Last lecture (1)

- Course info
- Definition of plasma
- Solar interior and atmosphere
- Plasma physics 1

Today's lecture (2)

- Plasma physics 2
- Solar activity

Steps to take to take the course

1) Make sure you have signed up for the course.

   If you haven’t: contact your Masters coordinator or studievägledare

2) Register for the course! (My Pages)

   You have to do this yourself!

Examination

1. Written examination (open book*), 30/10

100 p

2. Continous examination (mini-group works)

25 p

Grades:

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

(Fx)

Written examination,
26/10 2016, 08.00-13.00, F2

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.

Written examination,
28/10 2015, 08.00-13.00, Q21, Q26

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

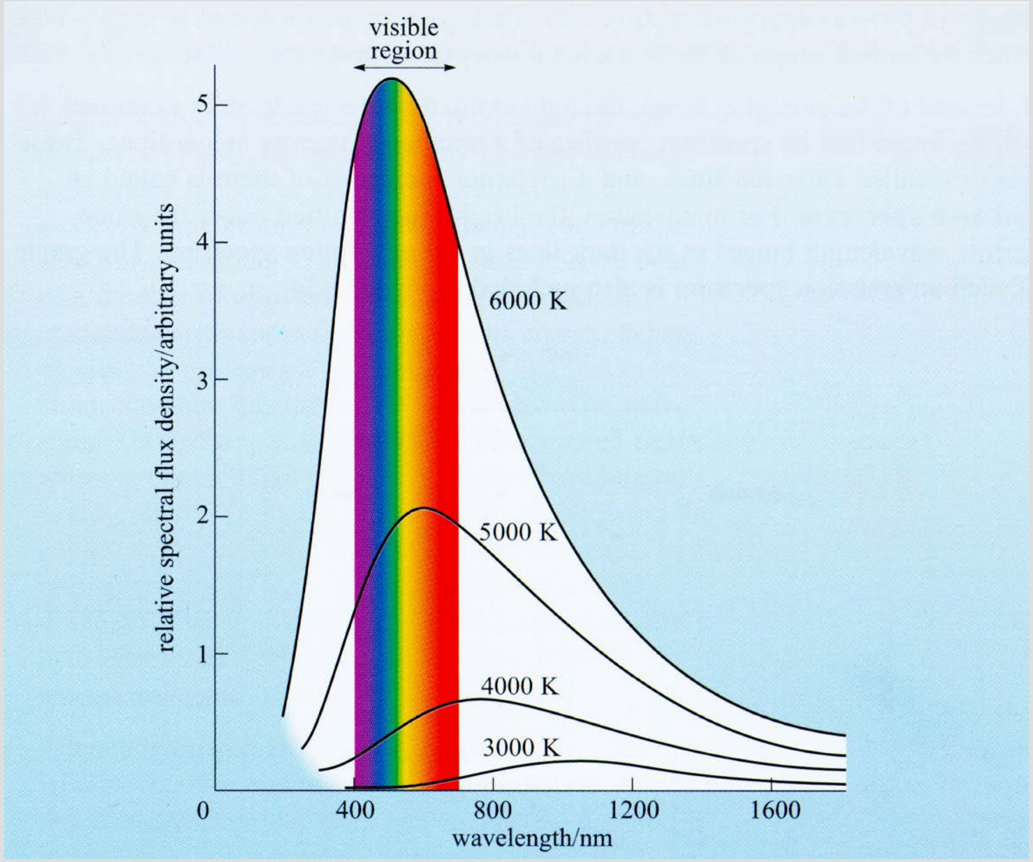
- C-G. Fälthammar, ”Space Physics” (compendium), 2nd Ed, Third Printing, 2001.
- Larry Lyons, ”Space Plasma Physics”, from *Encyclopedia of Physical Science and Technology, 3rd edition, 2002.*
- Lecture notes and extra material handed out during lectures.

Today

Activity	Date	Time	Room	Subject	Litterature
L1	29/8	13-15	E52	Course description, Introduction, The Sun 1, Plasma physics 1	**CGF** Ch 1, 5, (p 110-113)
L2	1/9	15-17	L52	The Sun 2, Plasma physics 2	**CGF** Ch 5 (p 114-121), 6.3
L3	5/9	13-15	E51	Solar wind, The ionosphere and atmosphere 1, Plasma physics 3	**CGF** Ch 6.1, 2.1-2.6, 3.1-3.2, 3.5, **LL** Ch III, Extra material
T1	8/9	15-17	D41	Mini-group work 1	
L4	12/9	13-15	E35	The ionosphere 2, Plasma physics 4	**CGF** Ch 3.4, 3.7, 3.8
L5	14/9	10-12	V32	The Earth's magnetosphere 1, Plasma physics 5	**CGF** 4.1-4.3, **LL** Ch I, II, IV.A
T2	15/9	15-17	E51	Mini-group work 2	
L6	19/9	13-15	M33	The Earth's magnetosphere 2, Other magnetospheres	**CGF** Ch 4.6-4.9, **LL** Ch V.
T3	22/9	15-17	E51	Mini-group work 3	
L7	26/9	13-15	E31	Aurora, Measurement methods in space plasmas and data analysis 1	**CGF** Ch 4.5, 10**, LL** Ch VI, Extra material
L8	28/9	10-12	L52	Space weather and geomagnetic storms	**CGF** Ch 4.4, **LL** Ch IV.B-C, VII.A-C
T4	29/9	15-17	M31	Mini-group work 4	
L9	3/10	13-15	E52	Interstellar and intergalactic plasma, Cosmic radiation,	**CGF** Ch 7-9
T5	6/10	15-17	E31	Mini-group work 5	
L10	10/10	13-15	E52	Swedish and international space physics research.	
T6	13/10	15-17	E31	Round-up, old exams.	
Written examination	26/10	8-13	F2		

L = Lecture, T = Tutorial

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

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

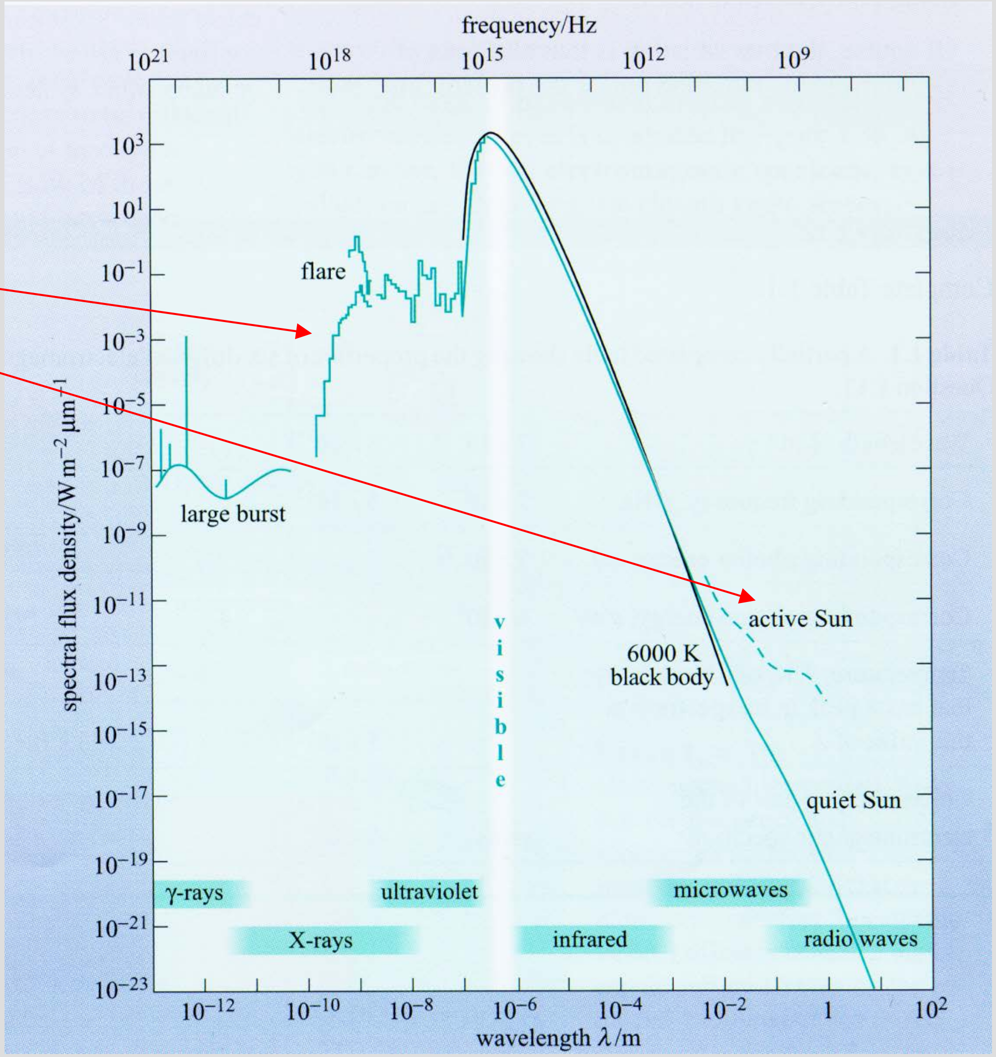
Stefan-Bolzmanns law

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

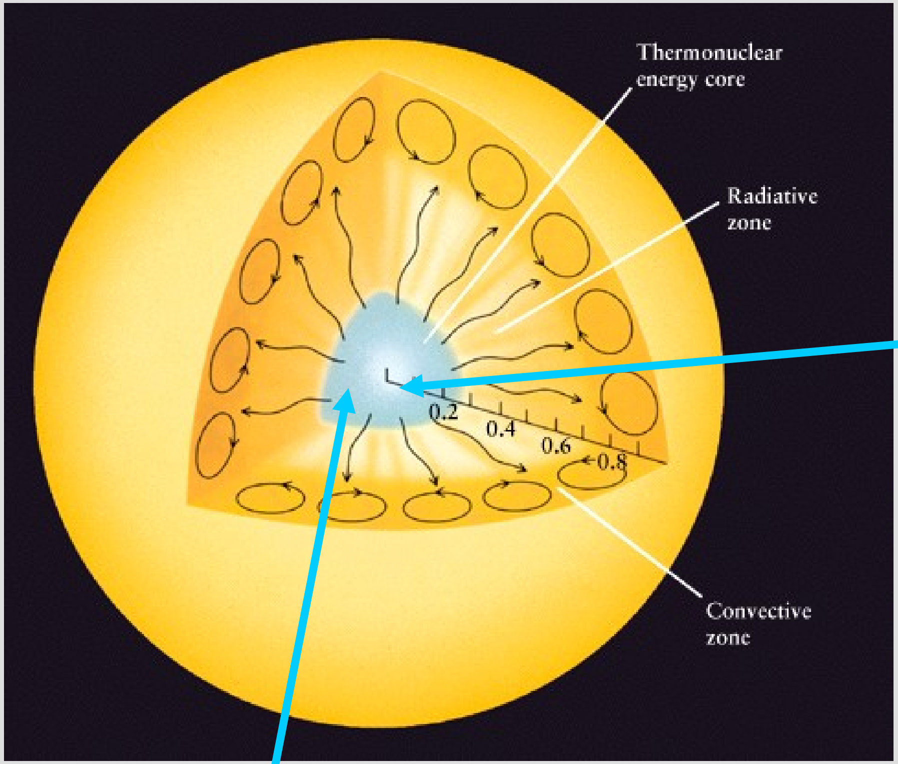
(J = total energy radiated per unit area per unit time)

The solar spectrum

Non-blackbody contributions



Sun´s interior

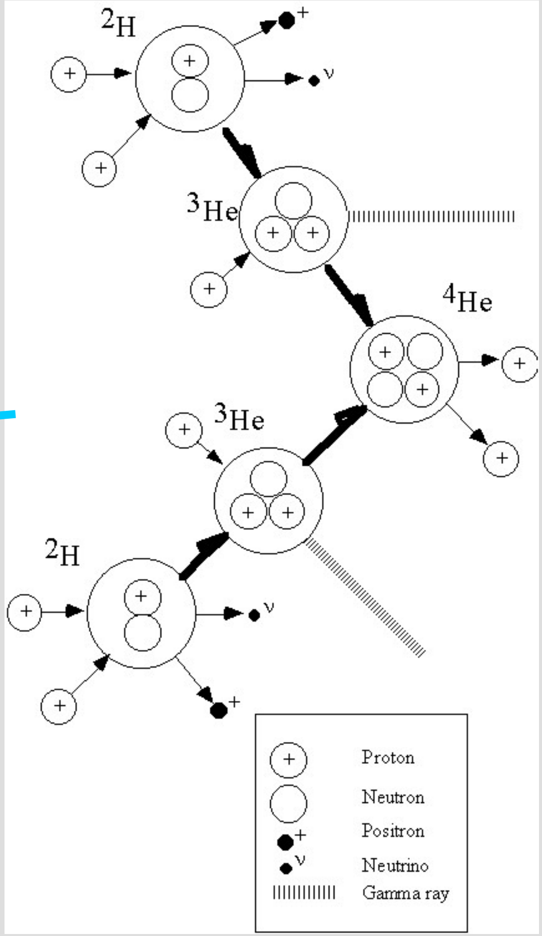


T = 15 · 10^6 K

P = 4 · 10^{26} W

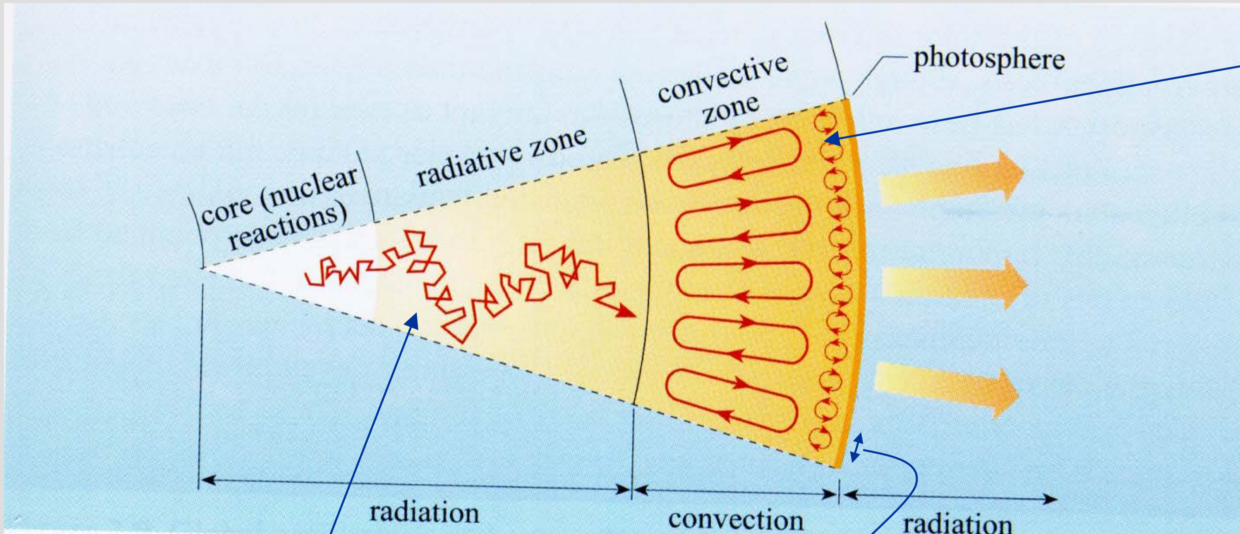
(P/m ~ 1mW/kg)

