 | Q21 | Mini-group work 1 | |
| L4 | 6/9 | 15-17 | Q2 | The ionosphere 2, Plasma physics 3 | **CGF** Ch 3.4, 3.7, 3.8 |
| T2 | 10/9 | 15-17 | Q21 | Mini-group work 2 | |
| L5 | 11/9 | 10-12 | E3 | The Earth's magnetosphere 1, Plasma physics 4 | **CGF** 4-1-4.3, **LL** Ch I, II, IV.A |
| T3 | 17/9 | 8-10 | Q21 | Mini-group work 3 | |
| L6 | 18/9 | 13-15 | Q33 | The Earth's magnetosphere 2, Other magnetospheres | **CGF** Ch 4.6-4.9, **LL** Ch V. |
| L7 | 19/9 | 13-15 | Q2 | Aurora, Measurement methods in space plasmas and data analysis 1 | **CGF** Ch 4.5, 10**,** **LL** Ch VI, Extra material |
| T4 | 24/9 | 8-10 | Q2 | Mini-group work 4 | |
| L8 | 24/9 | 15-17 | V3 | Space weather and geomagnetic storms | **CGF** Ch 4.4, **LL** Ch IV.B-C, VII.A-C |
| T5 | 2/10 | 8-10 | Q31 | Mini-group work 5 | |
| L9 | 2/10 | 13-15 | Q2 | Alfvén waves, Interstellar and intergalactic plasma, Cosmic radiation | **CGF** Ch 7-9, Extra material |
| T6 | 8/10 | 15-17 | Q21 | | |
| L10 | 9/10 | 10-12 | Q2 | Guest Lecture by Swedish astronaut Christer Fuglesang | |
| Written examination | 16/10 | 14-19 | L21, L22, L31 | | |

# Think about this:



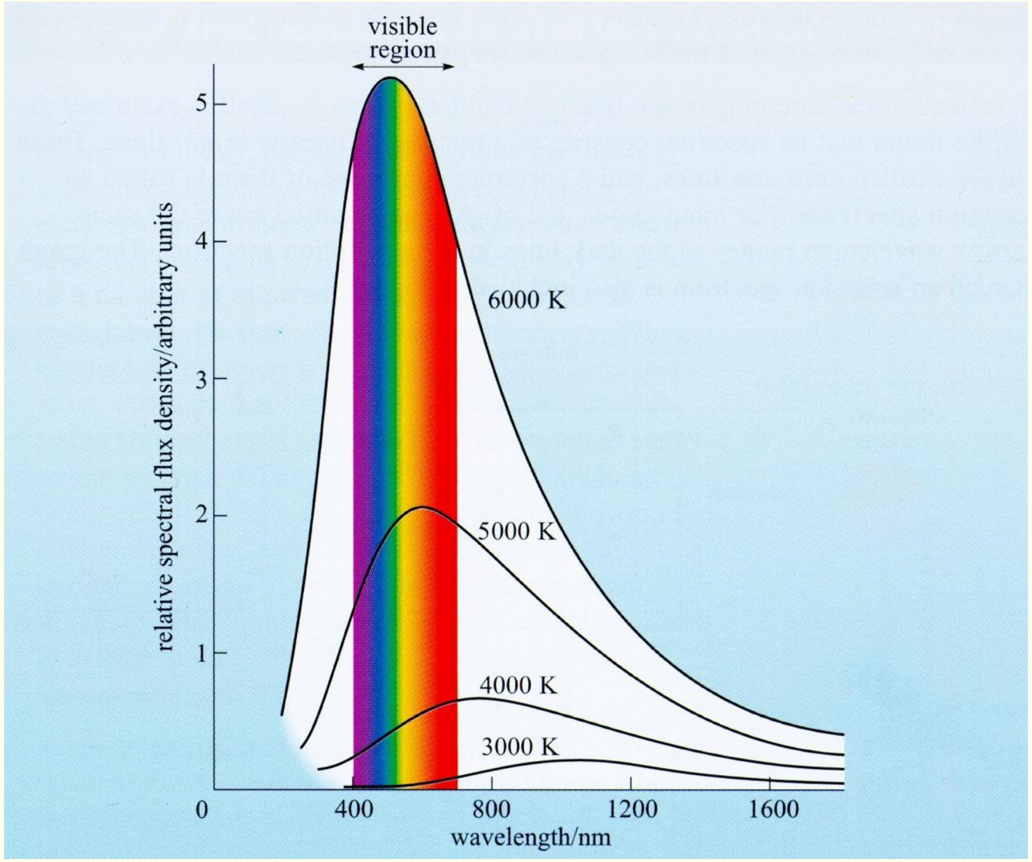

**The temperature of the solar surface is approximately 6000 K.**

**How can we know that ???**

Hot steel emitting red light.


Chart to estimate steel temperature in steelworks.

# Black-body radiation




*Black-body good approximation for opaque bodies where emitted light is much more likely to interact with the material of the source than to escape.*

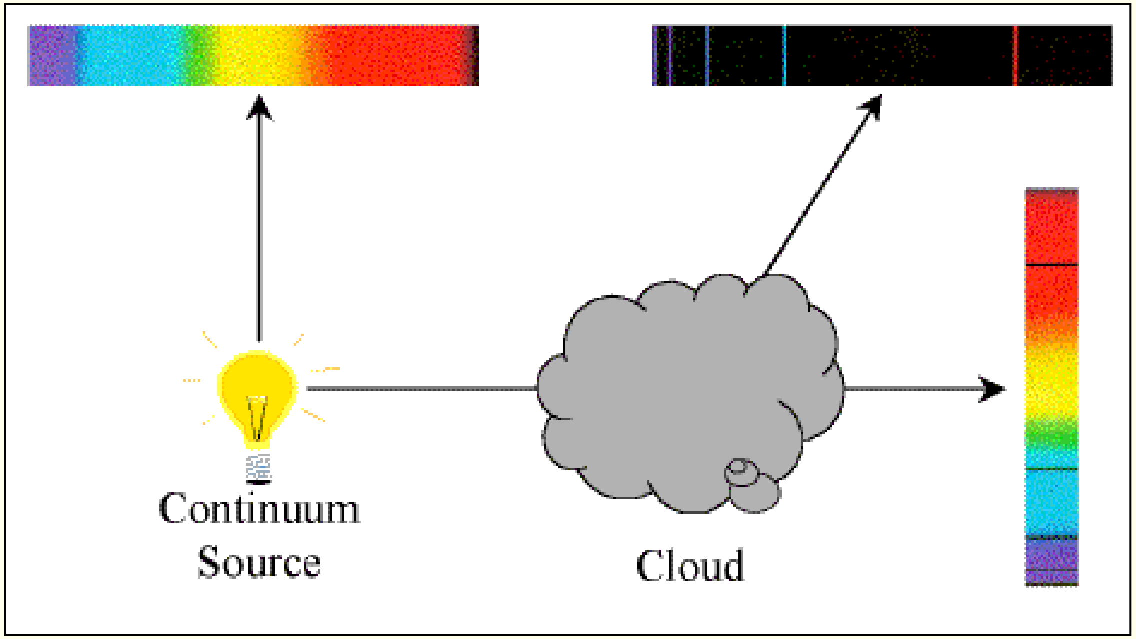
Wien's displacement law

$$\lambda_{peak} = \frac{2.90 \times 10^{-3}}{T}$$

Stefan-Bolzmanns law

$$J = \sigma_{SB} T^4$$

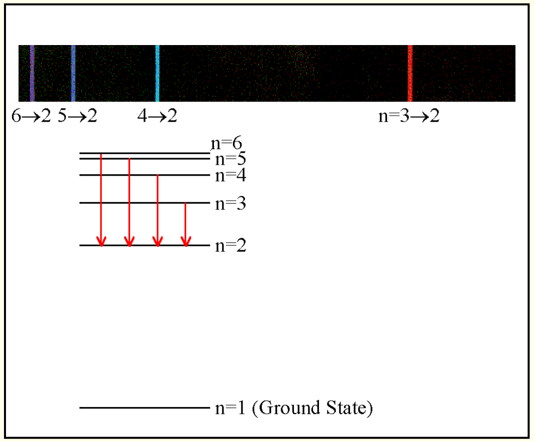
(J = total energy radiated per unit area per unit time )




*For non-blackbody thermal light emitter (for example a thin gas) it is more complicated. Spectrum depends on e.g. chemical composition, and how many atoms/molecules happen to be in state with high probability to decay and cause emission.*

## *Black-body radiation*

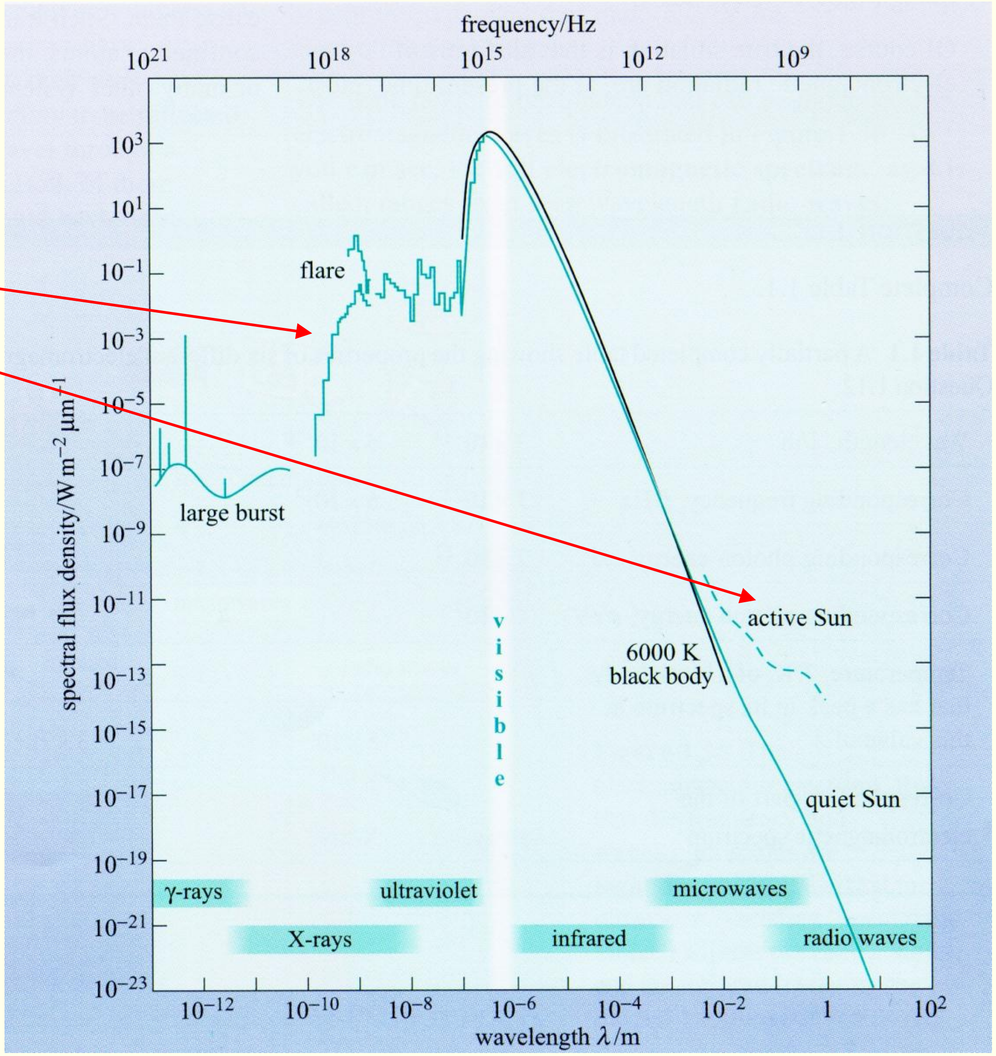
$$\lambda_{peak} = \frac{2.90\times 10^{-3}}{T}$$