The proton cycle



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

Energy transport in the sun



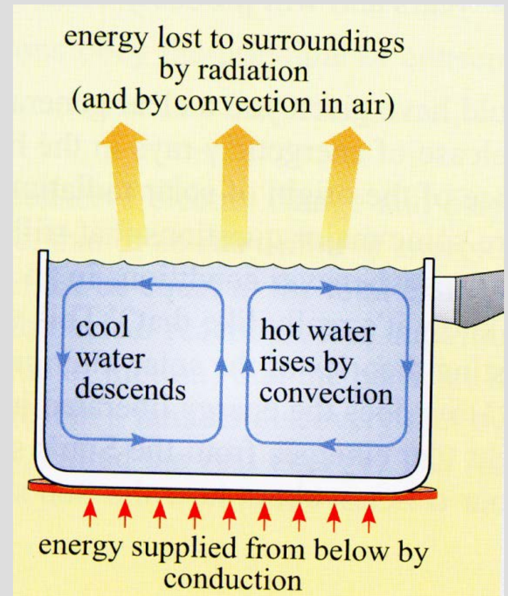
Transport by convection

~1000 km

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

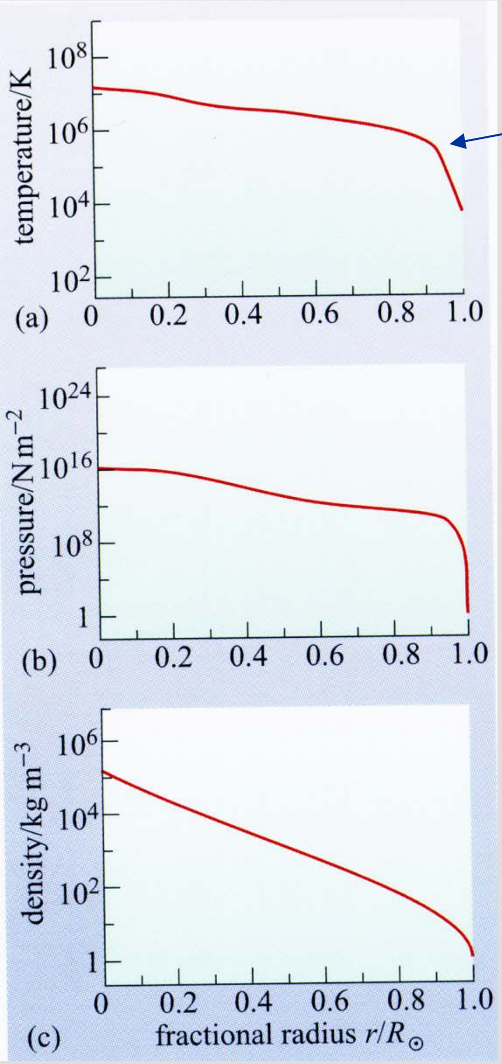
I takes on average 200 000 years for a photon to reach the photosphere!

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.

Sun's interior



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

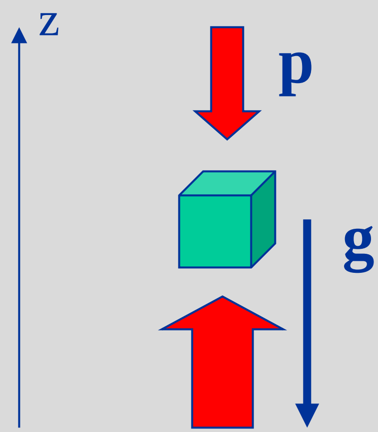
As a consequence also the temperature, and pressure drops.

$$p_{pl} = nk_B T$$

Example of exponential density variation in balance between pressure and gravity

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

Atmospheric scale height



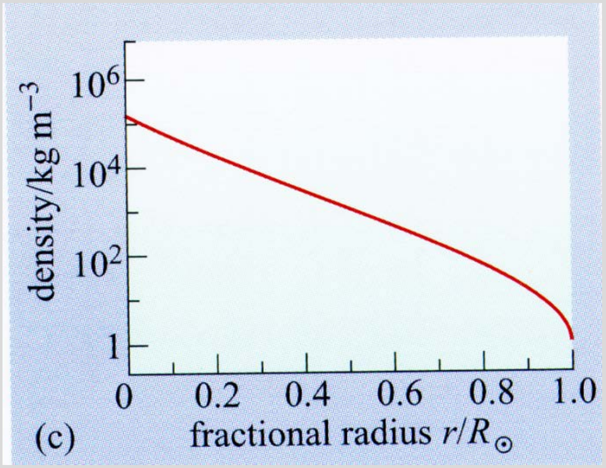
$$-\frac{dp}{dz} = g\rho$$ hydrostatic equilibrium for a volume element

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

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

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

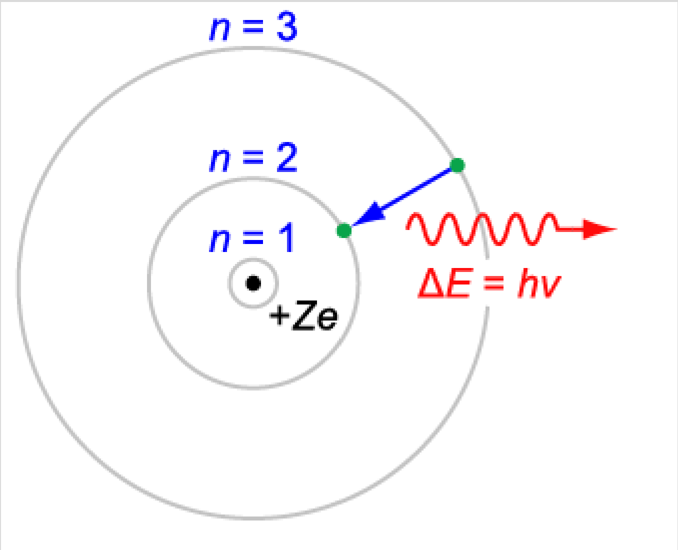
$$\log \rho = const - \frac{z}{H}$$

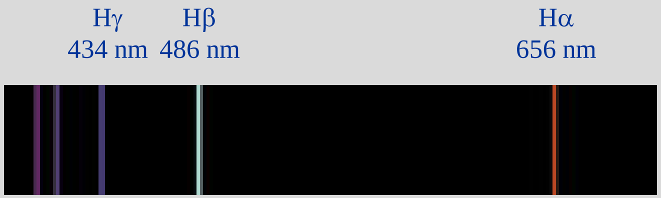


Scale height

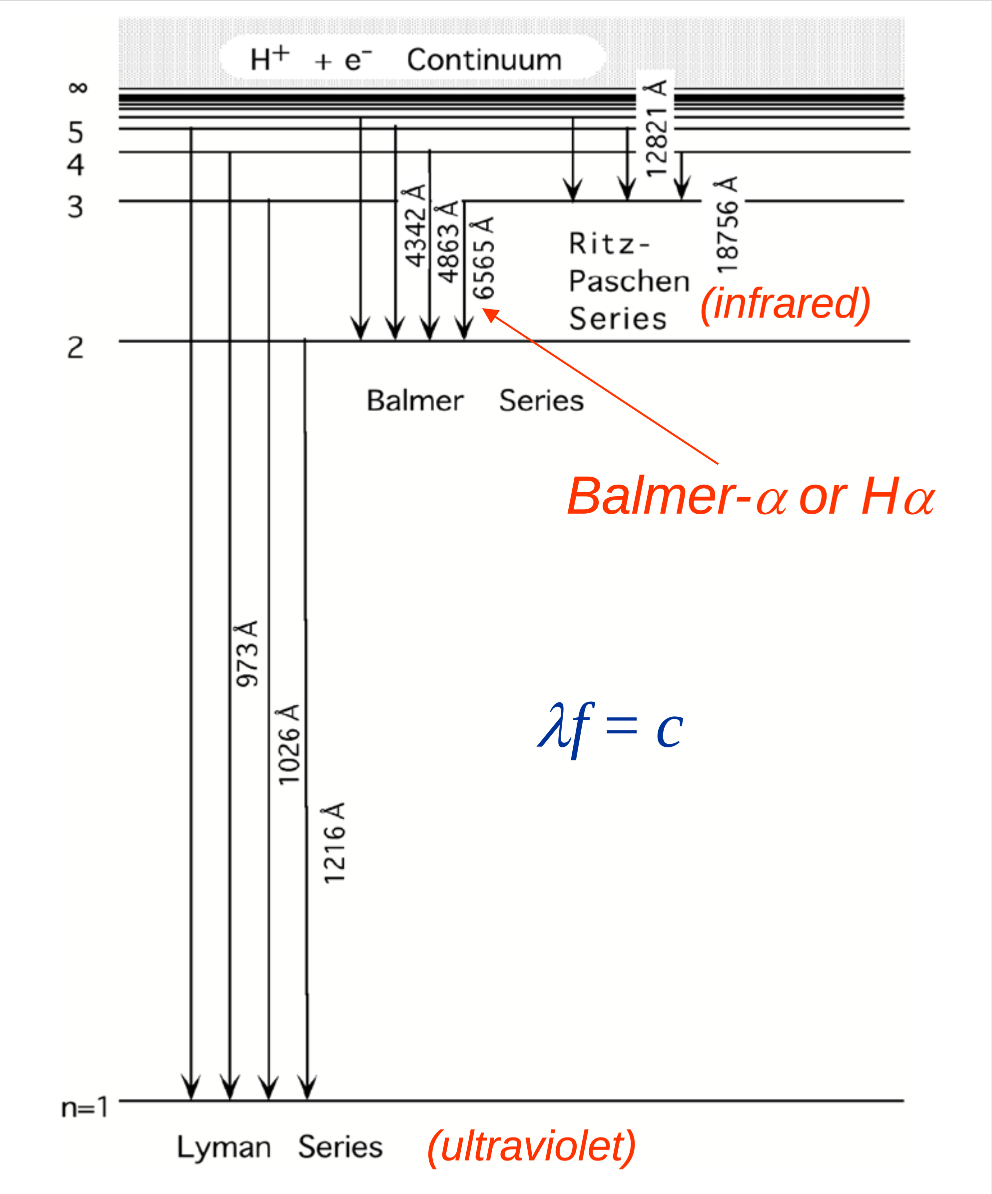
$H = k_B T/gm$

Hydrogen atom





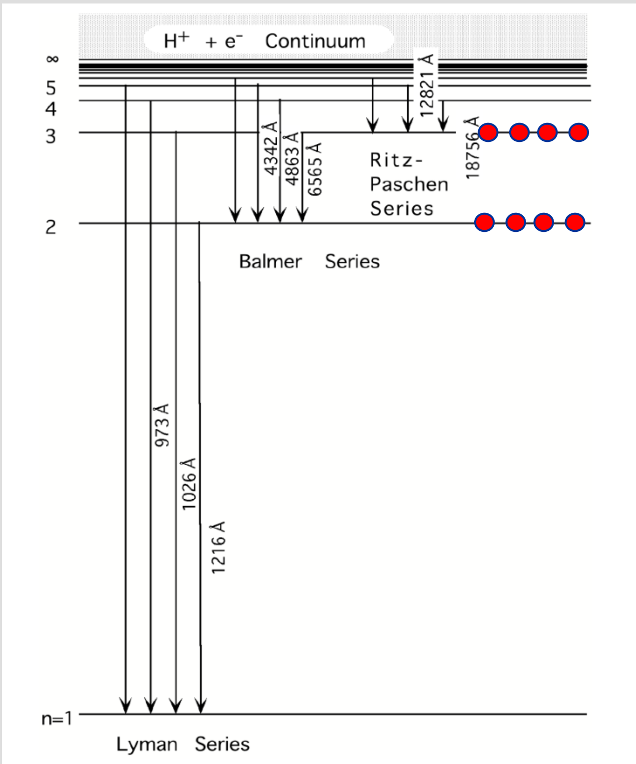
Balmer series



$$\lambda f = c$$

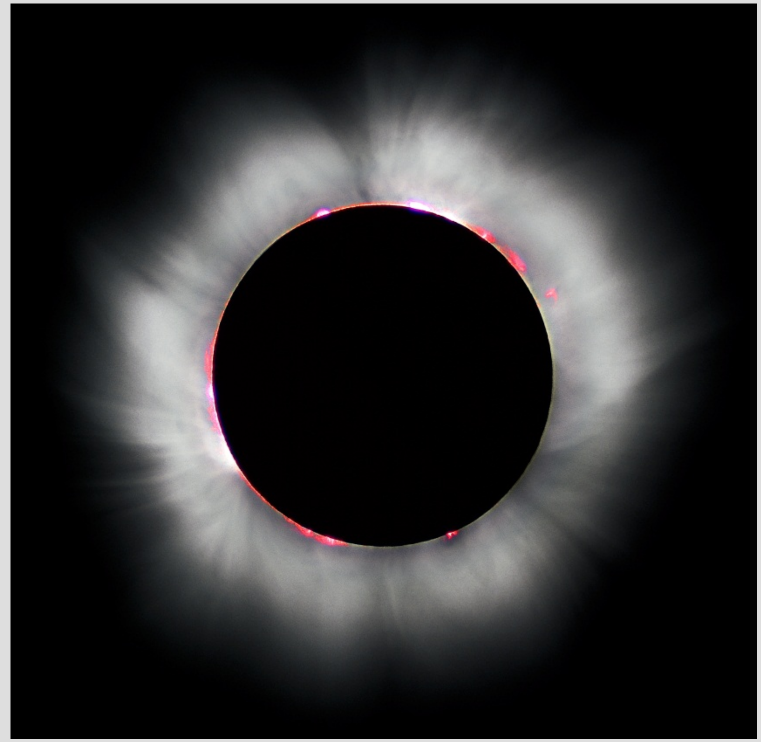
Why is the chromosphere red?

Hydrogen spectrum



T_2

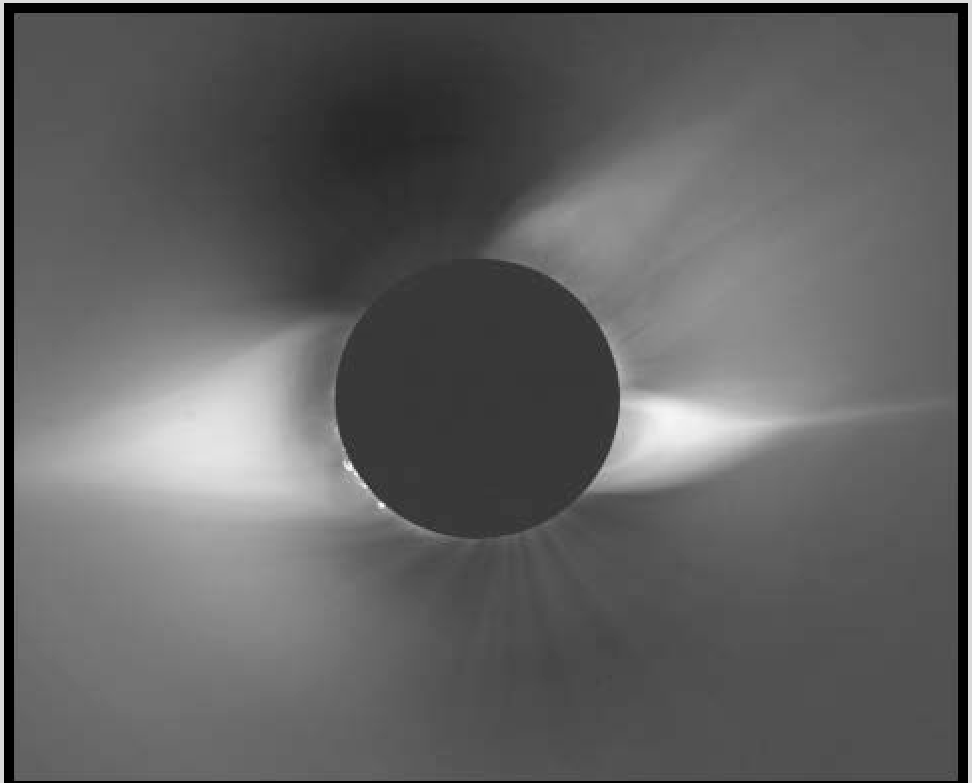
T_1



Hγ 434 nm Hβ 486 nm Hα 656 nm

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

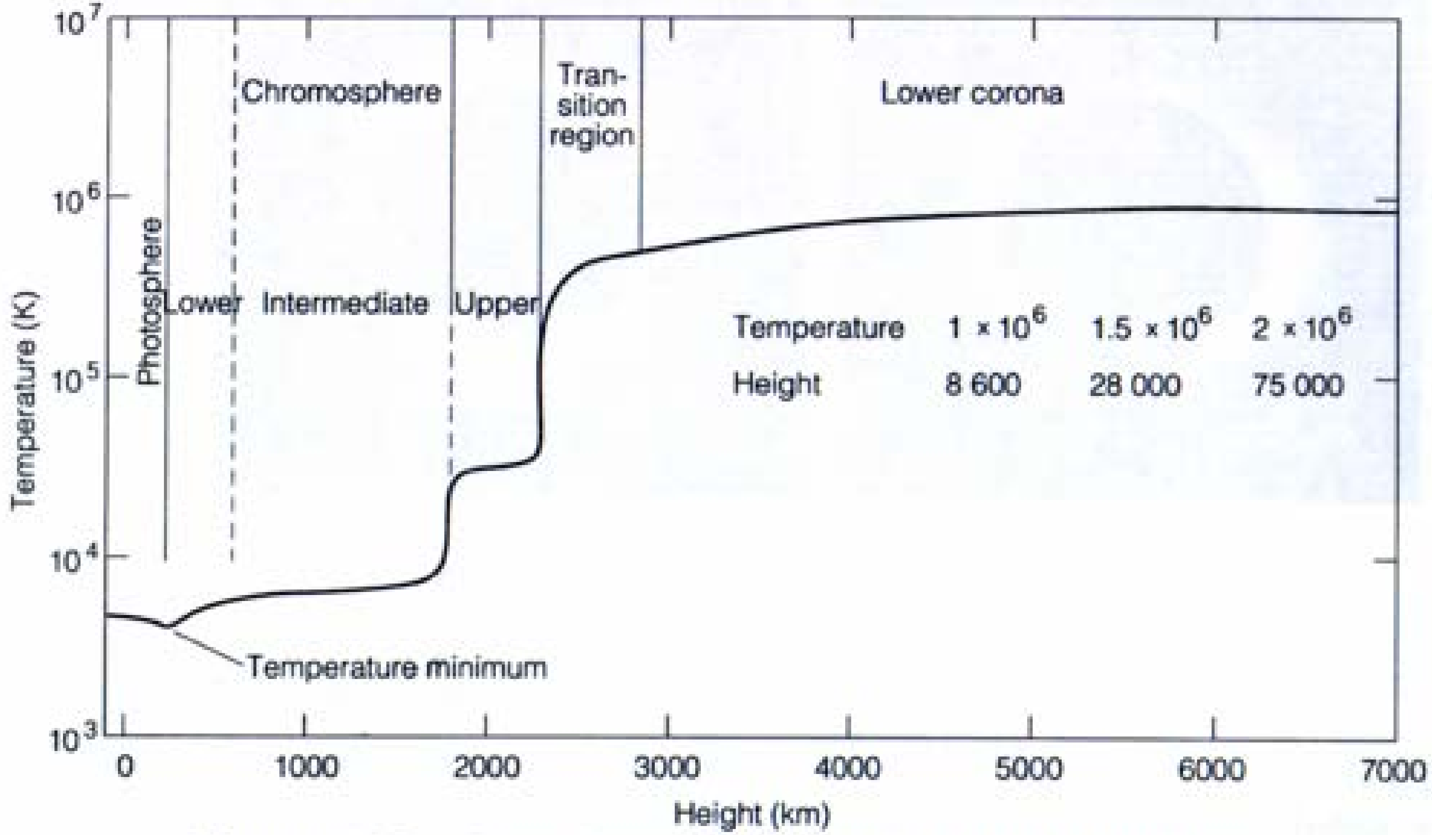
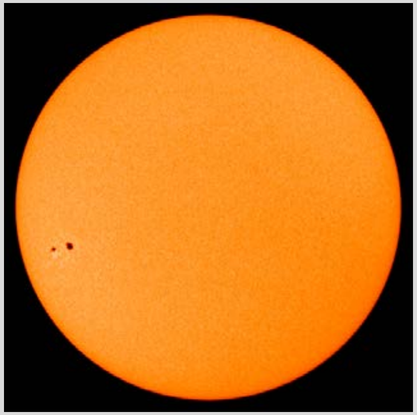
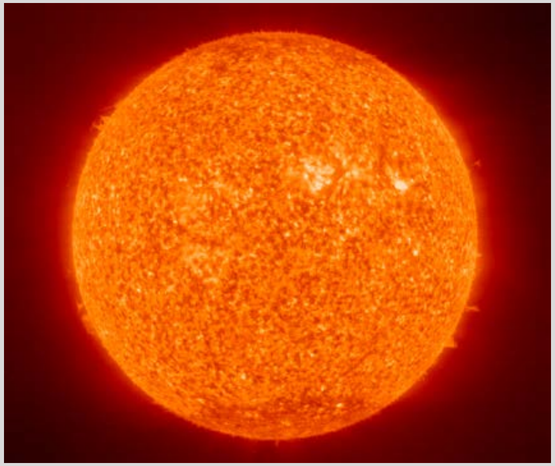


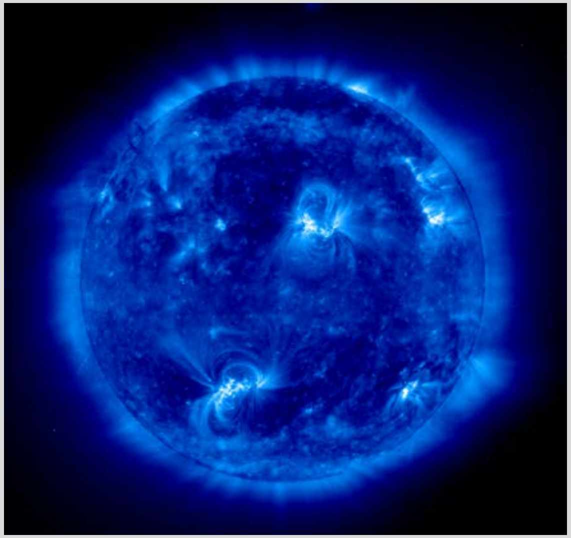
Figure 5.3. Distribution of average temperature in the solar atmosphere (Athay 1976).



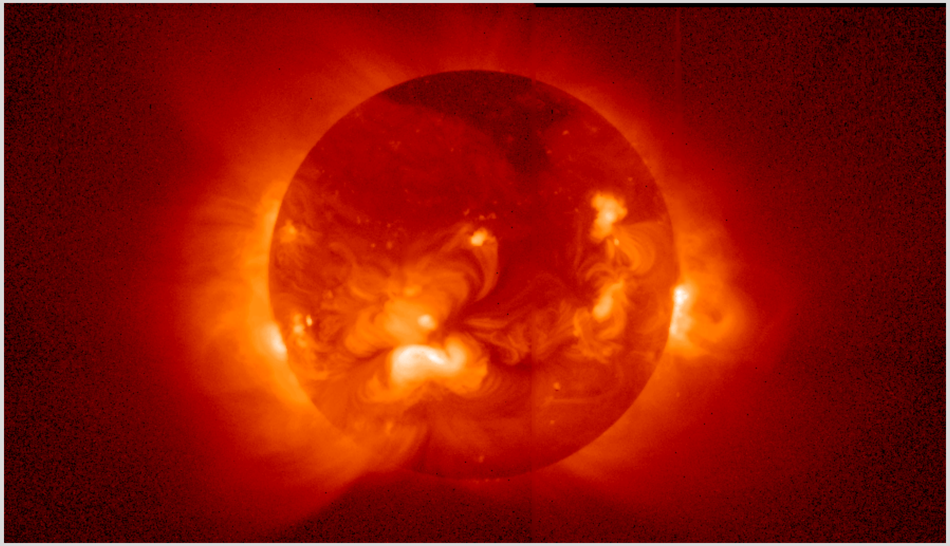
Visible light ~ 6768 Å



He II emission line at 304 Å



(Fe IX/X) at 171 Å



X-ray at 0.3-5 Å

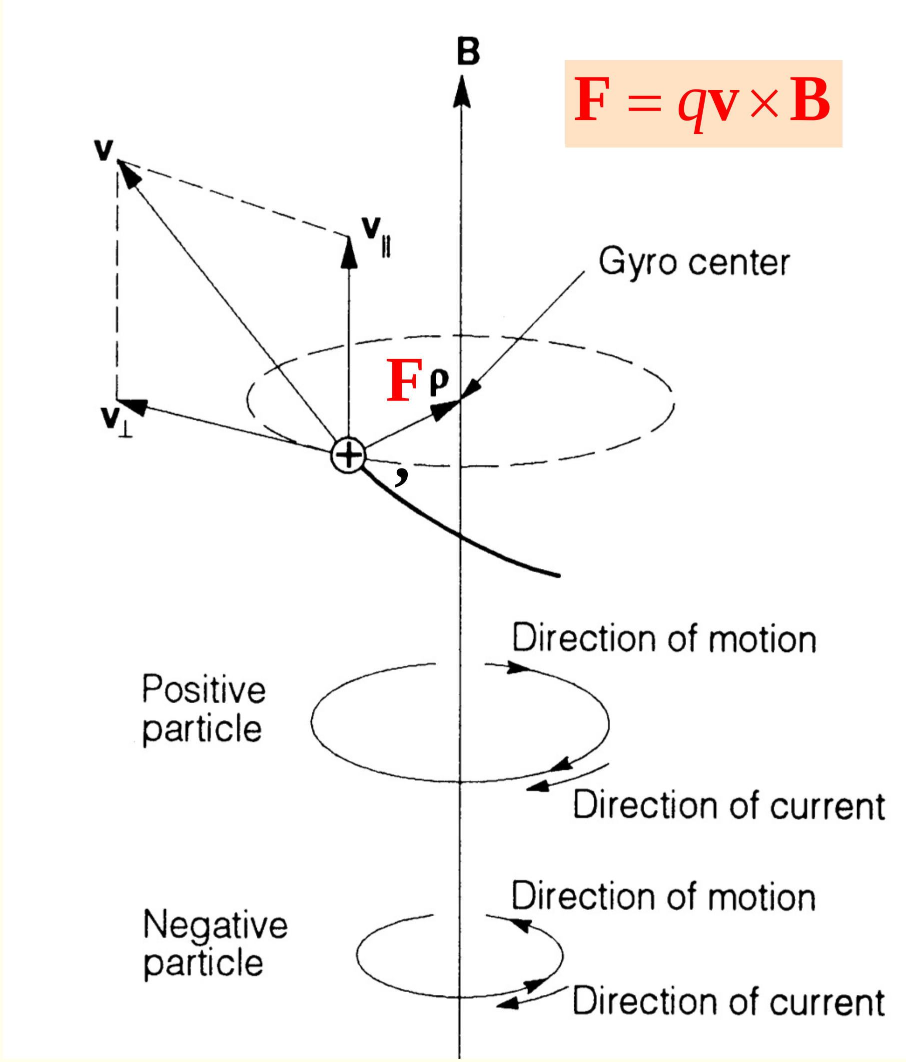
Coronal loops

Why does the plasma follow the magnetic field lines?

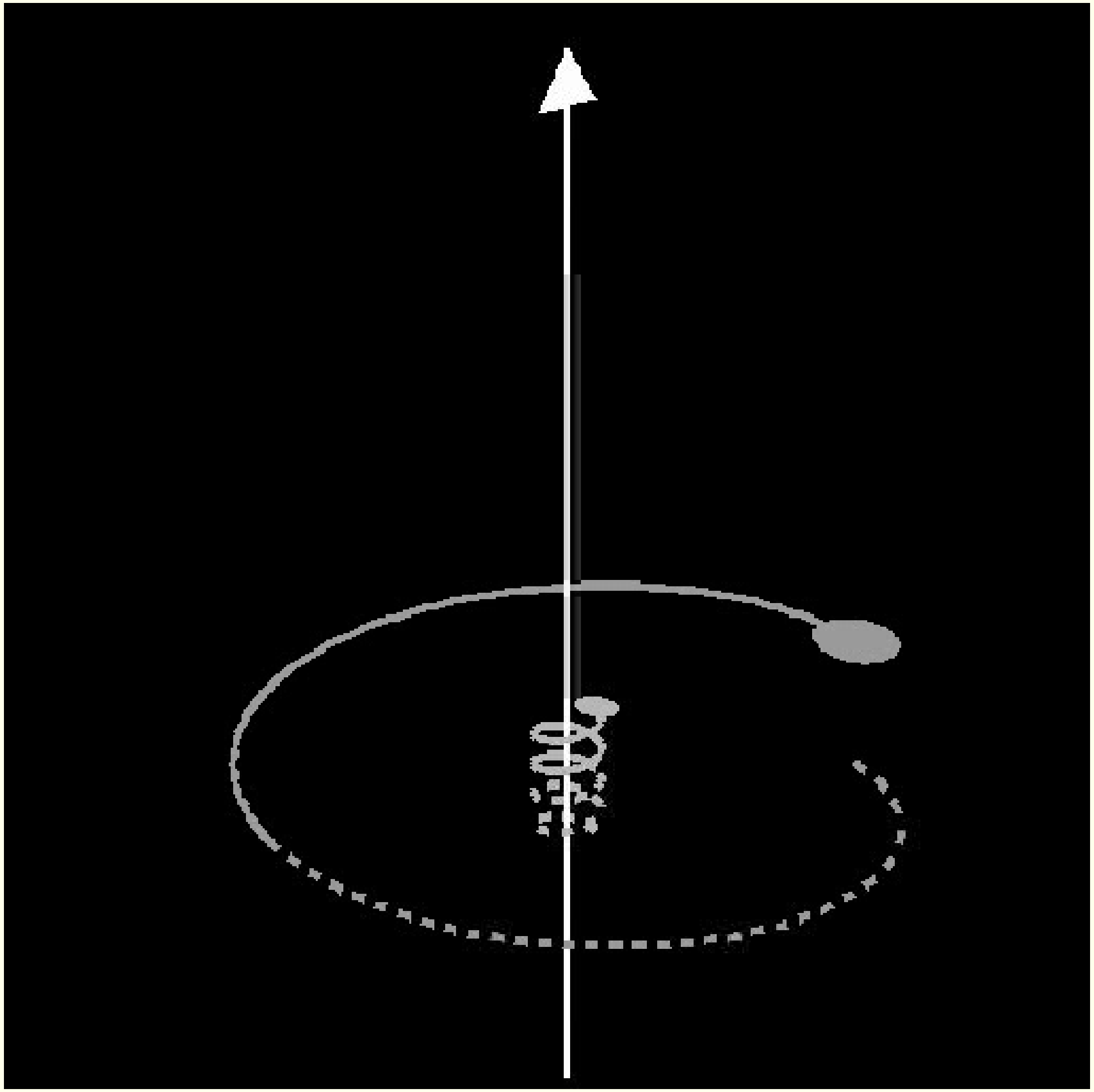
Magnetized plasma

Extremely common in space.

In single particle description of plasma, the particles gyrate in the plane perpendicular to **B**.

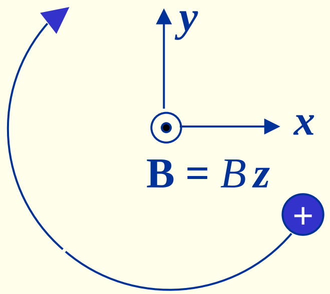


Gyro motion



Gyro motion

Consider a positively charged particle in a magnetic field.