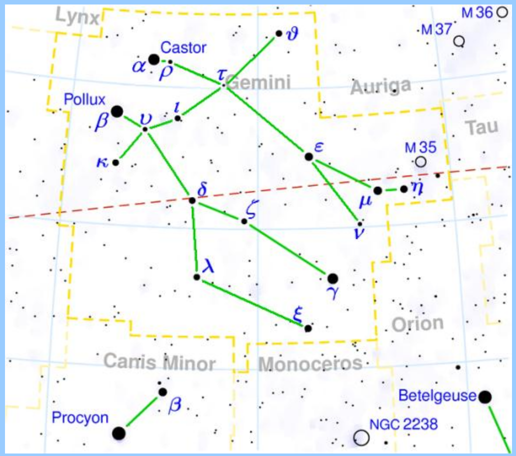

Atomic energy levels

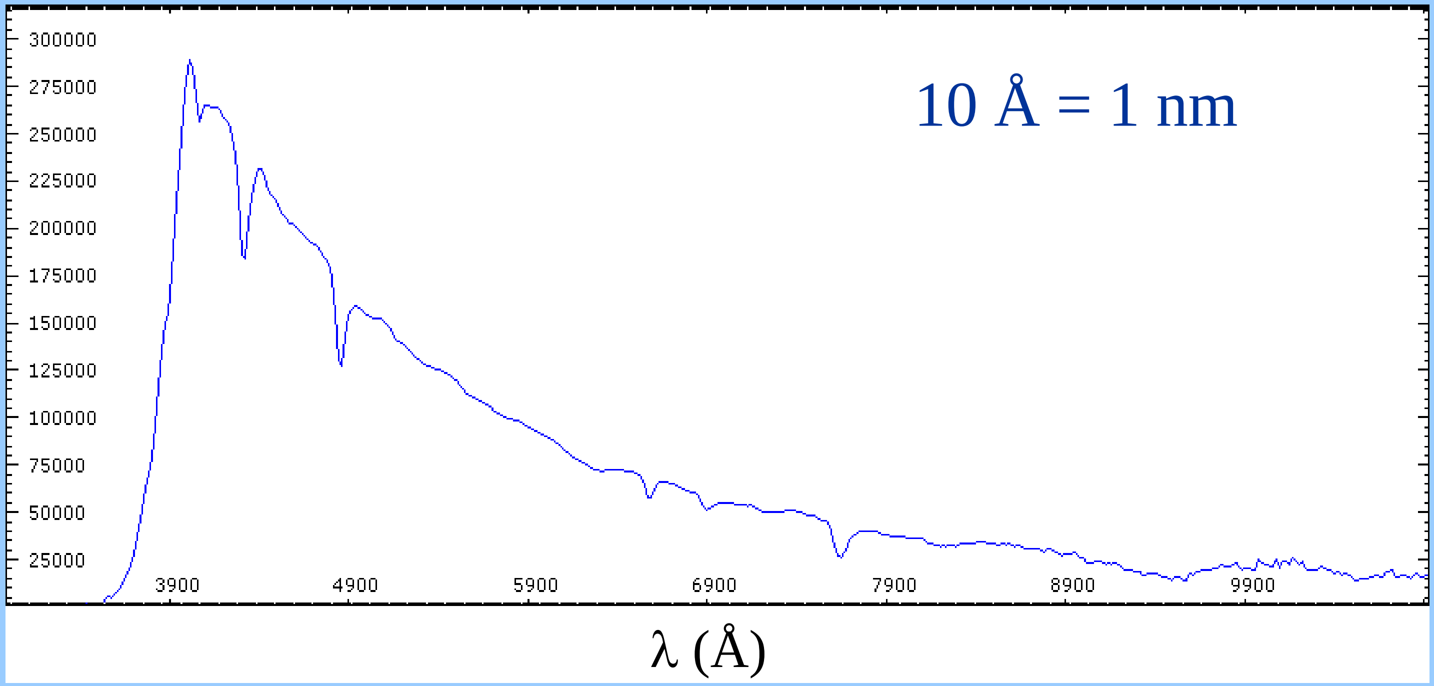
# The solar spectrum

Non-blackbody contributions



# Estimate the temperature of the star *Gamma Geminorum A0iv* !




| | | | |
|---|---|---|---|
| Red | T = 2100 K | Green | T = 7200 K |
| Blue | T = 4700 K | Yellow | T = 9300 K |

# Estimate the temperature of the star *Gamma Geminorum A0iv* !

Wien's displacement law

$$\lambda_{peak} = \frac{2.90 \times 10^{-3}}{T}$$

$$T = \frac{2.90 \times 10^{-3}}{\lambda_{peak}} \approx \frac{2.90 \times 10^{-3}}{400 \times 10^{-9}} \mathrm{K} \approx 7250 \mathrm{~K}$$

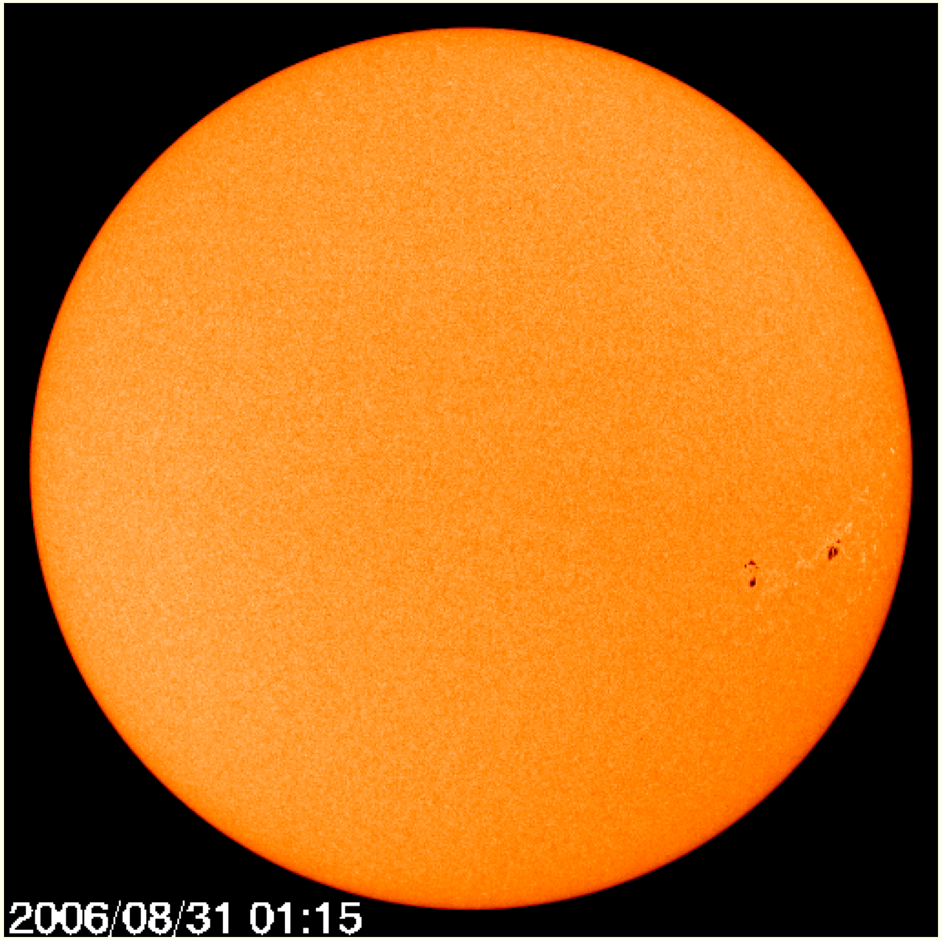
Green T = 7200 K

# BREAK!

## But think about this:

### How can we know anything about the solar interior?

# The Sun



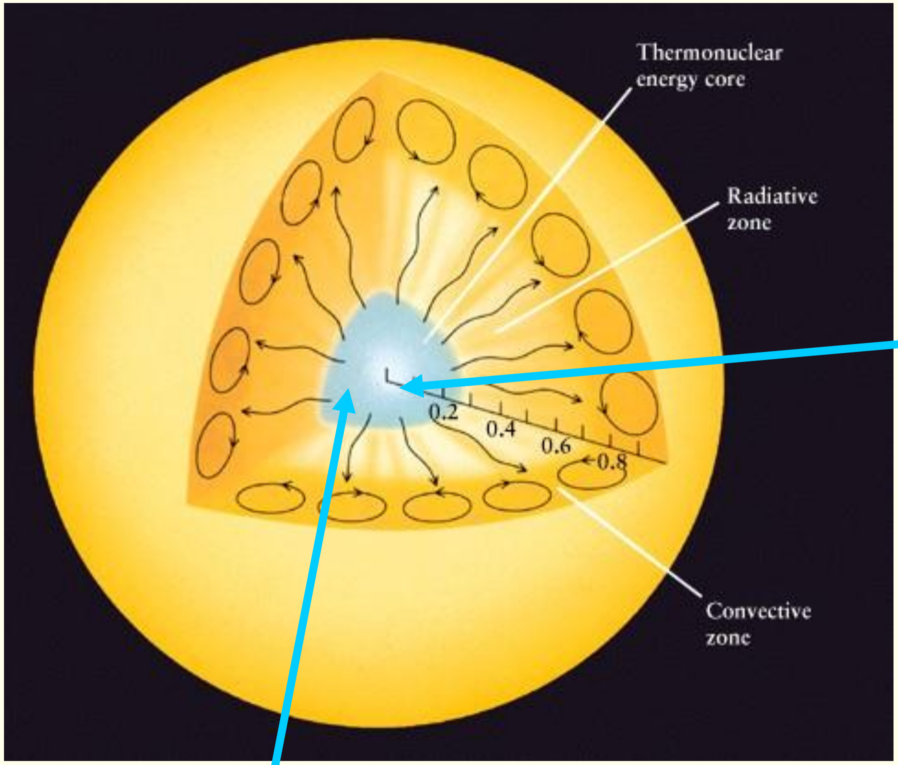

*SOHO Michelson Doppler Imager (MDI) 6767 Å continuum images from Stanford University*

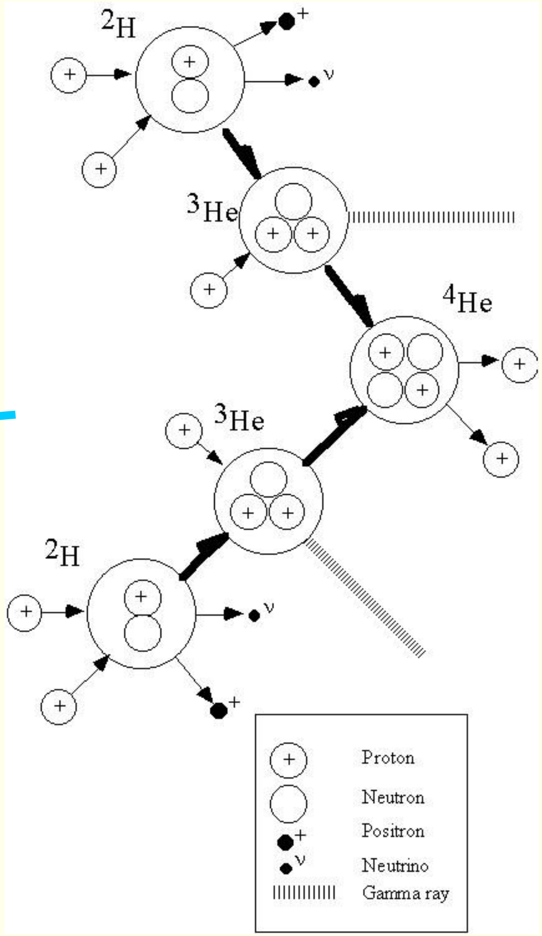
## Basic facts

- *diameter:* $1.39 \cdot 10^9$ m $\approx 109\, d_E$
- *mass:* $2 \cdot 10^{30}$ kg $\approx 333\,000\, m_E$
- *density:* $1.4$ kg/dm$^3$
- *radiated effect:* $4 \cdot 10^{26}$ W
- *age:* $4.5 \cdot 10^9$ years

# Sun's interior

## The proton cycle




$T = 15 \cdot 10^6$ K

$P = 4 \cdot 10^{26}$ W

*($P/m \sim 1 mW/kg$)*

$$4\,{}^1_1\mathrm{H} \rightarrow {}^4_2\mathrm{He} + 2e^+ + 2\nu_e + 2\gamma$$

# Proton cycle

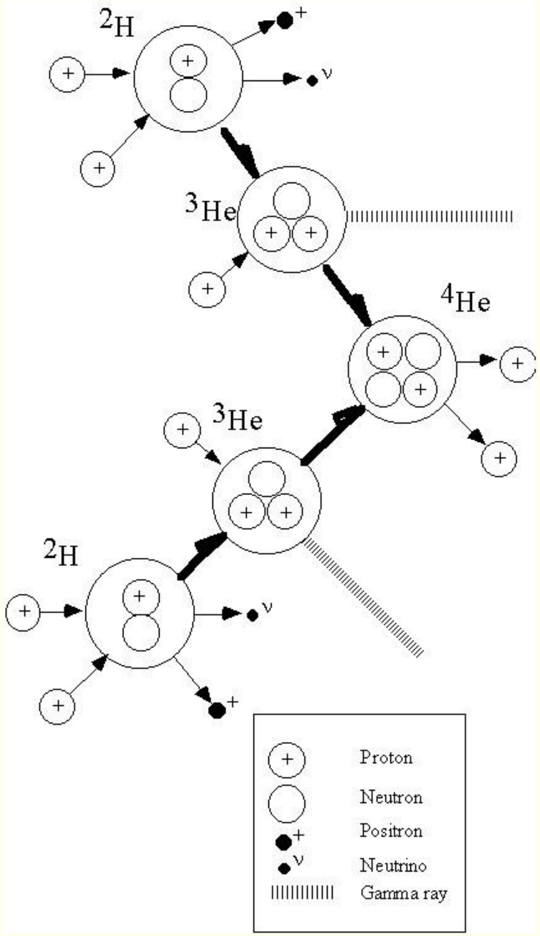
$$2\,{}^1_1\mathrm{H} \rightarrow {}^2_1\mathrm{D} + \mathrm{e}^+ + \nu_e$$

$$2\,{}^1_1\mathrm{H} \rightarrow {}^2_1\mathrm{D} + \mathrm{e}^+ + \nu_e$$

$${}^2_1\mathrm{D} + {}^1_1\mathrm{H} \rightarrow {}^3_2\mathrm{He} + \gamma$$

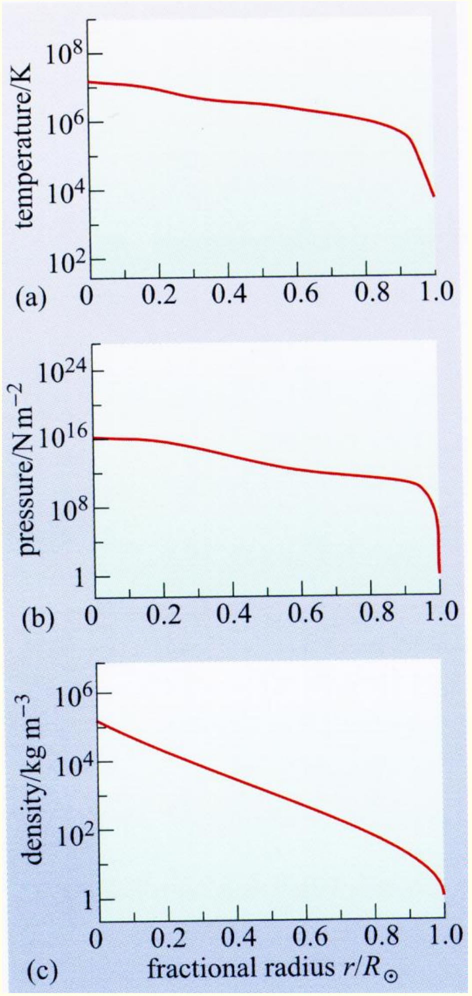
$${}^2_1\mathrm{D} + {}^1_1\mathrm{H} \rightarrow {}^3_2\mathrm{He} + \gamma$$

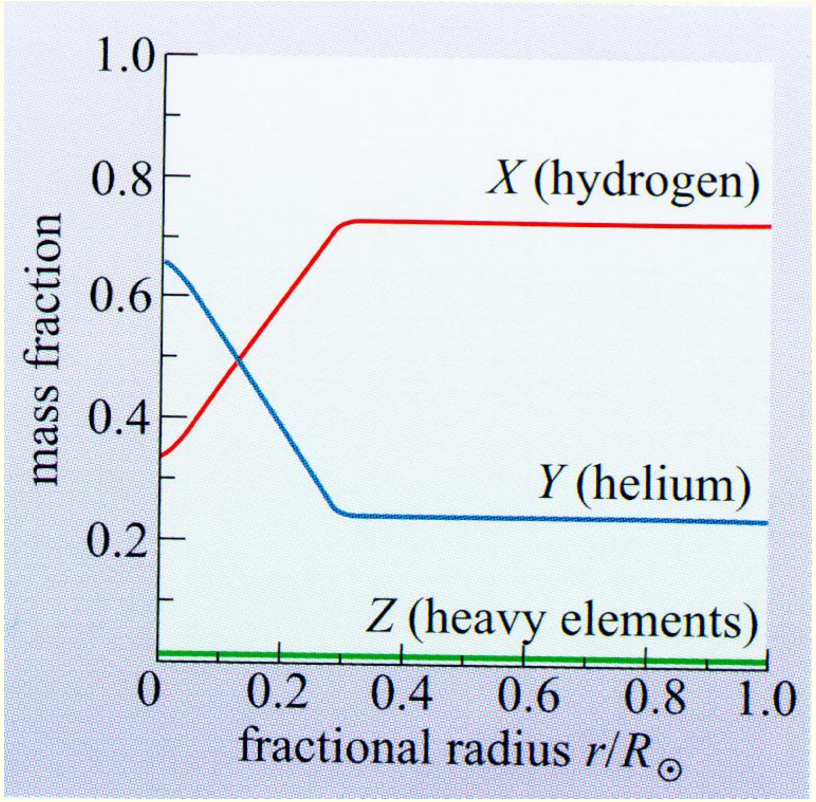
$$2\,{}^3_2\mathrm{He} \rightarrow {}^4_2\mathrm{He} + 2\,{}^1_1\mathrm{H}$$