Assume that the magnetic field is in the z-direction.

$$m\frac{d\mathbf{v}}{dt} = q\mathbf{v}\times\mathbf{B} \Rightarrow$$

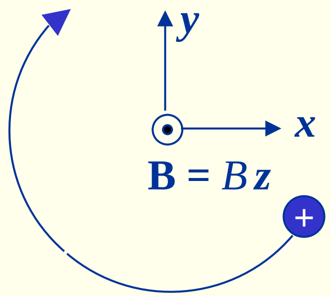
$$\begin{cases} m\dfrac{dv_x}{dt} = qv_yB \\ m\dfrac{dv_y}{dt} = -qv_xB \\ m\dfrac{dv_z}{dt} = 0 \end{cases} \Rightarrow$$

Constant velocity along $\mathbf{z}$

$$\begin{cases} \dfrac{d^2v_x}{dt^2} = \dfrac{qB}{m}\dfrac{dv_y}{dt} = \omega_g\dfrac{dv_y}{dt} = -\omega_g^2 v_x \\ \dfrac{d^2v_y}{dt^2} = -\dfrac{qB}{m}\dfrac{dv_x}{dt} = -\omega_g\dfrac{dv_x}{dt} = -\omega_g^2 v_y \end{cases}$$

$$\Rightarrow$$

Gyro motion



$$\begin{cases} \dfrac{d^2 v_x}{dt^2} = -\omega_g^2 v_x \\ \dfrac{d^2 v_y}{dt^2} = -\omega_g^2 v_y \end{cases}$$

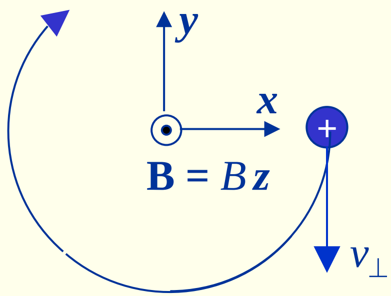
$\Rightarrow$

$$\begin{cases} v_x = Re\left(v_{0x} e^{i(\omega_g t + \delta_x)}\right) = v_{0x} cos(\omega_g t + \delta_x) \\ v_y = Re\left(v_{0y} e^{i(\omega_g t + \delta_y)}\right) = v_{0y} cos(\omega_g t + \delta_y) \end{cases}$$

and

$$\begin{cases} x = \dfrac{v_{0x}}{\omega_g} sin(\omega_g t + \delta_x) \\ y = \dfrac{v_{0y}}{\omega_g} sin(\omega_g t + \delta_y) \end{cases}$$

Gyro motion



$$\begin{cases} v_x = v_{0x} cos(\omega_g t + \delta_x) \\ v_y = v_{0y} cos(\omega_g t + \delta_y) \end{cases}$$

$$\begin{cases} x = \dfrac{v_{0x}}{\omega_g} sin(\omega_g t + \delta_x) \\ y = \dfrac{v_{0y}}{\omega_g} sin(\omega_g t + \delta_y) \end{cases}$$

For a particle starting at time t=0 at (x_0,0) with velocity (0,-$v_\perp$) we get (by definition v_{0x}, v_{0y}, $v_\perp$ > 0).

$$\begin{cases} v_y(0) = v_{0y} \cos\delta_y = -v_\perp & \Longrightarrow v_{0y} = v_\perp,\ \delta_y = \pi \\ v_x(0) = v_{0x} \cos\delta_x = 0 & \Longrightarrow \quad \delta_x = \pm\dfrac{\pi}{2} \end{cases}$$

and

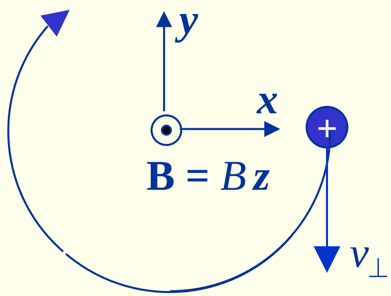
$$\begin{cases} x(0) = \dfrac{v_{0x}}{\omega_g} \sin\delta_x = x_0 & \Rightarrow\ \delta_x = \dfrac{\pi}{2},\ x_0 = \dfrac{v_{0x}}{\omega_g} \\ y(0) = \dfrac{v_\perp}{\omega_g} \sin\pi = 0 \end{cases}$$

So

$$\begin{cases} v_x = v_{0x} cos\left(\omega_g t + \dfrac{\pi}{2}\right) = -v_{0x} sin(\omega_g t) \\ v_y = v_\perp cos(\omega_g t + \pi) = -v_\perp cos(\omega_g t) \end{cases}$$

$$\begin{cases} x = \dfrac{v_{0x}}{\omega_g} sin\left(\omega_g t + \dfrac{\pi}{2}\right) = \dfrac{v_{0x}}{\omega_g} cos(\omega_g t) = \dfrac{v_{0x}}{\omega_g} cos(-\omega_g t) \\ y = \dfrac{v_\perp}{\omega_g} sin(\omega_g t + \pi) = -\dfrac{v_\perp}{\omega_g} sin(\omega_g) = \dfrac{v_\perp}{\omega_g} sin(-\omega_g t) \end{cases}$$

Gyro motion



$$\begin{cases} v_x = -v_{0x} sin(\omega_g t) \\ v_y = -v_\perp cos(\omega_g t) \end{cases}$$

$$\begin{cases} x = \frac{v_{0x}}{\omega_g} cos(-\omega_g t) \\ y = \frac{v_\perp}{\omega_g} sin(-\omega_g t) \end{cases}$$

Then (because the force is all the time perpendicular to the velocity)

$$v_x{}^2 + v_y{}^2 = v_{0x}{}^2 sin^2(\omega_g t) + v_\perp{}^2 cos^2(\omega_g t) = v_\perp{}^2$$

so

$$v_{0x} = v_\perp$$

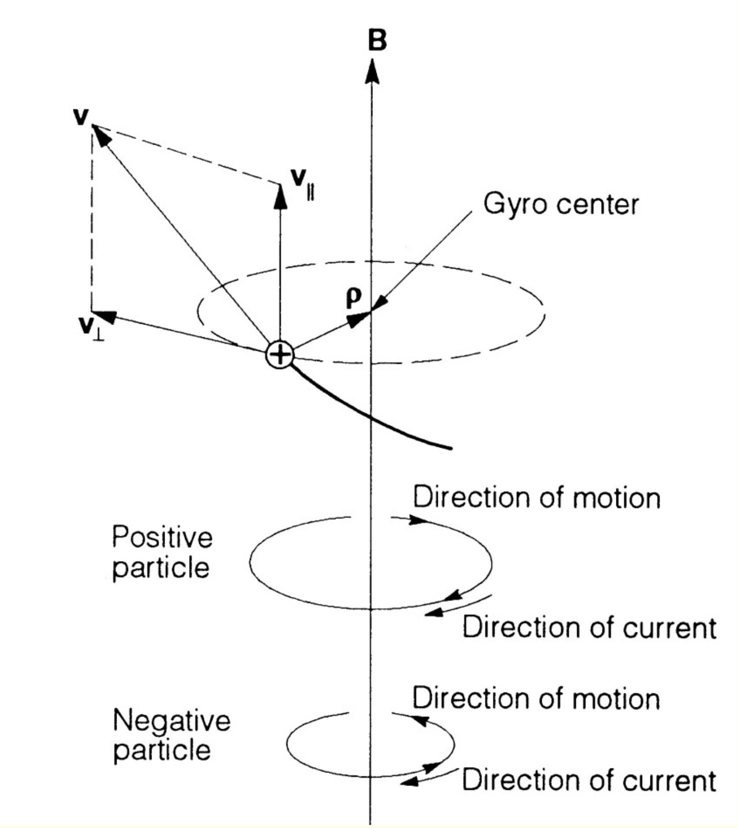
So

$$\begin{cases} x = \frac{v_\perp}{\omega_g} cos(-\omega_g t) \\ y = \frac{v_\perp}{\omega_g} sin(-\omega_g t) \end{cases}$$

and

$$x^2 + y^2 = \frac{v_\perp{}^2}{\omega_g{}^2} \equiv r_L{}^2 = \varrho^2$$

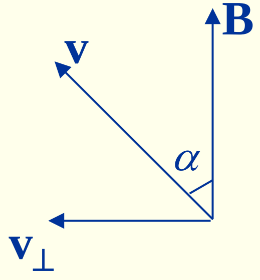
Gyro (Larmor) radius



Magnetic force: $\mathbf{F} = q\mathbf{v}_{\perp} \times \mathbf{B}$

Centripetal force: $\mathbf{F} = \dfrac{m v_{\perp}^{2}}{\rho}\hat{\boldsymbol{\rho}}$

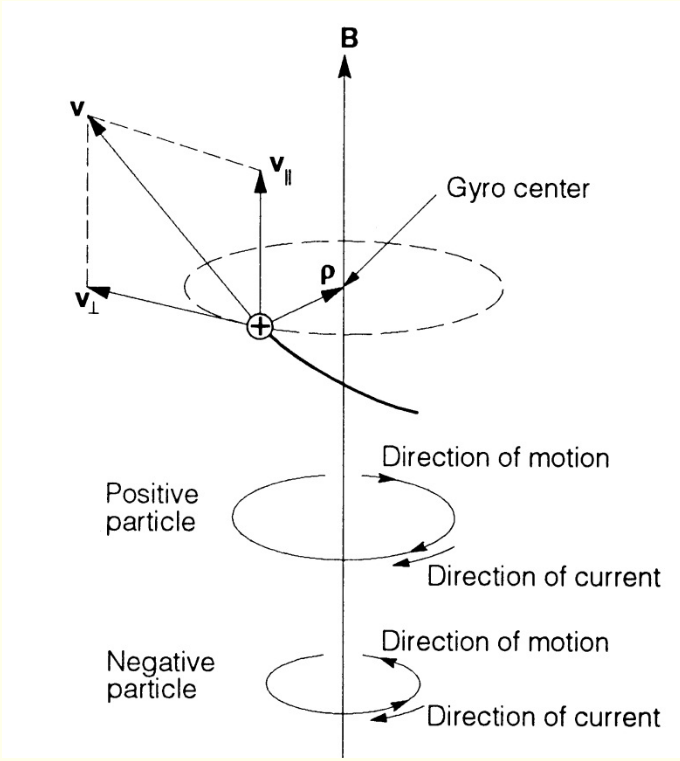
$\Leftrightarrow$



$v_{\perp} = v \cdot \sin\alpha$

$$\boxed{\rho = \frac{m v_{\perp}}{qB}}$$

Gyro frequency



$$\rho = \frac{mv_\perp}{qB}$$

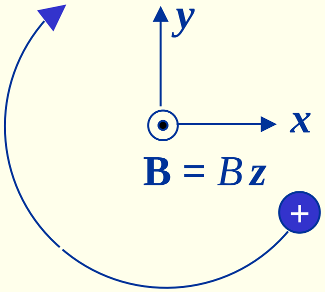
$$\omega\rho = v_\perp$$

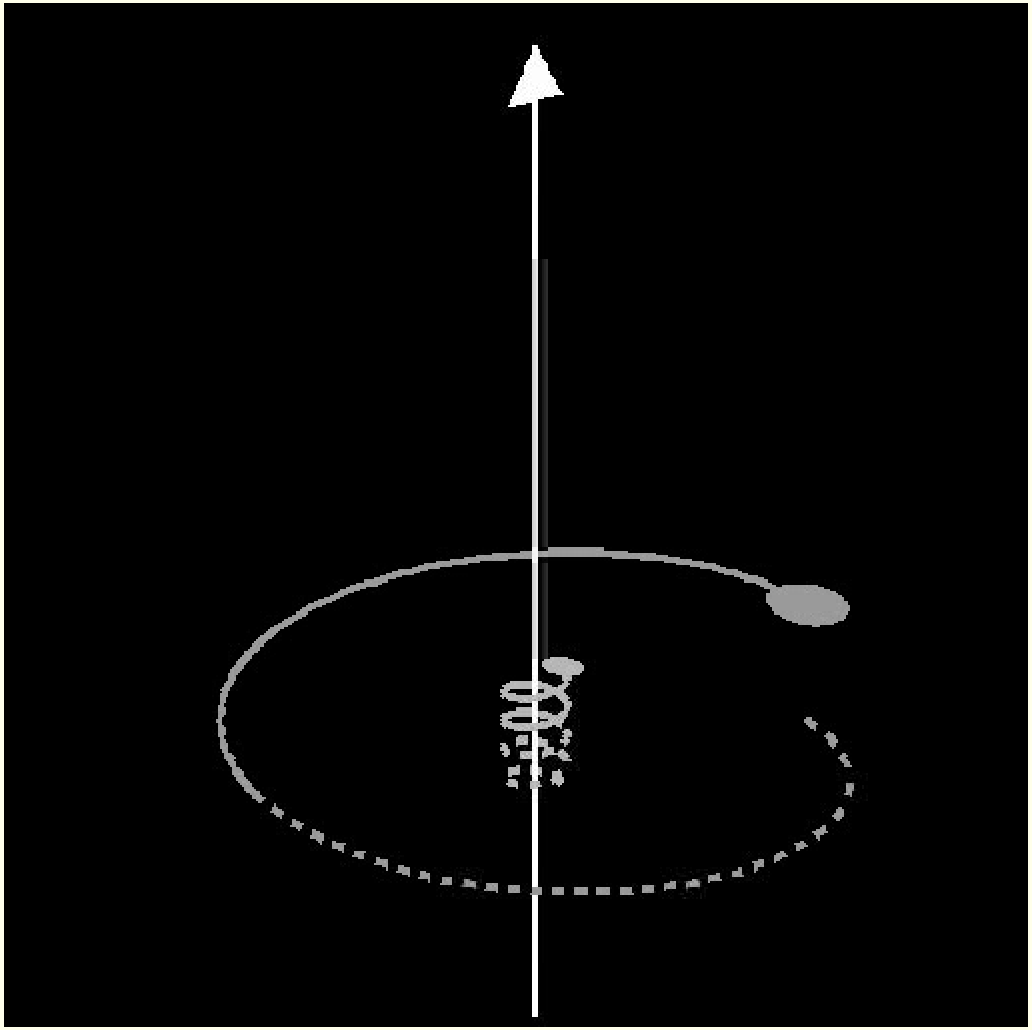
$$\Rightarrow$$

$$\boxed{\omega_g = \frac{qB}{m}}$$

$$\omega = 2\pi f$$

Drift motion





Then

$$x = r_L cos(-\omega_g t)$$
$$y = r_L sin(-\omega_g t)$$

$$\omega_g = \frac{qB}{m}$$

$$r_L = \frac{mv_\perp}{qB}$$

Magnetized plasma

A magnetic field drastically changes some of the plasma properties because the plasma particles are tightly bound to the magnetic field lines.

It is difficult for the particles to move perpendicular to **B**, but easy to move along **B**.