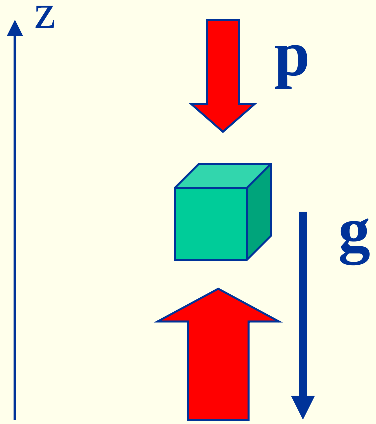

$$4\,{}^1_1\mathrm{H} \rightarrow {}^4_2\mathrm{He} + 2\mathrm{e}^+ + 2\nu_e + 2\gamma$$

# Sun's interior



# Atmospheric scale height




$$-\frac{dp}{dz} = g\rho$$

hydrostatic equilibrium for a volume element

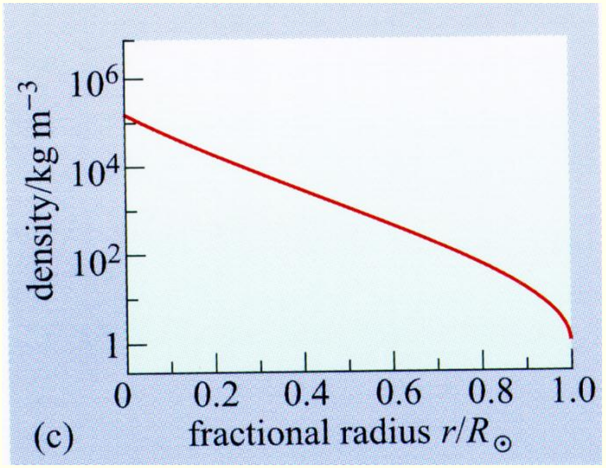
$$p = nk_B T = \frac{\rho k_B T}{m}$$

ideal gas law

$$-\frac{k_B T}{m}\frac{d\rho}{dz} = g\rho$$

if T is constant

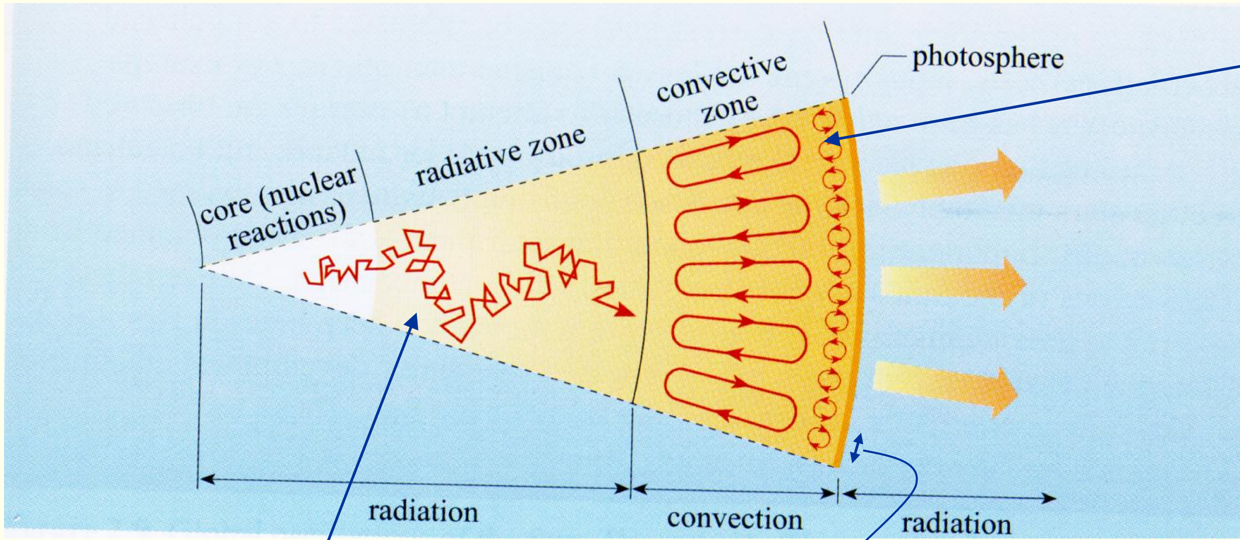
$$\rho = const \cdot e^{-z/(k_B T/gm)} = const \cdot e^{-z/H}$$




**Scale height**

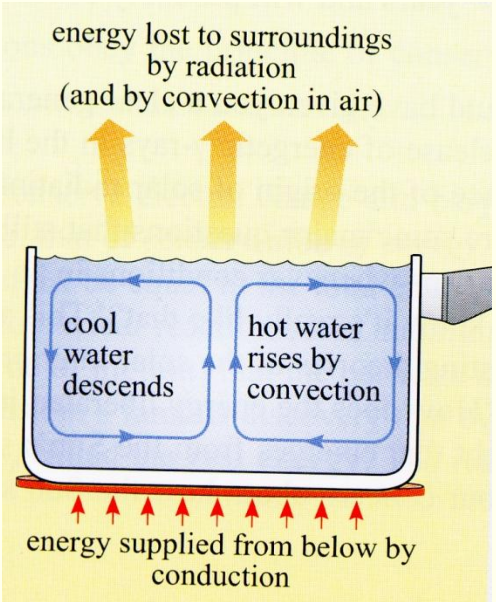
$H = k_B T/gm$

# Energy transport in the sun




Transport by convection

~1000 km




Transport by radiation, which interacts with the dense solar matter (scattering and absorption/re-emission).

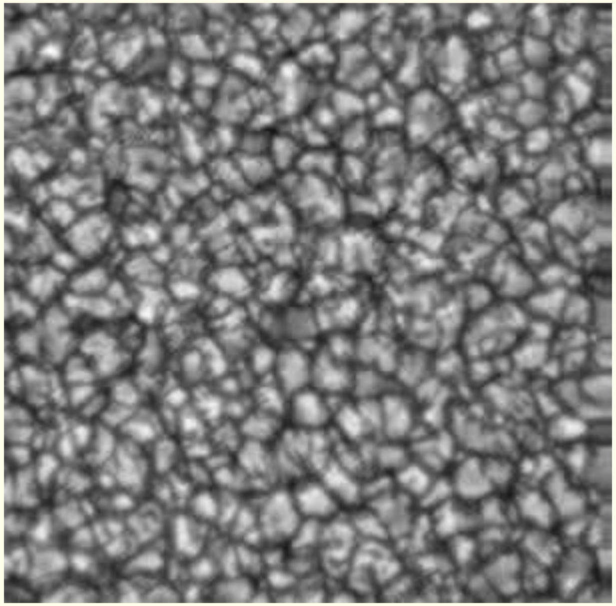
I takes on average 200 000 years for a photon to reach the photosphere!

These convection cells are called *granulation*.

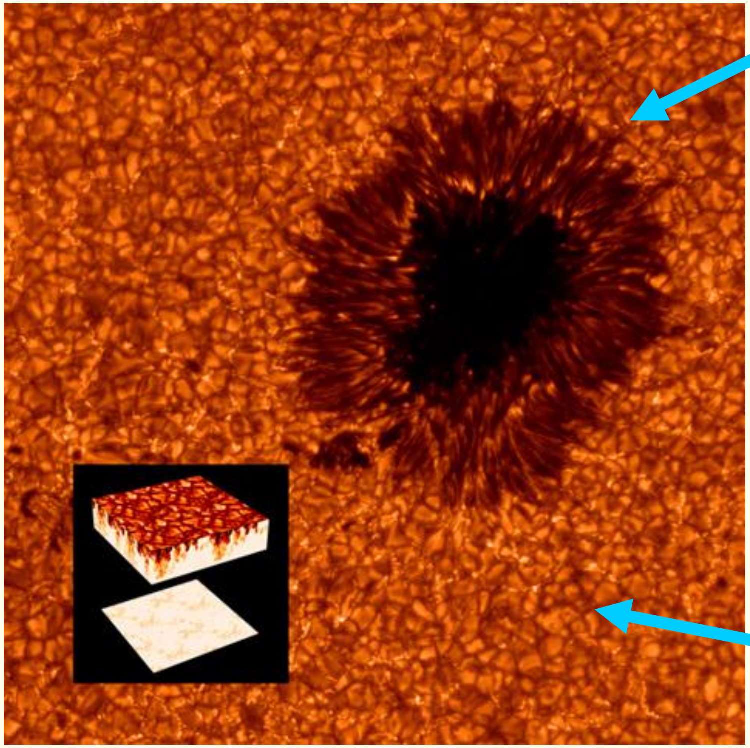
At the photosphere the mean free path of the photons becomes so large that they can reach directly out into space.

# Granulation in photosphere

T = 35 min



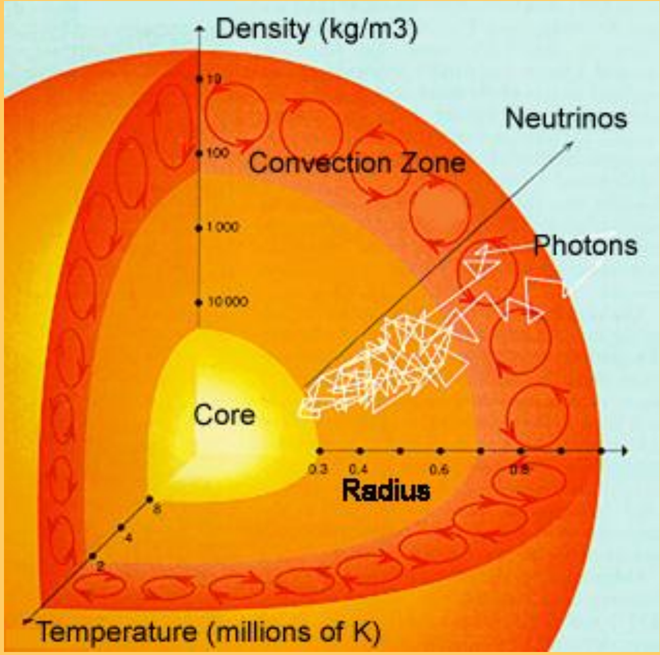
1000 - 50 000 km



300 - 2000 km

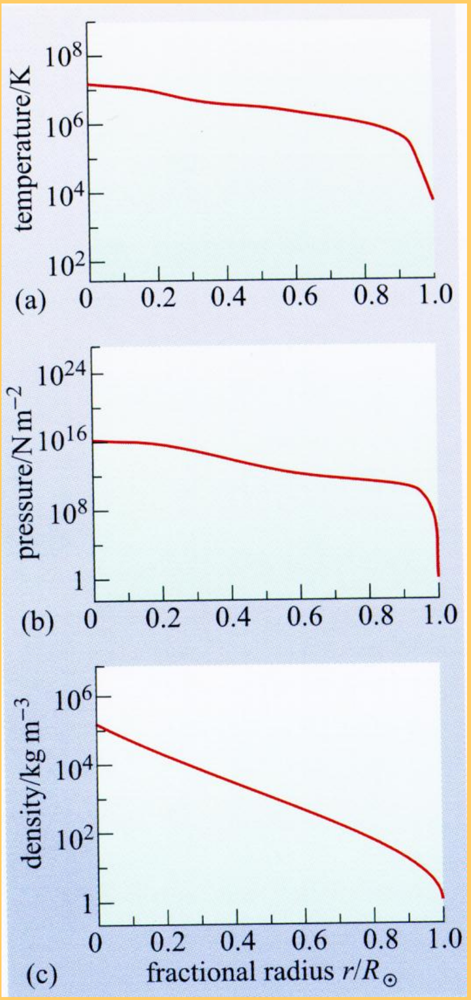
~27 000  km

Life time ~10 min




# So how can we know all these details about the solar interior?

# 1. Solar models



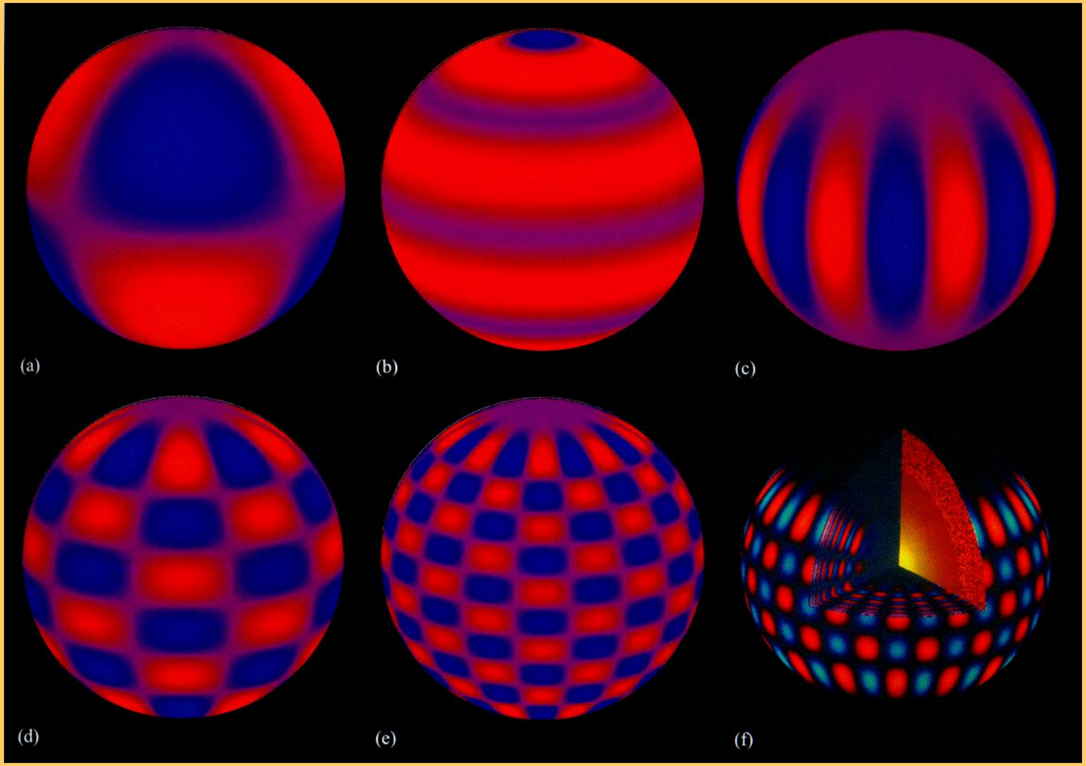

$$4\,{}^1_1\mathrm{H} \rightarrow {}^4_2\mathrm{He} + 2\mathrm{e}^+ + 2\nu_e + 2\gamma$$

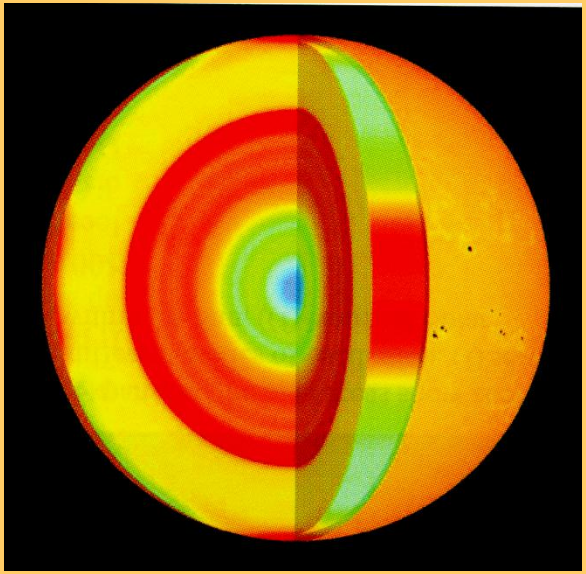
Models of nuclear reactions etc are tuned to *boundary conditions.*

These are e.g.

- *sun's radius R*
- *total mass M*
- *luminosity, L,*
- *surface temperature T,*
- *chemical composition etc.*

# 2. Helioseismology



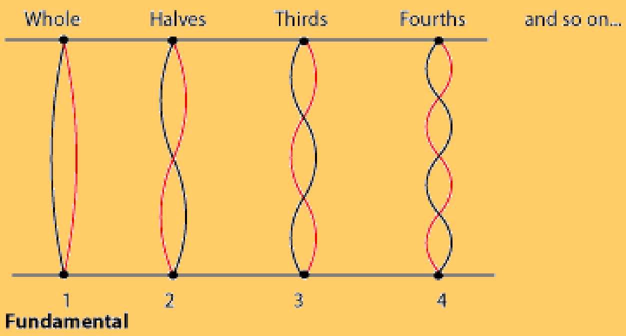



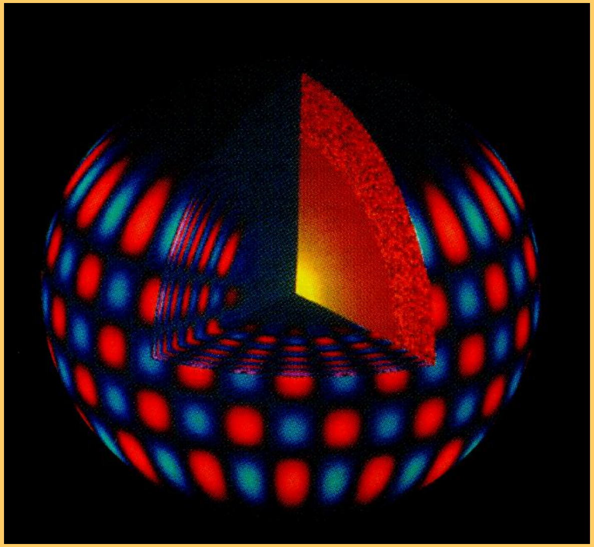
*Sound speed.*

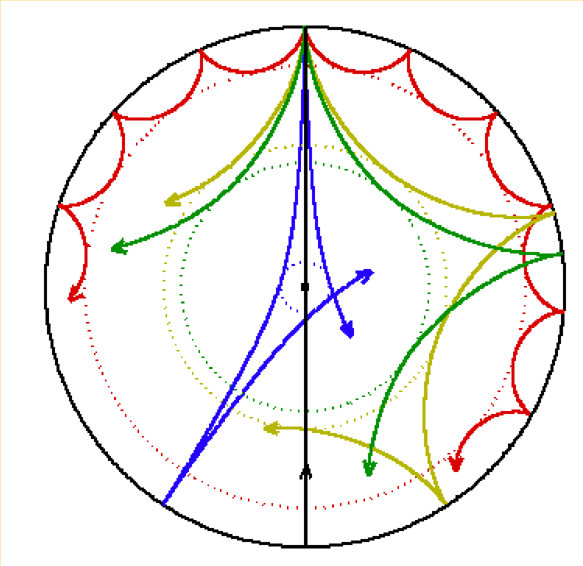
Pressure waves (”sound waves”) on the solar surface can give information of e.g. sound speed in solar interior, which depends on temperature and density.