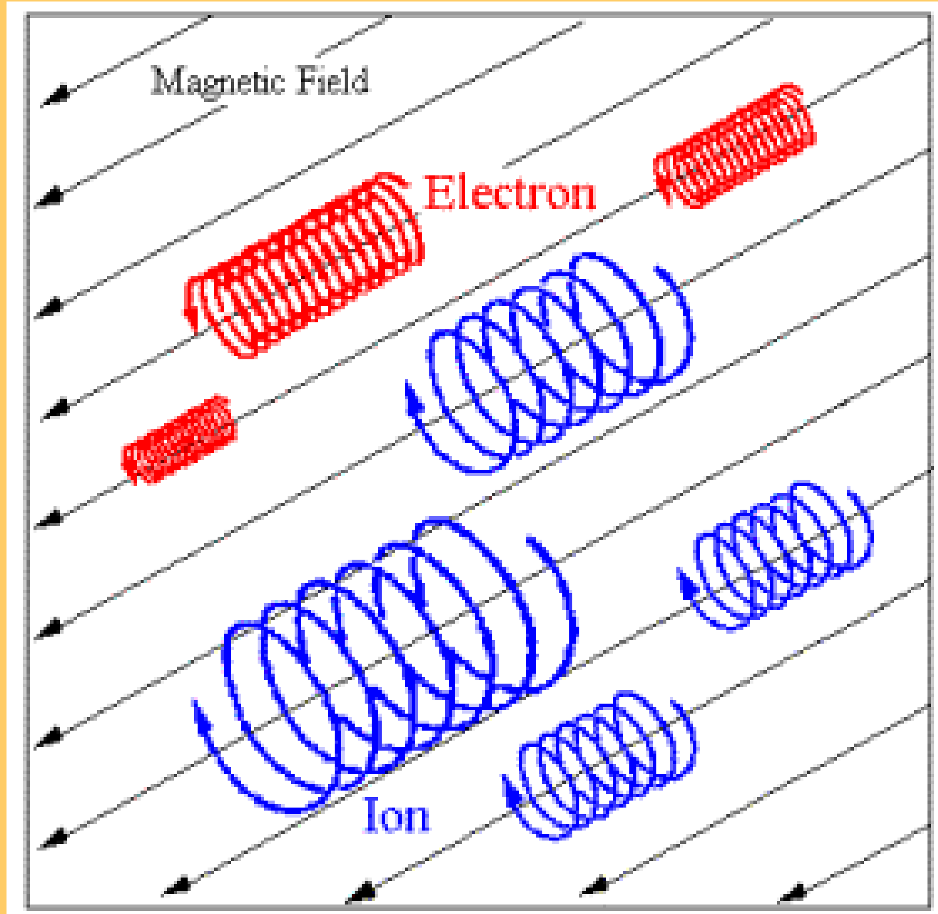
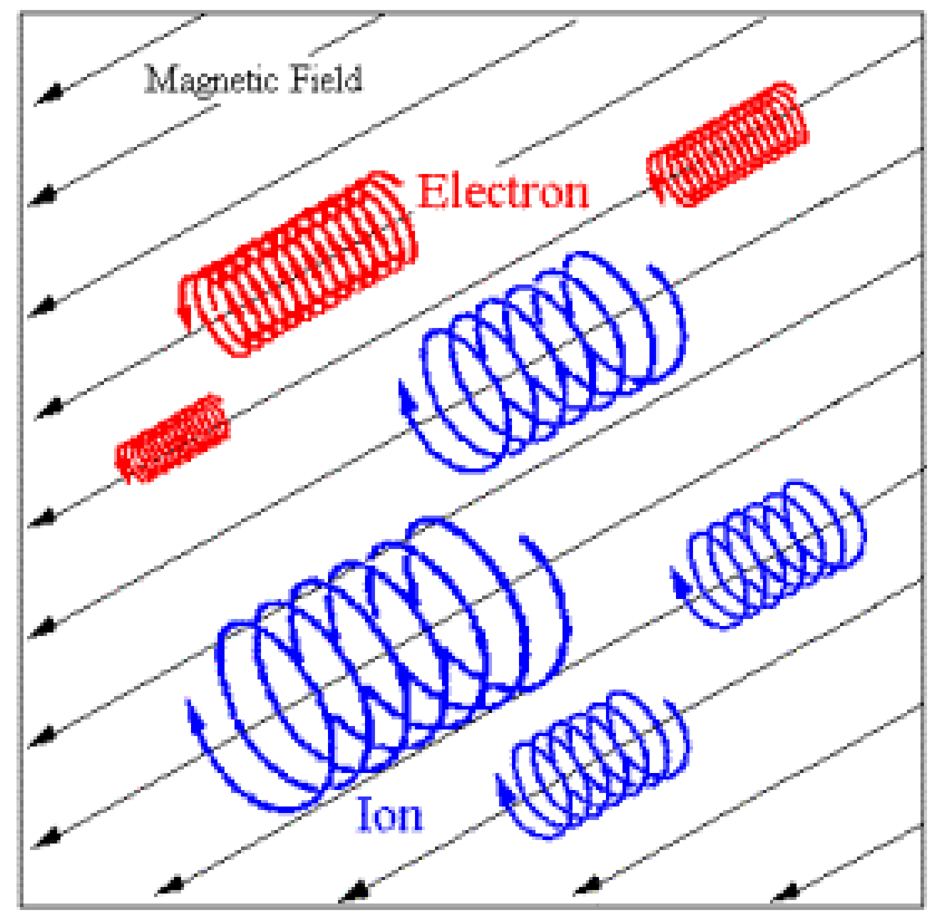


Figure 10: Gyration of charged particle along magnetic field lines.

Think about this:



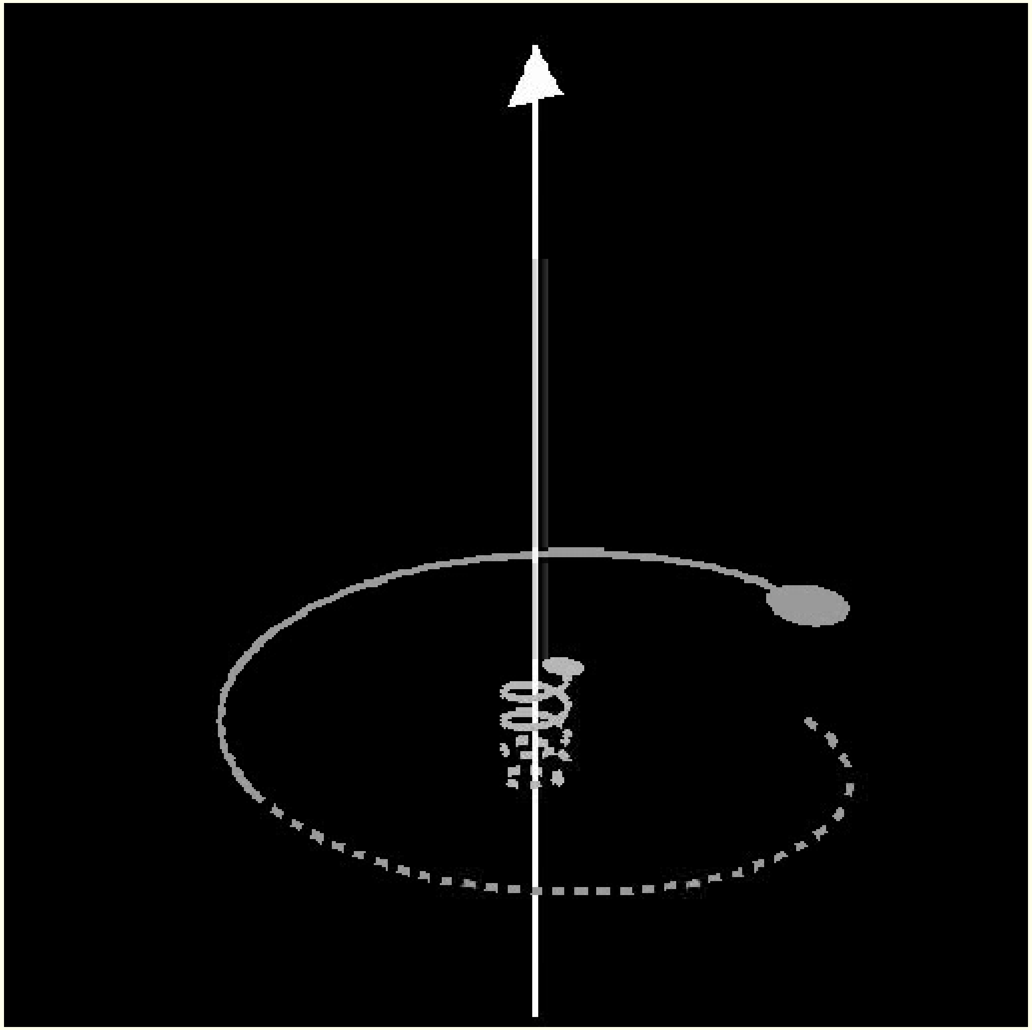
Can you think about a physical property of the plasma that varies with the direction?

(Such a property is called *anisotropic*.)

Coronal loops

Why does the plasma follow the magnetic field lines?

Gyro motion



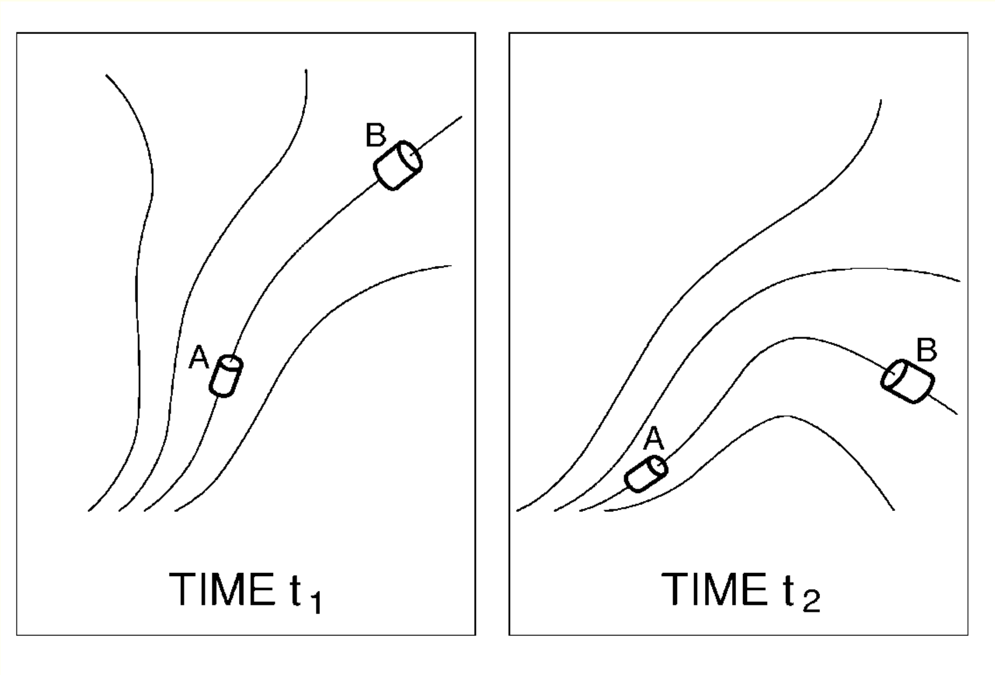
Equipartion principle

Statistically the kinetic energy is equally distributed along the three dimensions:

$$E_{\parallel} = \frac{1}{2} k_B T$$

$$E_{\perp} = \frac{2}{2} k_B T$$

Frozen in magnetic field lines



In fluid description of plasma two plasma elements that are connected by a common magnetic field line at time t_1 will be so at any other time t_2.

This applies if the magnetic Reynolds number is large:

$$R_m = \mu_0 \sigma l_c v_c >> 1$$

An example of the collective behaviour of plasmas.

Maxwell's equations

Gauss' law

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

No magnetic monopoles

$$\nabla \cdot \mathbf{B} = 0$$

Faraday's law

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

Ampére's law

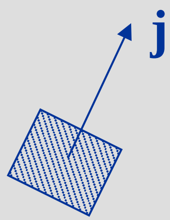
$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

Lorentz' force equation

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

Ohm's law

$$\mathbf{j} = \sigma \mathbf{E}$$



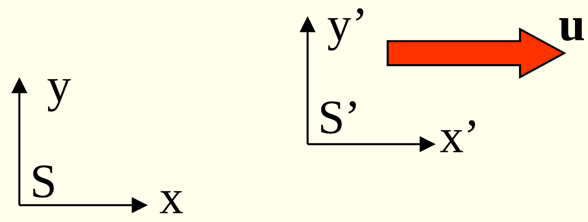
Energy density

$$W_B = \frac{B^2}{2\mu_0}, \quad W_E = \varepsilon_0 \frac{E^2}{2}$$

$$\nabla \cdot \mathbf{A} = \frac{\partial A_x}{\partial x} + \frac{\partial A_y}{\partial y} + \frac{\partial A_z}{\partial z}$$

$$\nabla \times \mathbf{A} = \left(\frac{\partial A_z}{\partial y} - \frac{\partial A_y}{\partial z}, \frac{\partial A_x}{\partial z} - \frac{\partial A_z}{\partial x}, \frac{\partial A_y}{\partial x} - \frac{\partial A_x}{\partial y} \right)$$

Field transformations (relativistic)



*Relativistic transformations (perpendicular to the velocity **u**):*

$$\mathbf{E}' = \frac{\mathbf{E} + \mathbf{u}\times\mathbf{B}}{\sqrt{1-u^2/c^2}}$$

$$\mathbf{B}' = \frac{\mathbf{B} - \left(\mathbf{u}/c^2\right)\times\mathbf{E}}{\sqrt{1-u^2/c^2}}$$

For $u << c$:

$$\mathbf{E}' = \mathbf{E} + \mathbf{u}\times\mathbf{B}$$

induced electric field

$$\mathbf{E} = \mathbf{E}' - \mathbf{u}\times\mathbf{B}$$

$$\mathbf{B}' = \mathbf{B}$$

Frozen in magnetic flux *PROOF*

(1) $\mathbf{j} = \sigma \mathbf{E}' = \sigma\left(\mathbf{E} + \mathbf{v}\times\mathbf{B}\right)$ Ohm's law

(2) $\mu_0 \mathbf{j} = \nabla\times\mathbf{B} - \cancel{\frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t}}$ Ampère's law

(3) $\frac{\partial \mathbf{B}}{\partial t} = -\nabla\times\mathbf{E}$ Faraday's law

(1) $\Rightarrow$ $\mathbf{E} = \frac{\mathbf{j}}{\sigma} - \mathbf{v}\times\mathbf{B}$

(3+1) $\Rightarrow$ $\frac{\partial \mathbf{B}}{\partial t} = -\nabla\times\left(\frac{\mathbf{j}}{\sigma} - \mathbf{v}\times\mathbf{B}\right)$

(2) $\Rightarrow$ $\frac{\partial \mathbf{B}}{\partial t} = -\nabla\times\left(\frac{\nabla\times\mathbf{B}}{\mu_0\sigma} - \mathbf{v}\times\mathbf{B}\right)$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla\times\left(\mathbf{v}\times\mathbf{B}\right) - \frac{1}{\mu_0\sigma}\nabla\times\left(\nabla\times\mathbf{B}\right) =$$

$$\nabla\times\left(\mathbf{v}\times\mathbf{B}\right) - \frac{1}{\mu_0\sigma}\left(\cancel{\nabla\left(\nabla\cdot\mathbf{B}\right)} - \nabla^2\mathbf{B}\right)$$

$$\because \quad \frac{\partial \mathbf{B}}{\partial t} = \nabla\times\left(\mathbf{v}\times\mathbf{B}\right) + \frac{1}{\mu_0\sigma}\nabla^2\mathbf{B}$$

Frozen in magnetic flux *PROOF II*

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \frac{1}{\mu_0 \sigma} \nabla^2 \mathbf{B}$$

A

B

Order of magnitude estimate:

$$\frac{A}{B} = \frac{\nabla \times (\mathbf{v} \times \mathbf{B})}{\frac{1}{\mu_0 \sigma} \nabla^2 \mathbf{B}} \approx \frac{\frac{v \Delta B}{L}}{\frac{\Delta B}{\mu_0 \sigma L^2}} = v L \mu_0 \sigma \equiv R_m$$

Magnetic Reynolds number R_m:

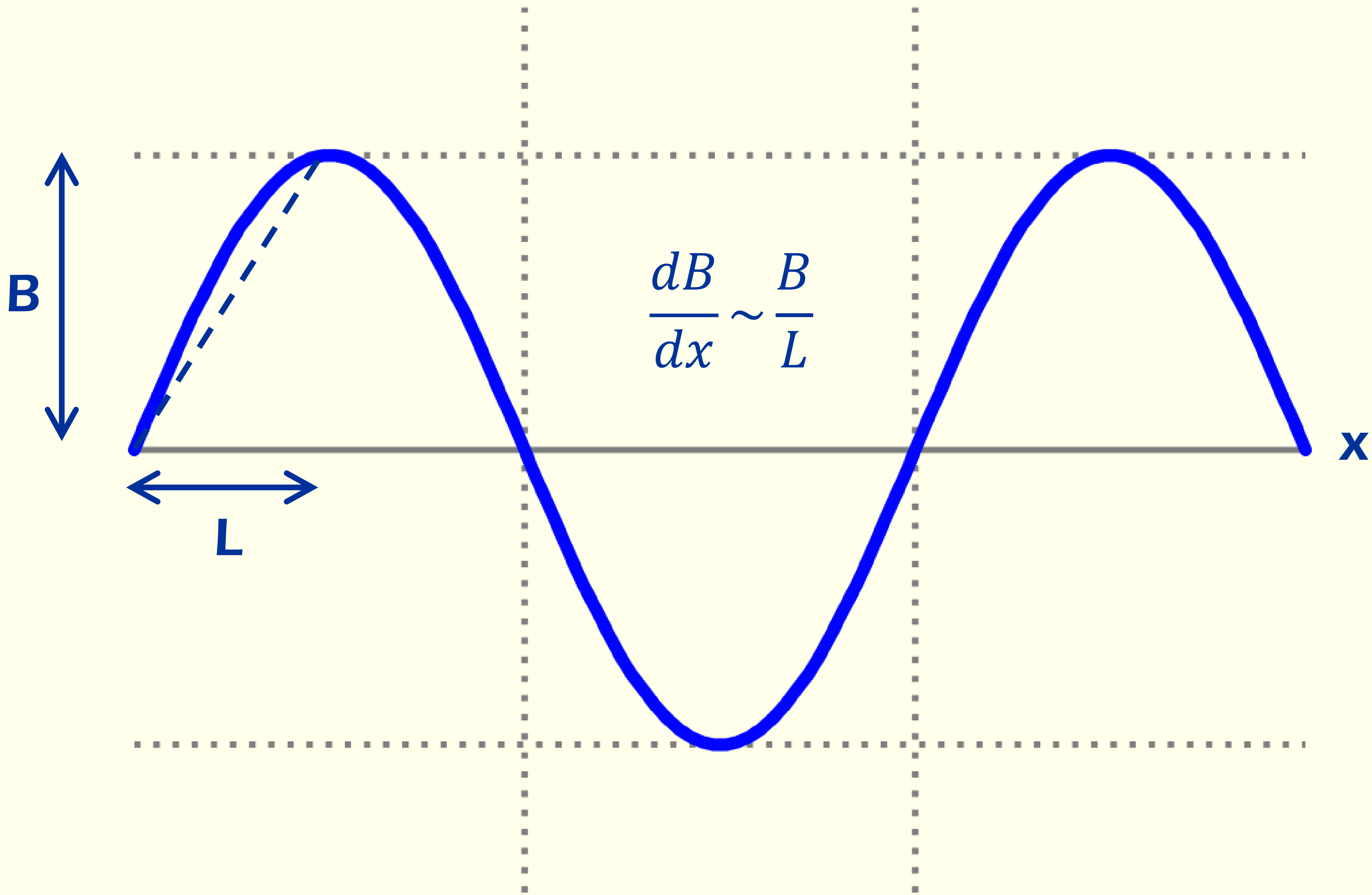
$$R_m >> 1 \Rightarrow \quad \frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})$$

Frozen-in fields!

$$R_m << 1 \Rightarrow \quad \frac{\partial \mathbf{B}}{\partial t} = \frac{1}{\mu_0 \sigma} \nabla^2 \mathbf{B}$$

Diffusion equation!

Typical length scale L

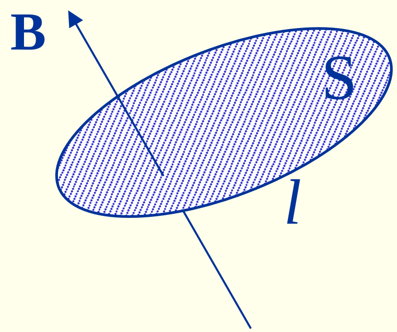


$$\frac{dB}{dx} \sim \frac{B}{L}$$

Frozen in magnetic flux *PROOF III*

$$R_m >> 1 \Rightarrow \boxed{\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left(\mathbf{v} \times \mathbf{B}\right)}$$

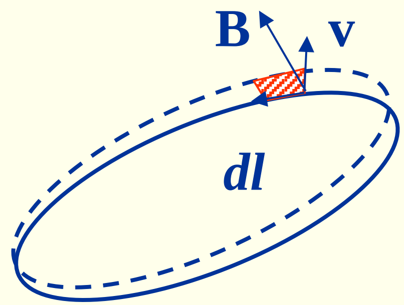
Consider the change of magnetic flux Φ through a surface S with contour l which follows plasma motion



$$\Phi = \int_S \mathbf{B} \cdot d\mathbf{S}$$

$$\frac{d\Phi}{dt} = \int_S \frac{\partial \mathbf{B}}{\partial t} \cdot d\mathbf{S} + \frac{d\Phi_c}{dt}$$

$\dfrac{d\Phi_c}{dt}$ This term is due to change in the surface S due to plasma motion

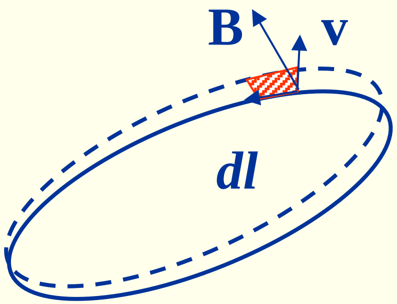


has an area of $\left(\mathbf{v} \cdot dt\right) \times d\mathbf{l}$

The flux through is $\left(\mathbf{v} \cdot dt\right) \times d\mathbf{l} \cdot \mathbf{B}$

$$\because \frac{d\Phi_c}{dt} = \int_l \mathbf{v} \times d\mathbf{l} \cdot \mathbf{B} =$$

Frozen in magnetic flux *PROOF IV*



$$\frac{d\Phi_c}{dt} = \int_l \mathbf{v}\times d\mathbf{l}\cdot\mathbf{B} =$$

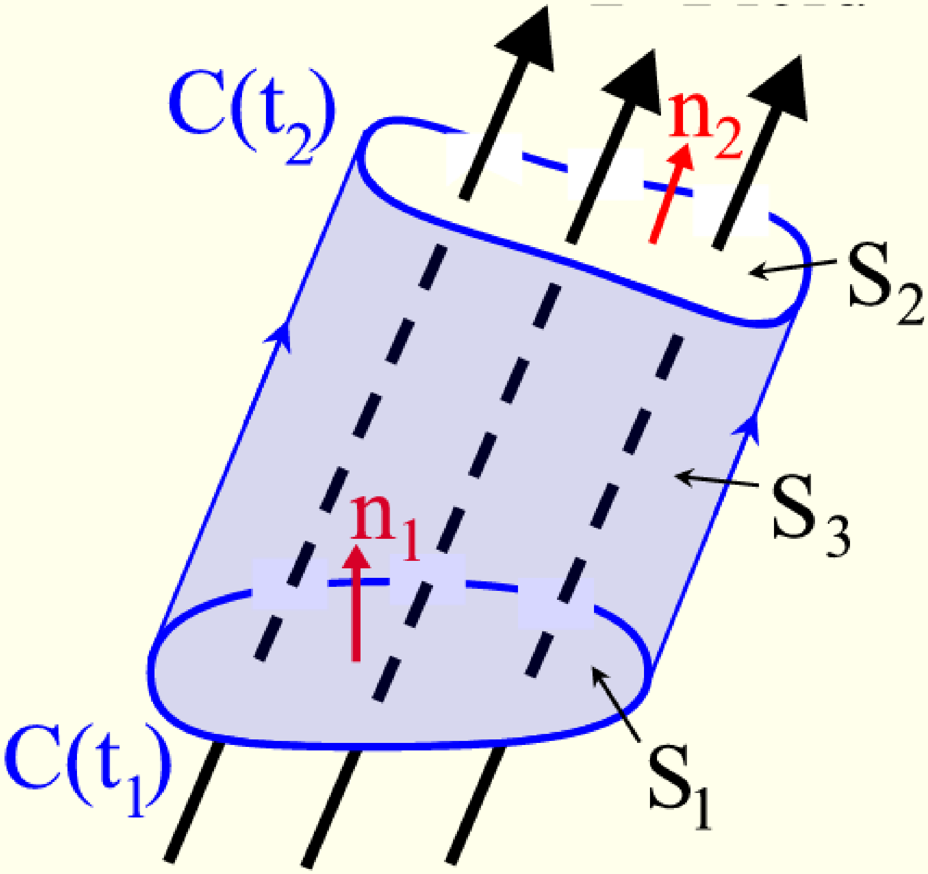
$$-\int_l \mathbf{v}\times\mathbf{B}\cdot d\mathbf{l} = -\int_S \nabla\times(\mathbf{v}\times\mathbf{B})\cdot d\mathbf{S}$$

$$\because \frac{d\Phi}{dt} = \int_S \frac{\partial\mathbf{B}}{\partial t}\cdot d\mathbf{S} - \int_S \nabla\times(\mathbf{v}\times\mathbf{B})\cdot d\mathbf{S} =$$

$$\int_S \left[\frac{\partial\mathbf{B}}{\partial t} - \nabla\times(\mathbf{v}\times\mathbf{B})\right]\cdot d\mathbf{S} = 0$$

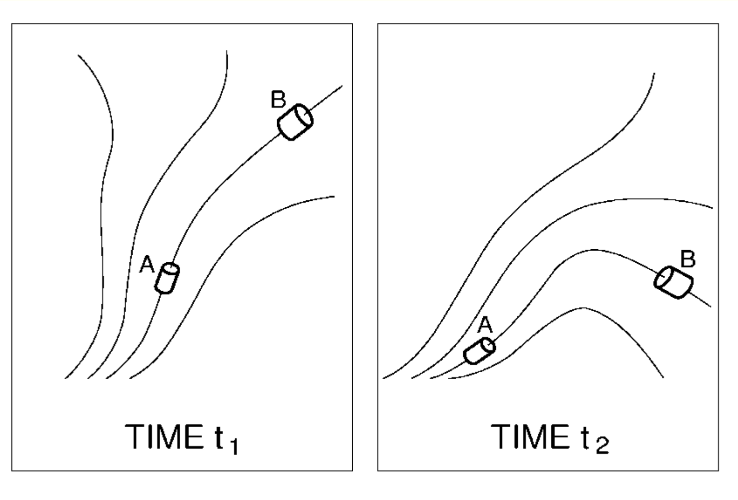
$$\boxed{\because \frac{d\Phi}{dt} = 0}$$

Frozen in magnetic field lines



A *flux tube* is defined by following **B** from the surface S. Due to the frozen-in theorem the flux tube keeps its identity and the plasma in a flux tube stays in it for ever.

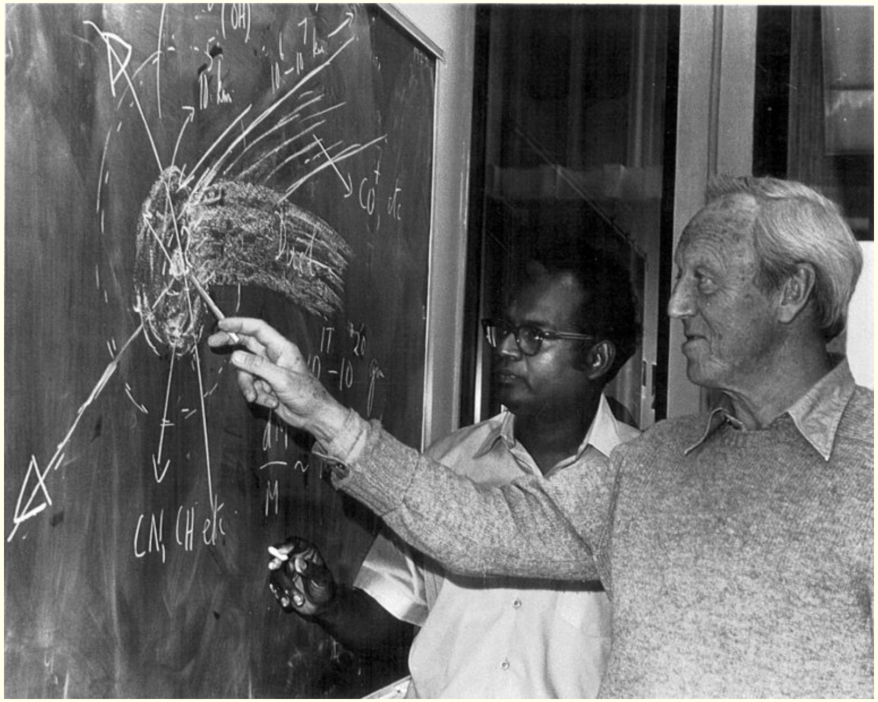
In particular if we let the tube become infinitely thin we have the theorem of frozen-in field lines.



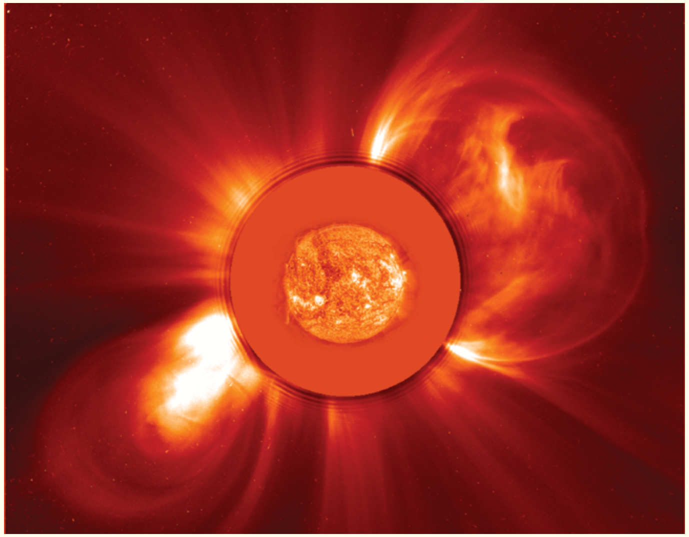
Frozen in magnetic field lines: some history

- Also known as *Alfvén's theorem*
- Hannes Alfvén (1908-1995), professor at KTH
- Alfvén received the Nobel prize in 1970

  'for fundamental work and discoveries in magneto-hydrodynamics with fruitful applications in different parts of plasma physics'



Magnetized plasma



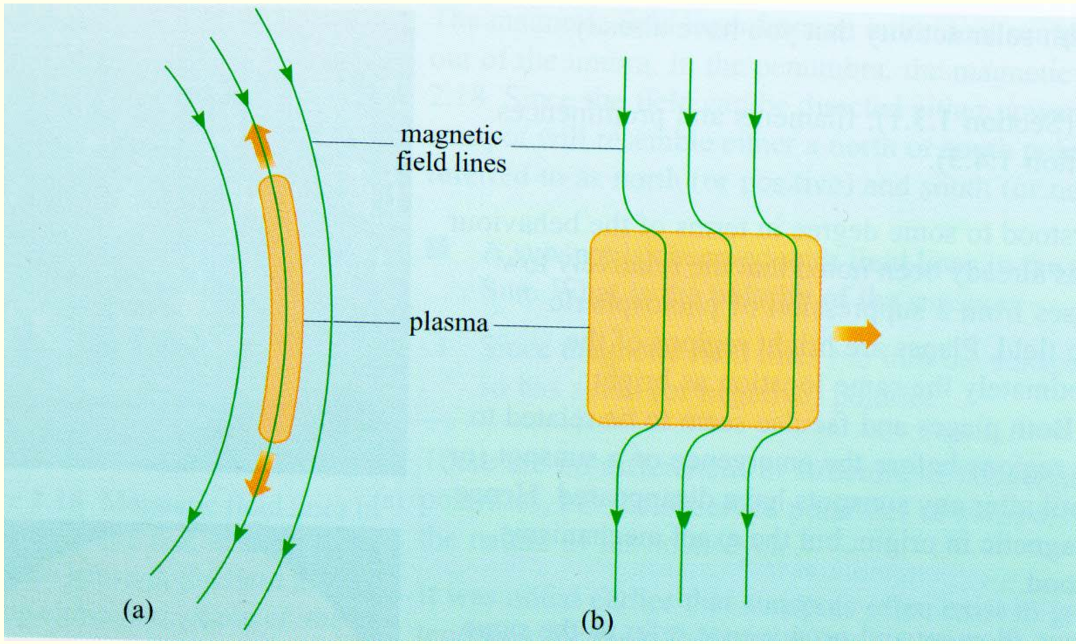
Solar magnetic field

Northern lights (aurora)

Different *plasma populations* (plasmas with different temperature and density) keep to their own field line, and thus "paint out" the magnetic field lines.