# Helioseismology

String





Fundamental: $\lambda = 2L$

$$\lambda f = c_S$$

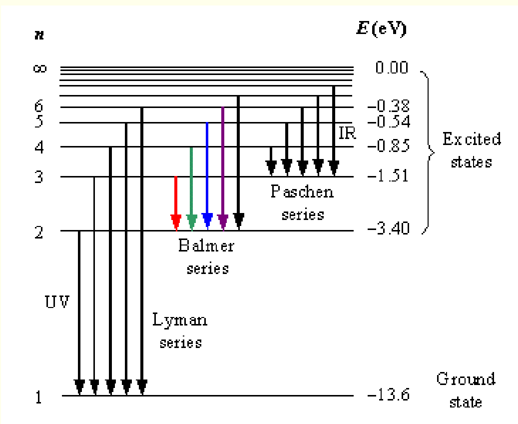
$$c_S = 2fL$$

$$c_S = \sqrt{\frac{5p}{3\rho}}$$

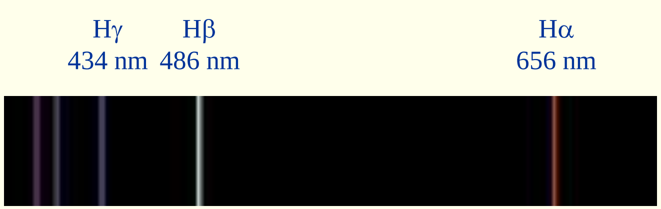
# Solar atmosphere

## Chromosphere

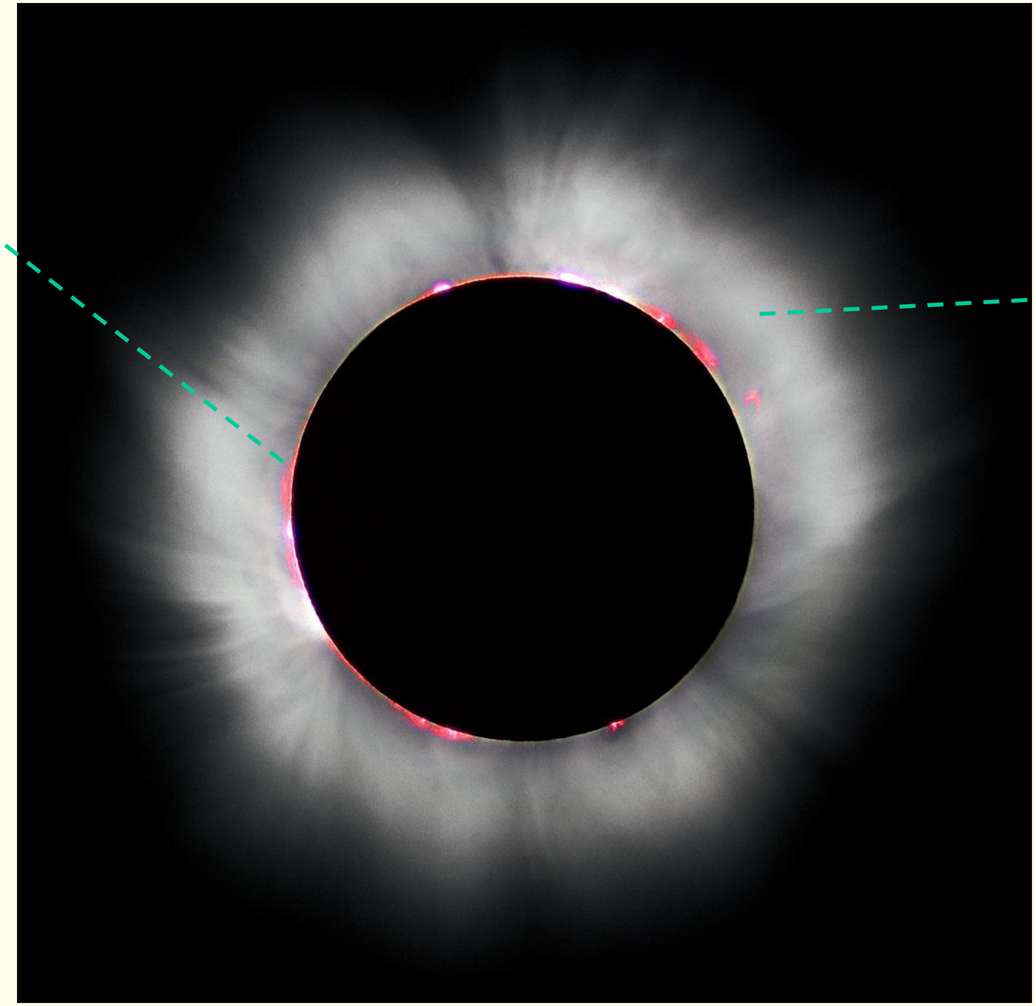
*Reddish colour due to $H\alpha$ emissions.*




Energy levels of the hydrogen atom with some of the transitions between them that give rise to the spectral lines indicated.




*Balmer series*

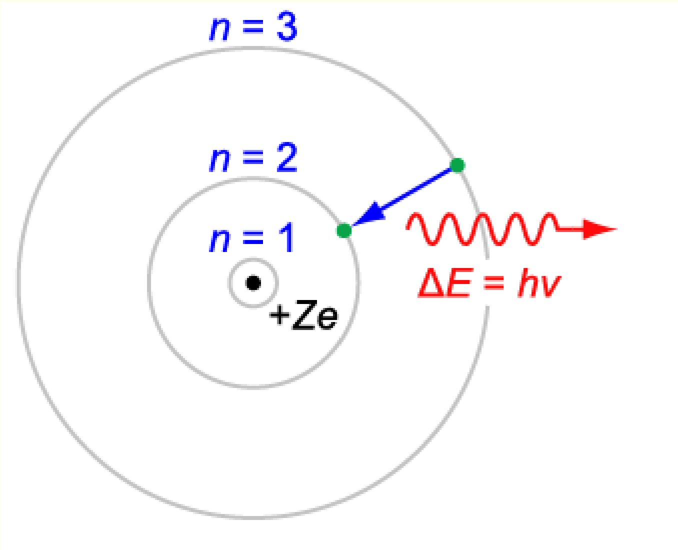


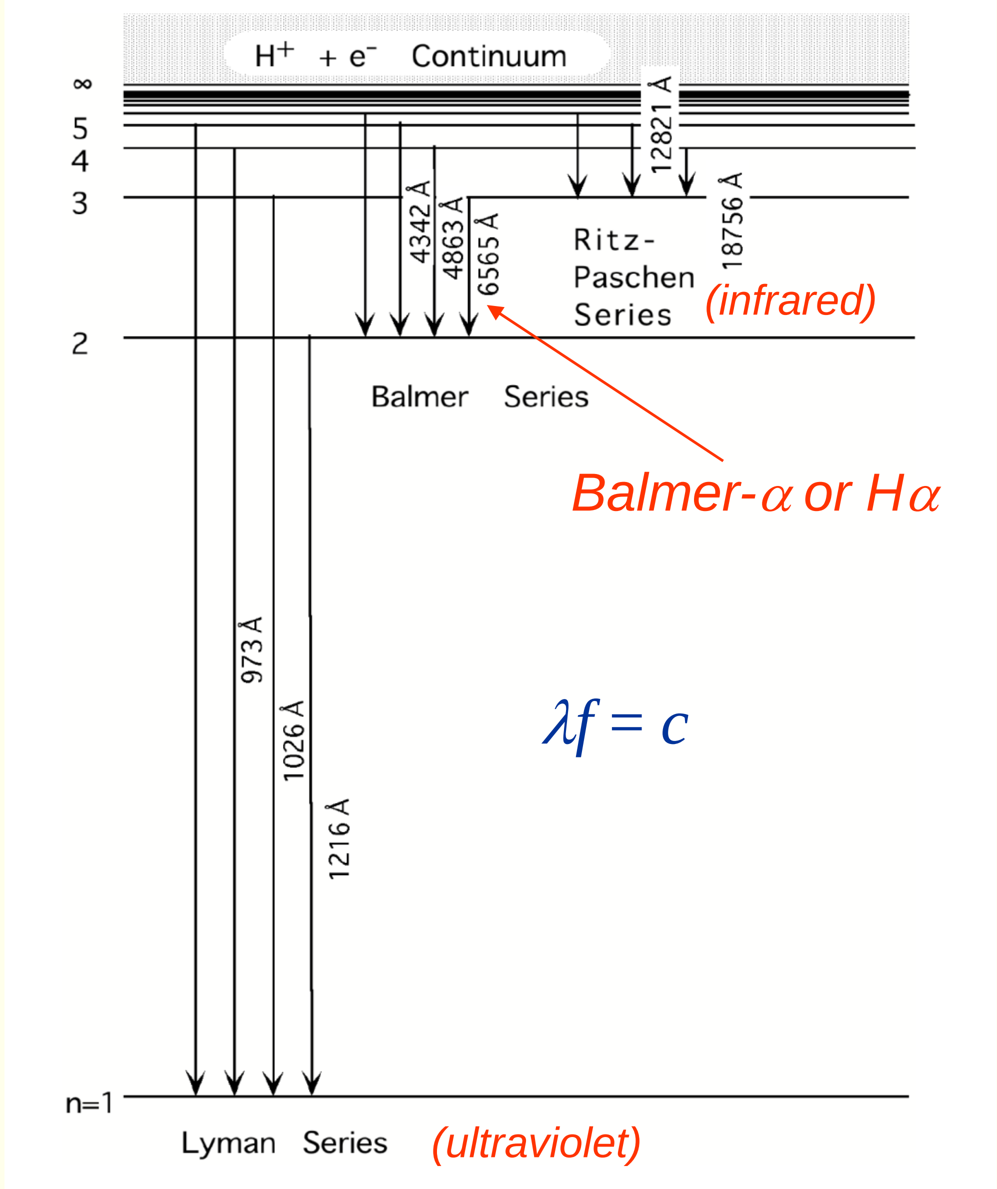
*Total solar eclips*

## Corona

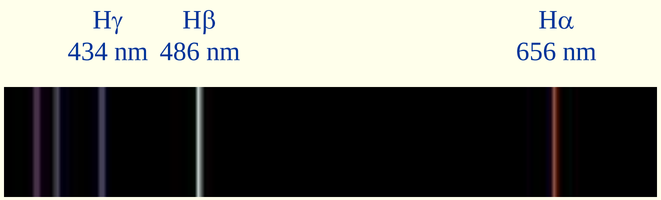
*White light scattered from photo-sphere*