Coronal loop

Does the plasma follow the magnetic field (a) or the other way around (b)?



Depends on relative energy density (pressure)

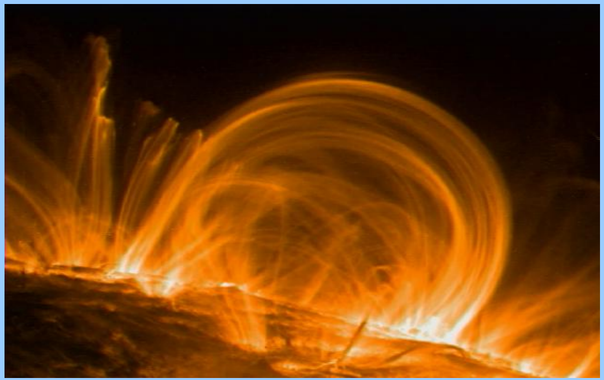
$$p_{pl} = nk_B T$$

$$p_B = \frac{B^2}{2\mu_0}$$

$$\beta = \frac{p_{pl}}{p_B}$$

$\beta << 1$ $\beta >> 1$

Plasma beta



Coronal loop

B = 0.2 T
n = 10^{23} m^{-3} (~1% of density at Earth surface)
T = 6000 K

Plasma (thermal) pressure/energy density: $p_{pl} = nk_bT$

Magnetic pressure/energy density: $p_b = B^2/2\mu_0$

$$\beta = \frac{p_{pl}}{p_B}$$

Green — $\beta >> 1$ The plasma dominates the magnetic field

Red — $\beta \sim 1$ Some complicated in-between behaviour

Blue — $\beta << 1$ The magnetic field dominates the plasma

Plasma beta

$B = 0.2$ T
$n = 10^{23}$ m^{-3} (~1% of density at Earth surface)
$T = 6000$ K

Plasma (thermal) pressure/energy density: $p_{pl} = nk_bT = \quad 10^{23} \cdot 1.38 \cdot 10^{-23} \cdot 6000 \approx 8.3\,\text{kPa}$

Magnetic pressure/energy density: $p_b = B^2/2\mu_0 = \dfrac{0.2^2}{2 \cdot 4\pi \cdot 10^{-7}} \approx 16\,\text{kPa}$

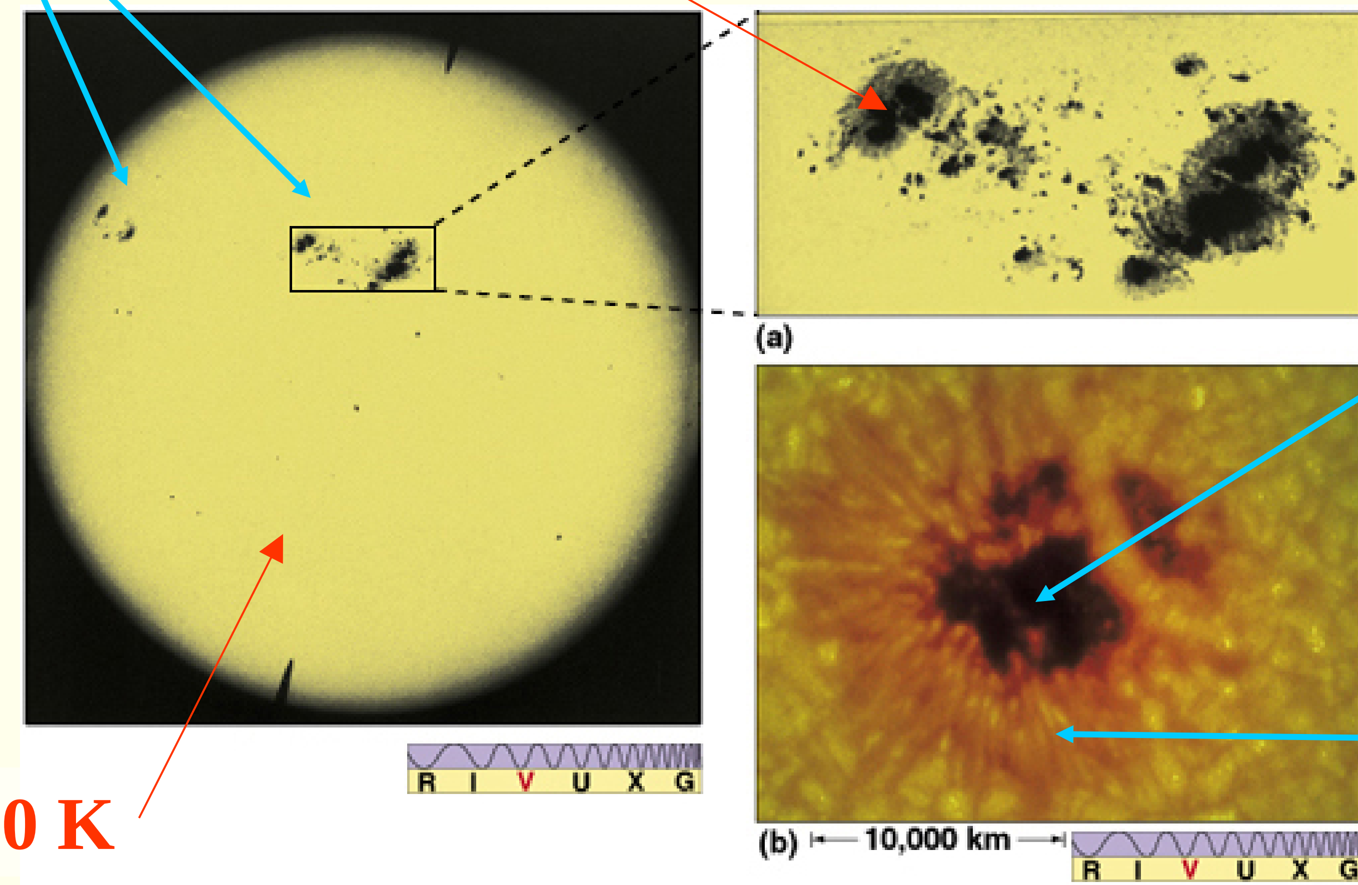
Red

$\beta \sim 1$ Some complicated in-between behaviour

Sunspots

Often seen in pairs

~4000 K

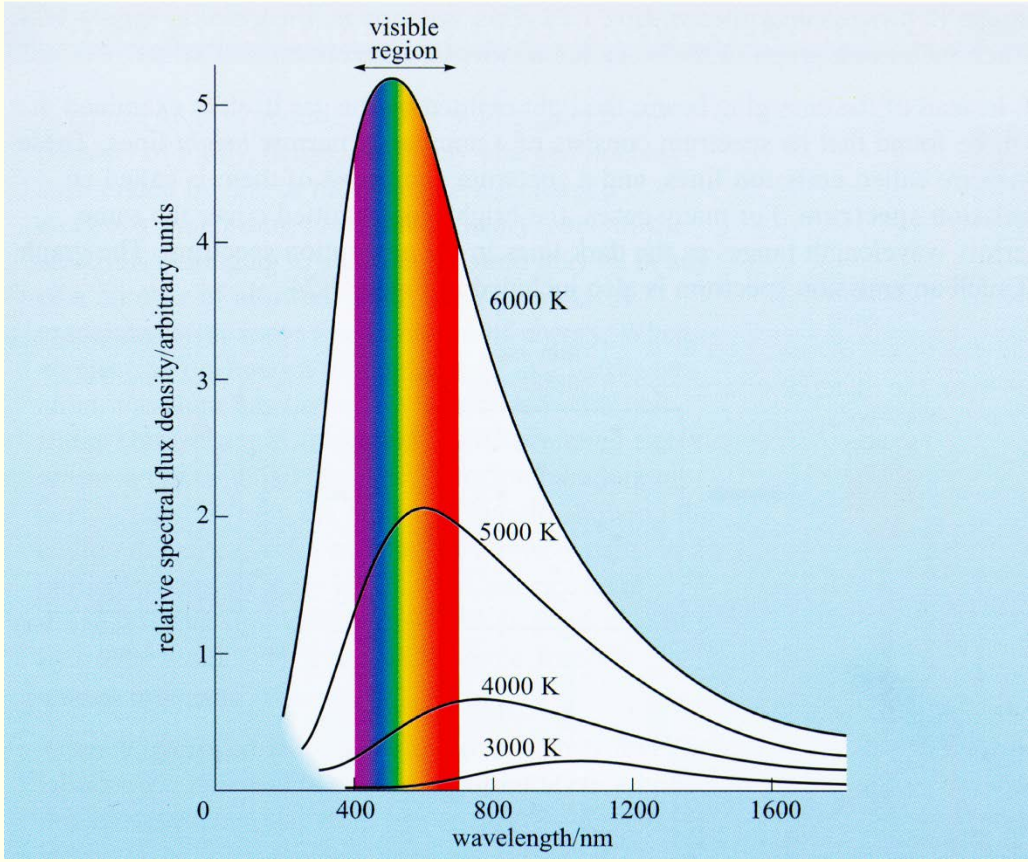


Umbra

Penumbra

~6000 K

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

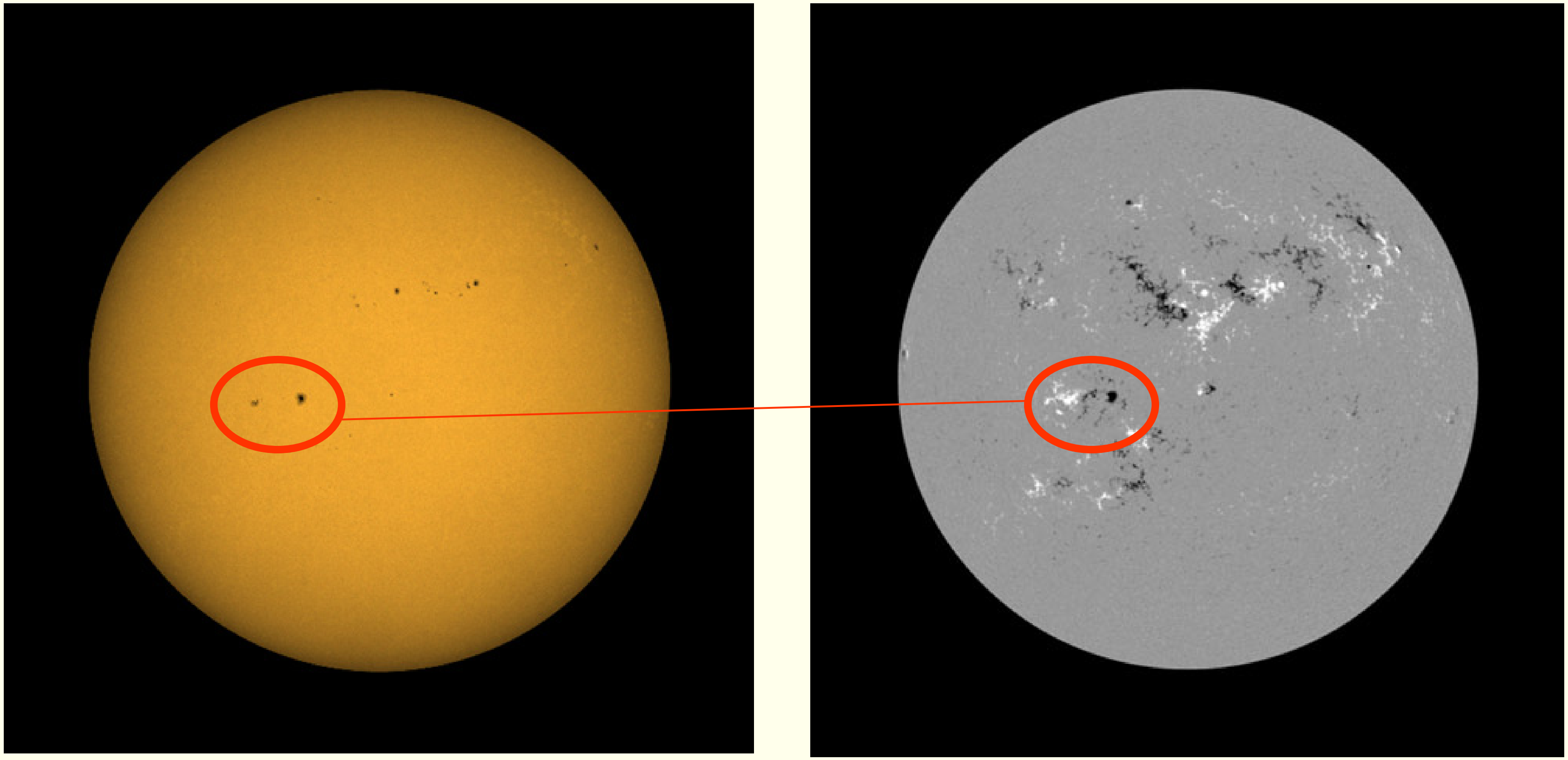
$$\lambda_{peak} = \frac{2.90 \times 10^{-3}}{T}$$

Stefan-Bolzmanns law

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

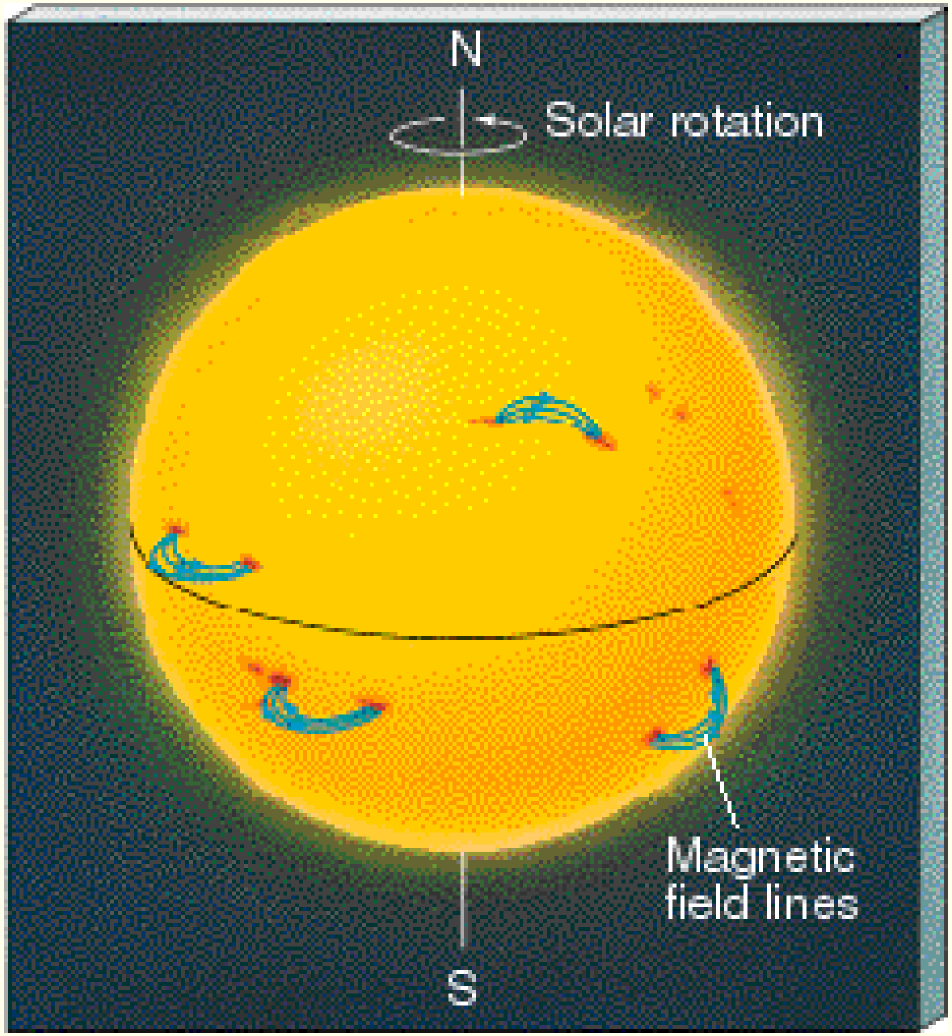
(J = total energy radiated per unit area per unit time)