# Hydrogen atom



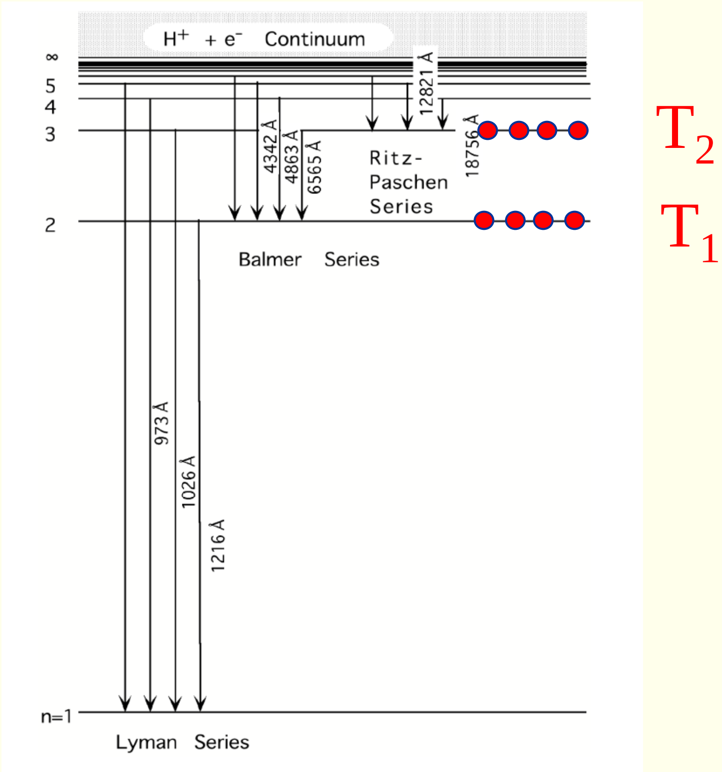

$$\lambda f = c$$

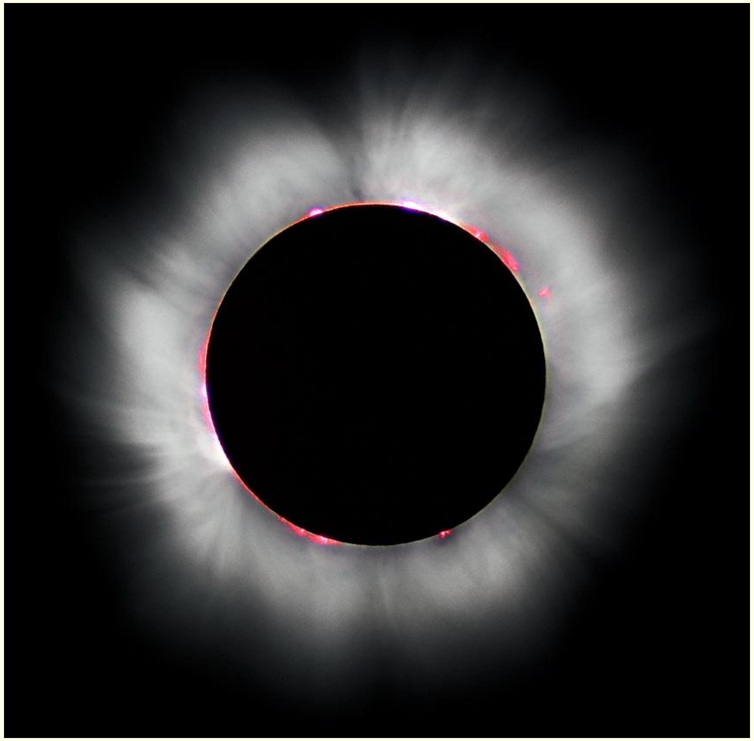



*Balmer series*

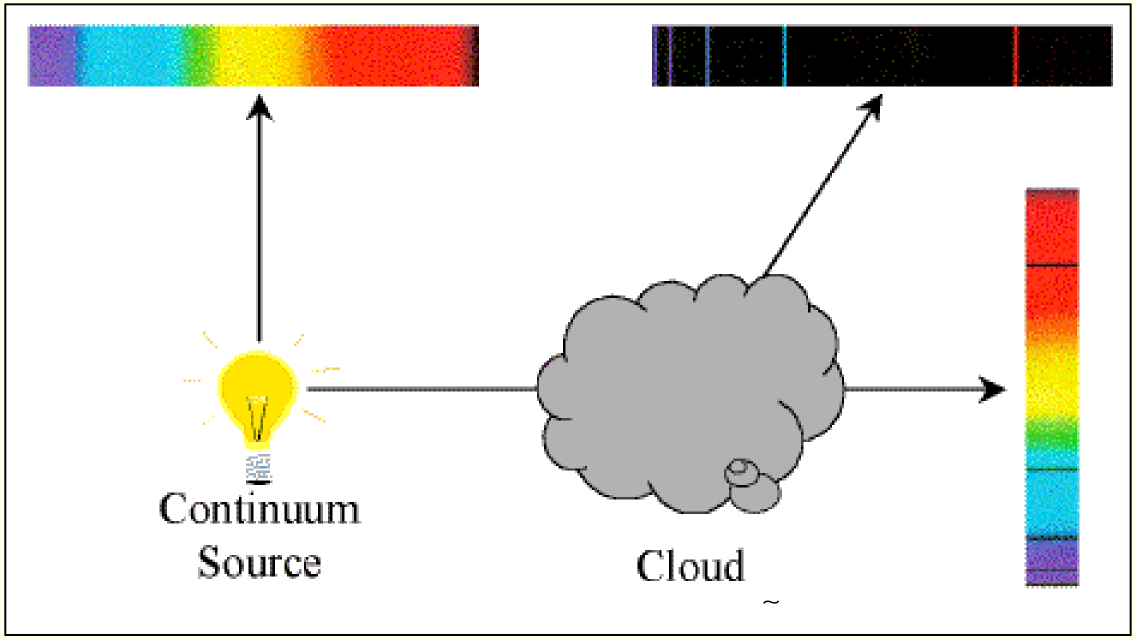
# Why is the chromosphere red?

## Hydrogen spectrum



Hγ 434 nm
Hβ 486 nm
Hα 656 nm

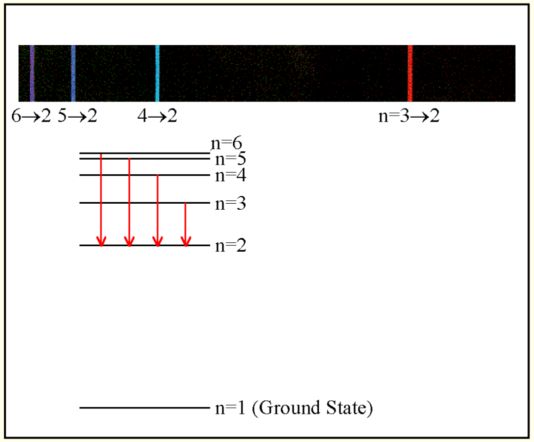



*For non-blackbody thermal light emitter (for example a thin gas) it is more complicated. Spectrum depends e.g. chemical composition, and how many atoms/molecules happen to be in state with high probability to decay and cause emission.*

*Energy (and wavelength) of emitted quantum can still be approximated:*

## *Black-body radiation*

$$\lambda_{peak} = \frac{2.90\times10^{-3}}{T}$$




Atomic energy levels

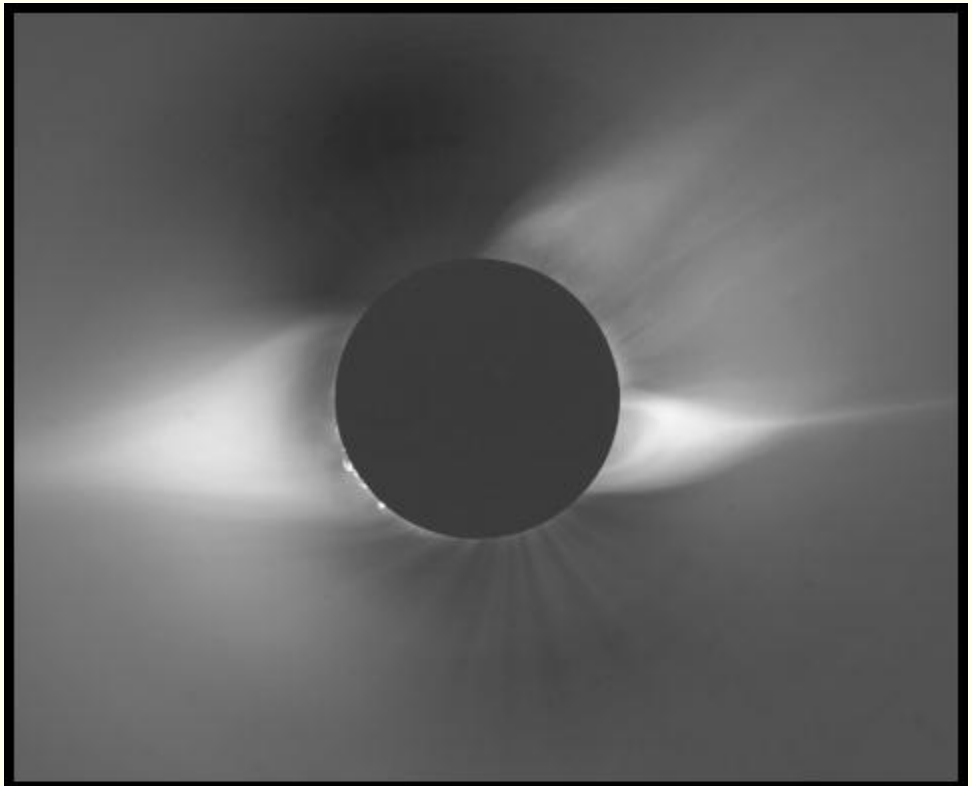
$$E \sim k_B T$$

$$E = hf$$

$$\lambda \sim \frac{hc}{k_B T}$$

# Corona

- Temperature: up to 2 MK
- Density: $10^{-18}$ g/cm$^3$ – $10^{-24}$ g/cm$^3$
- Turns into the solar wind at high altitudes, without a sharp boundary.



Solar Corona at Eclipse, 3 Nov 1994, Putre, Chile.
High Altitude Observatory, NCAR, Boulder, Colorado, USA.

# The layers of the solar atmosphere

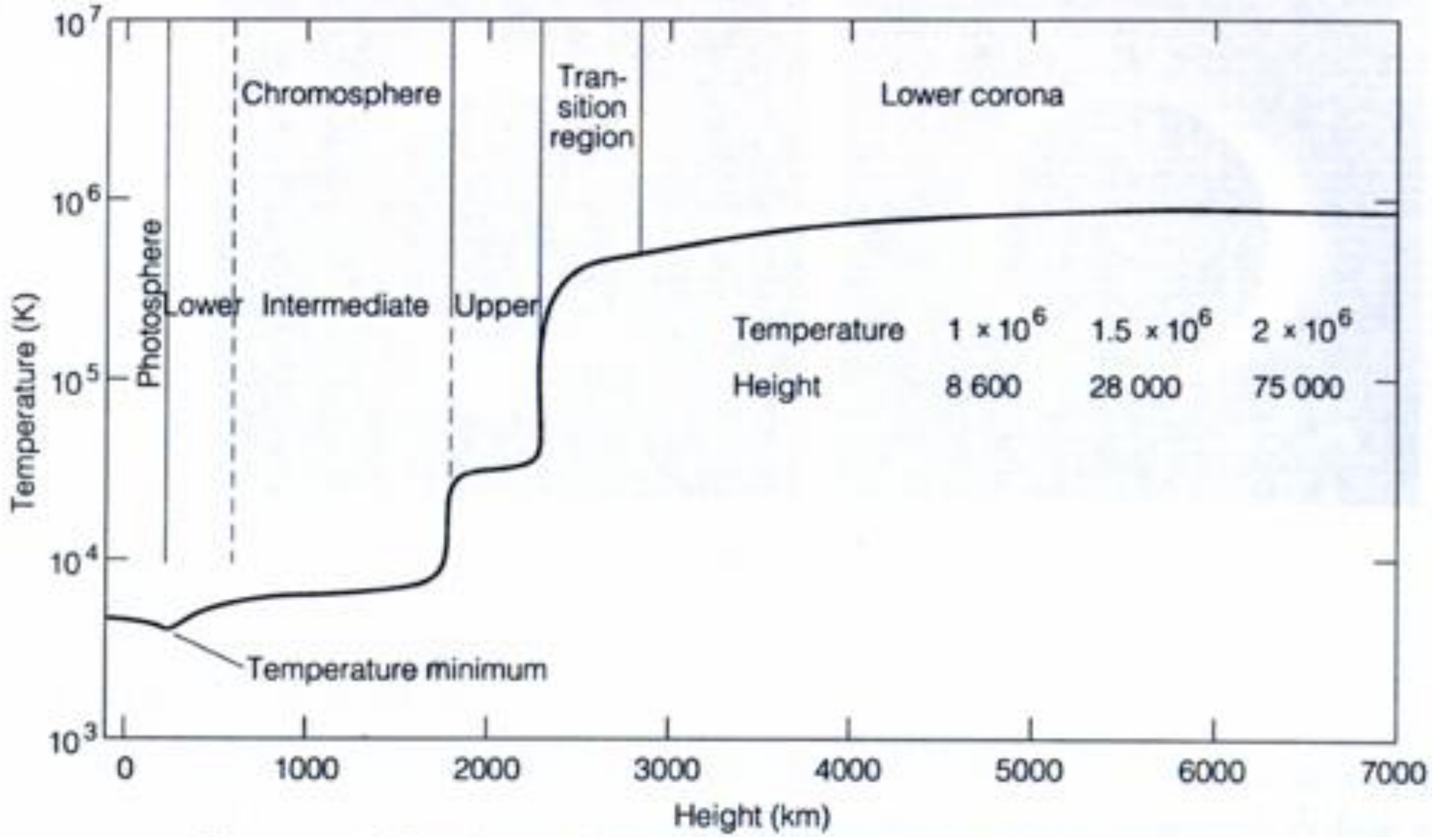
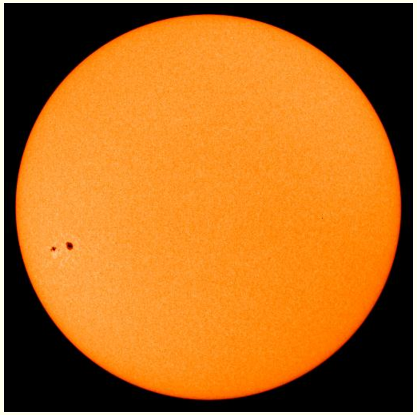
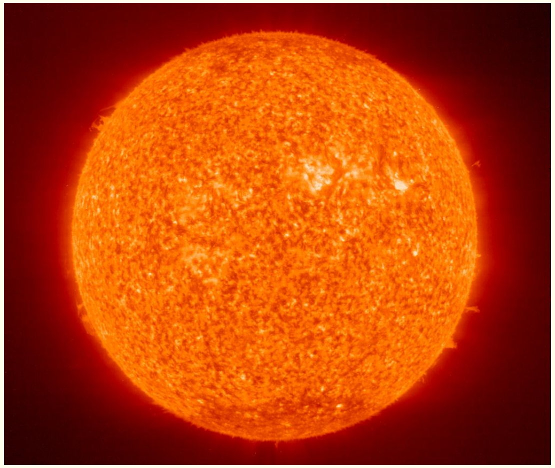


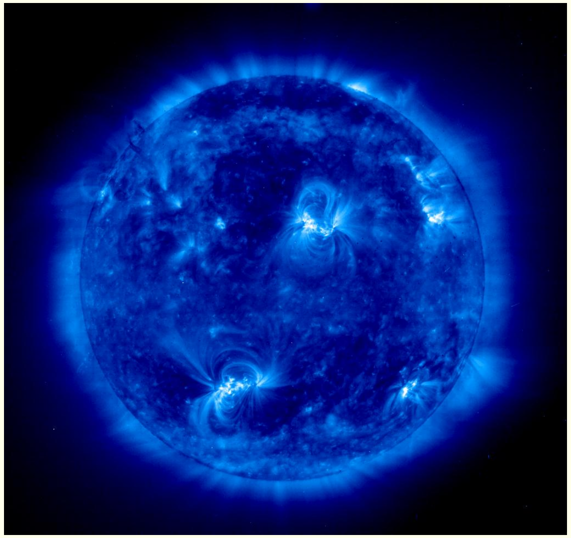

**Figure 5.3.** Distribution of average temperature in the solar atmosphere (Athay 1976).



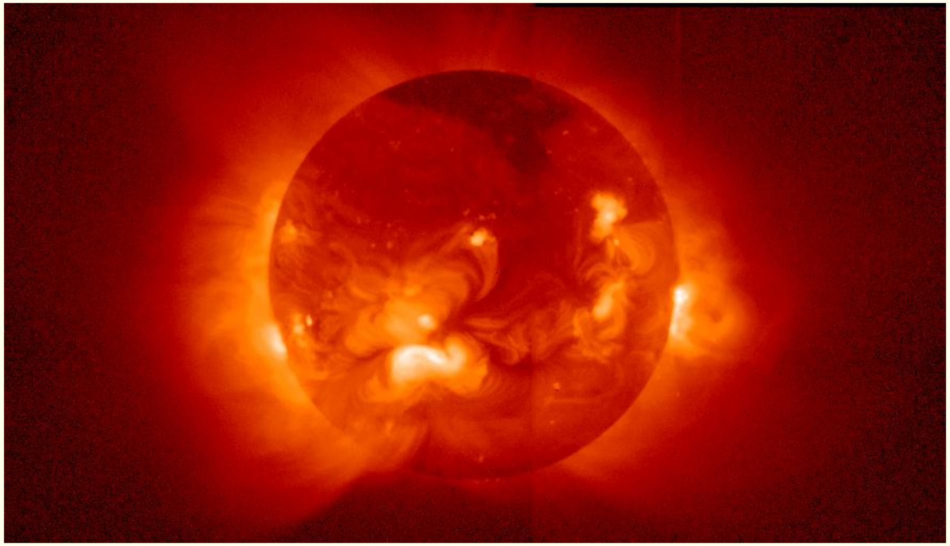
*Visible light ~ 6768 Å*



*He II emission line at 304 Å*

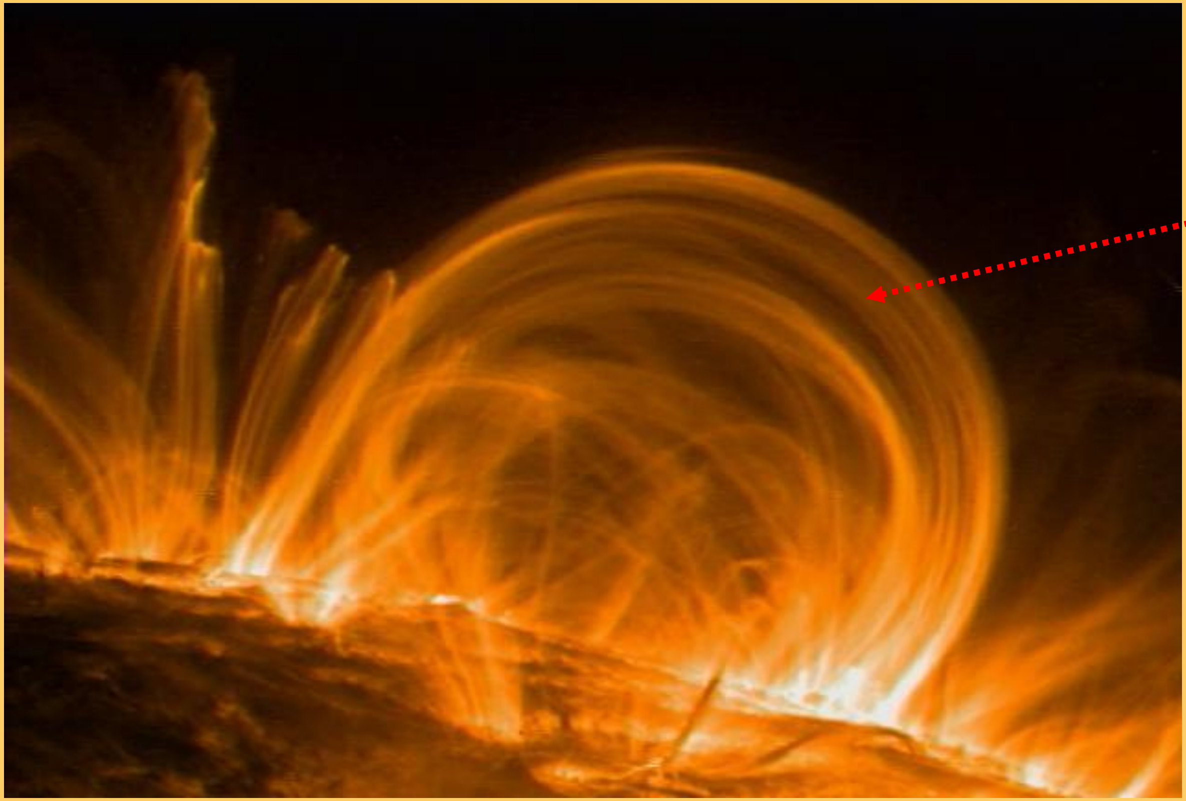


*(Fe IX/X) at 171 Å*



*X-ray at 0.3-5 Å*

# Coronal loops



**What gives the loops this structure???**