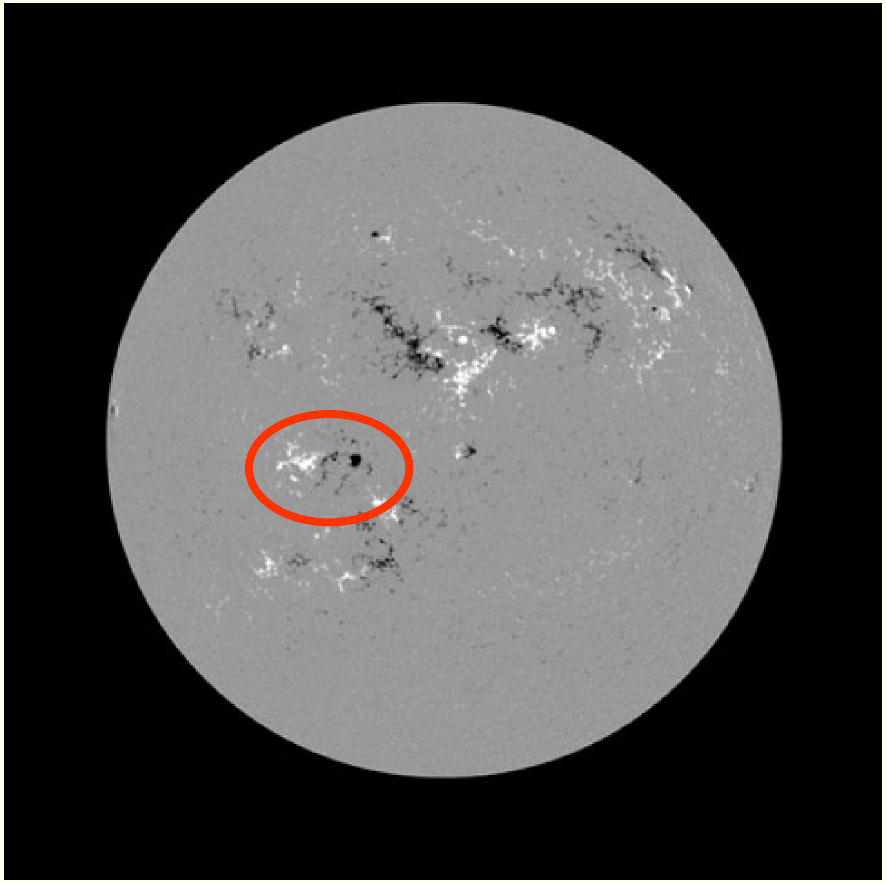
Sunspots and magnetic fields



Sunspots are associated with large magnetic fields

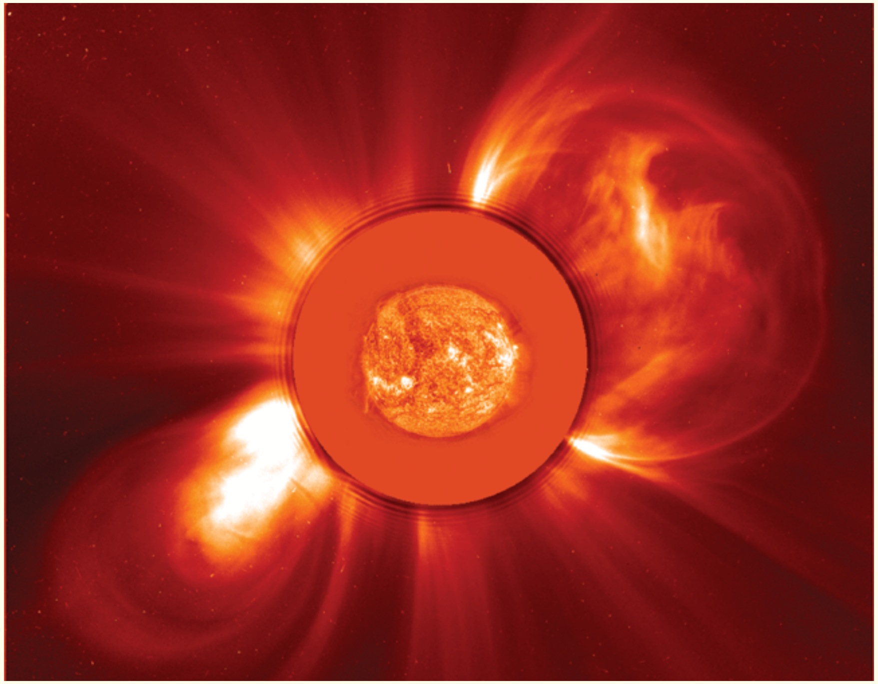
Sunspots and magnetic fields

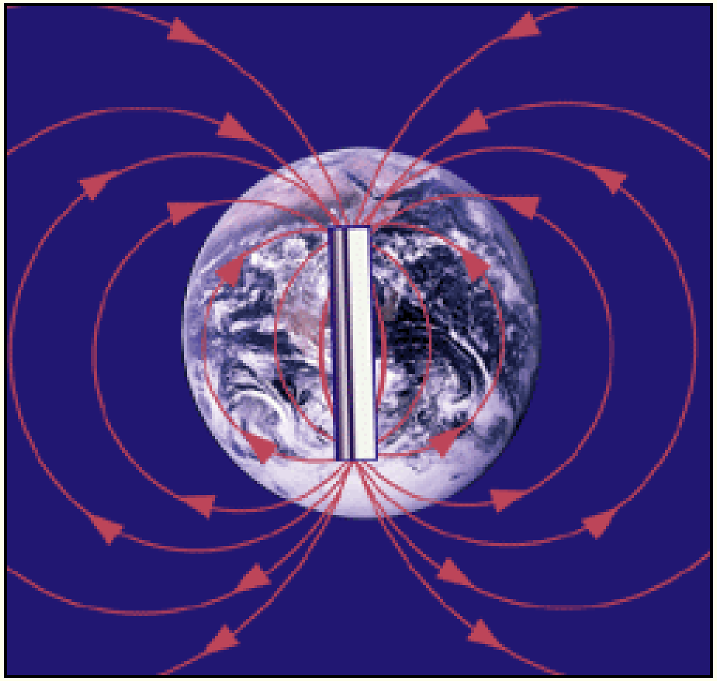




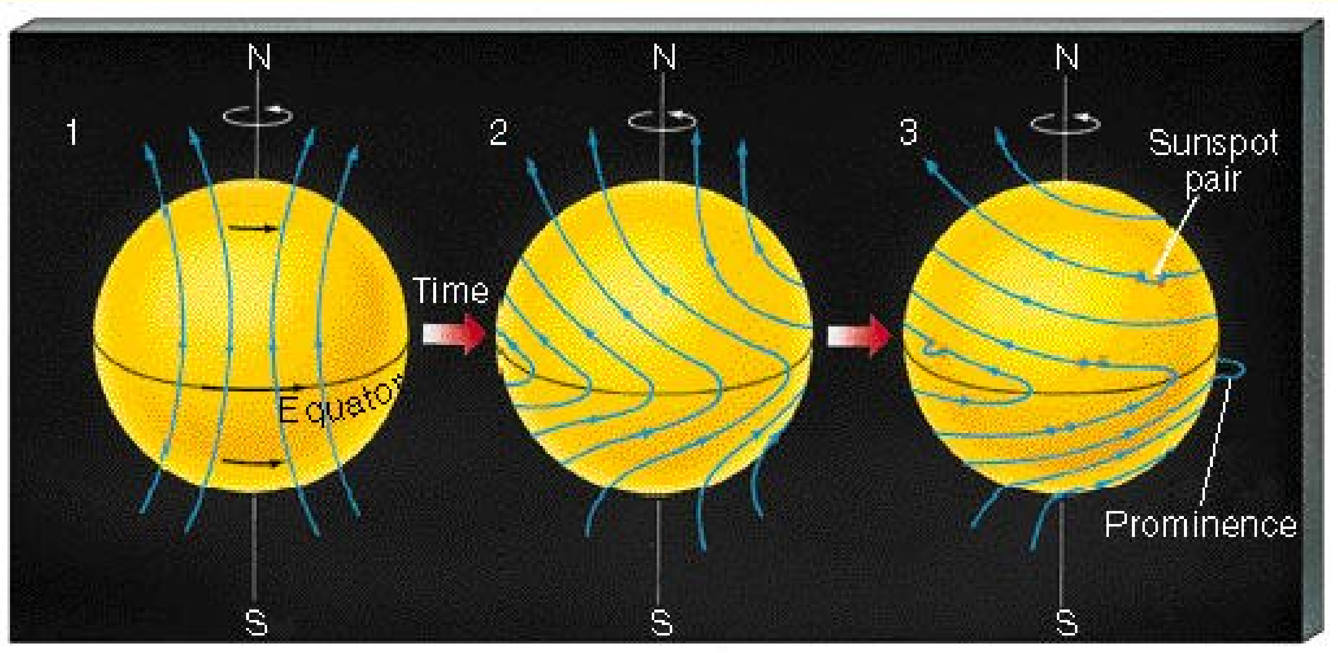
Sun's magnetic field

First guess/approximation: a dipole field, just as Earth





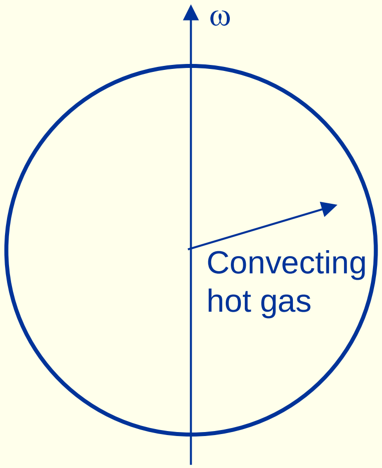
Sunspots and magnetic fields



Sun's rotational period as function of latitude λ

$$T_{rot} = \frac{25}{\left(1 - 0.19 sin^2 \lambda\right)}$$

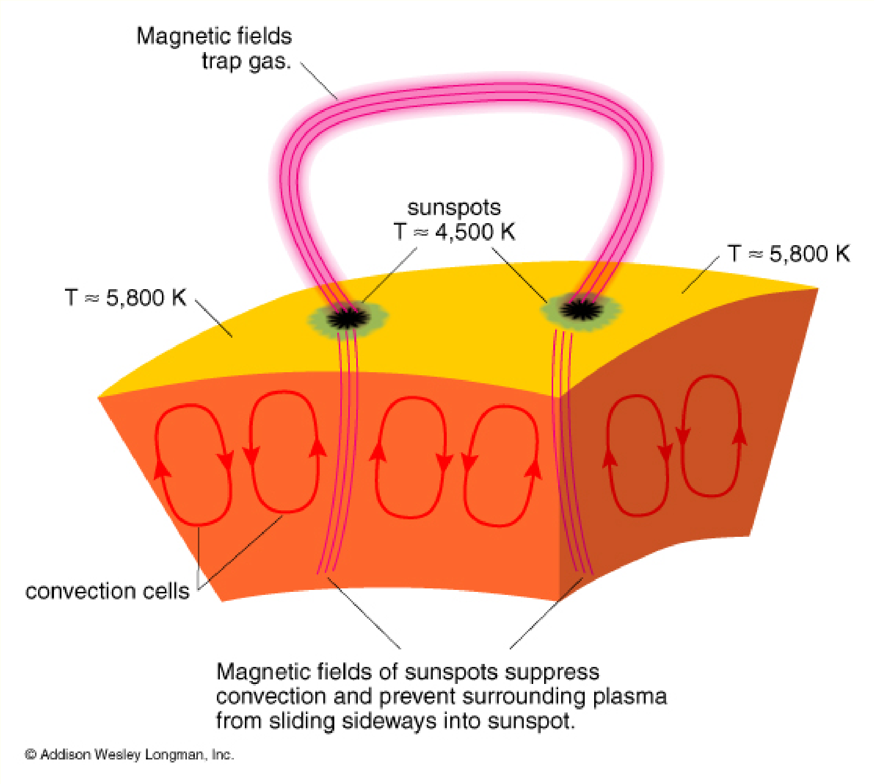
Differential rotation

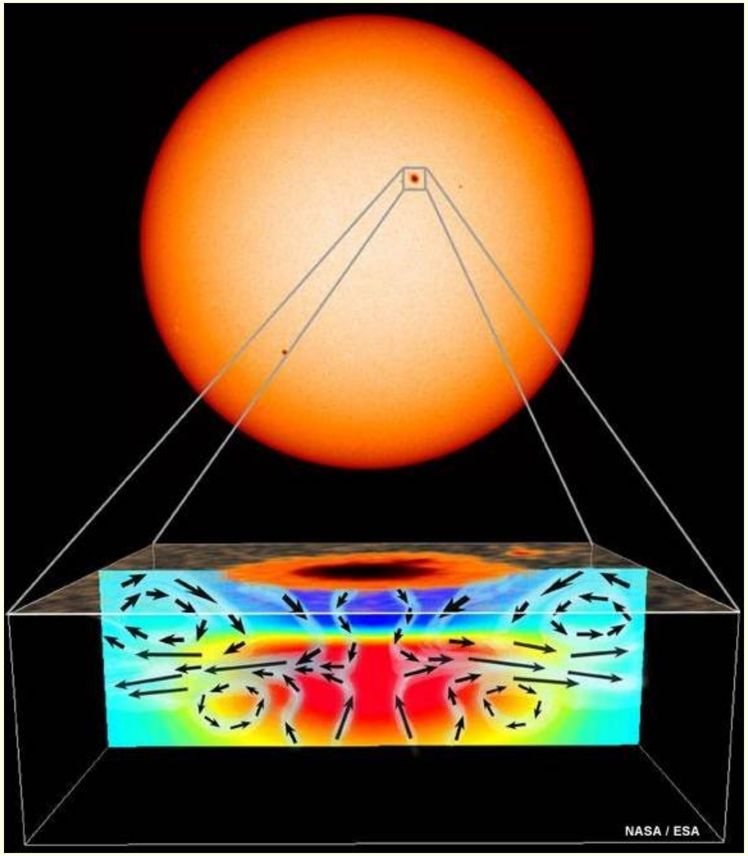


Differential rotation deforms the magnetic field lines. Sometimes a part of the field line may protrude ionto the solar atmosphere and cause loop, which may be associated with a pair of sunspots. (More complicated behaviour may of course also occur.)

Sunspots and magnetic fields

Sunspots

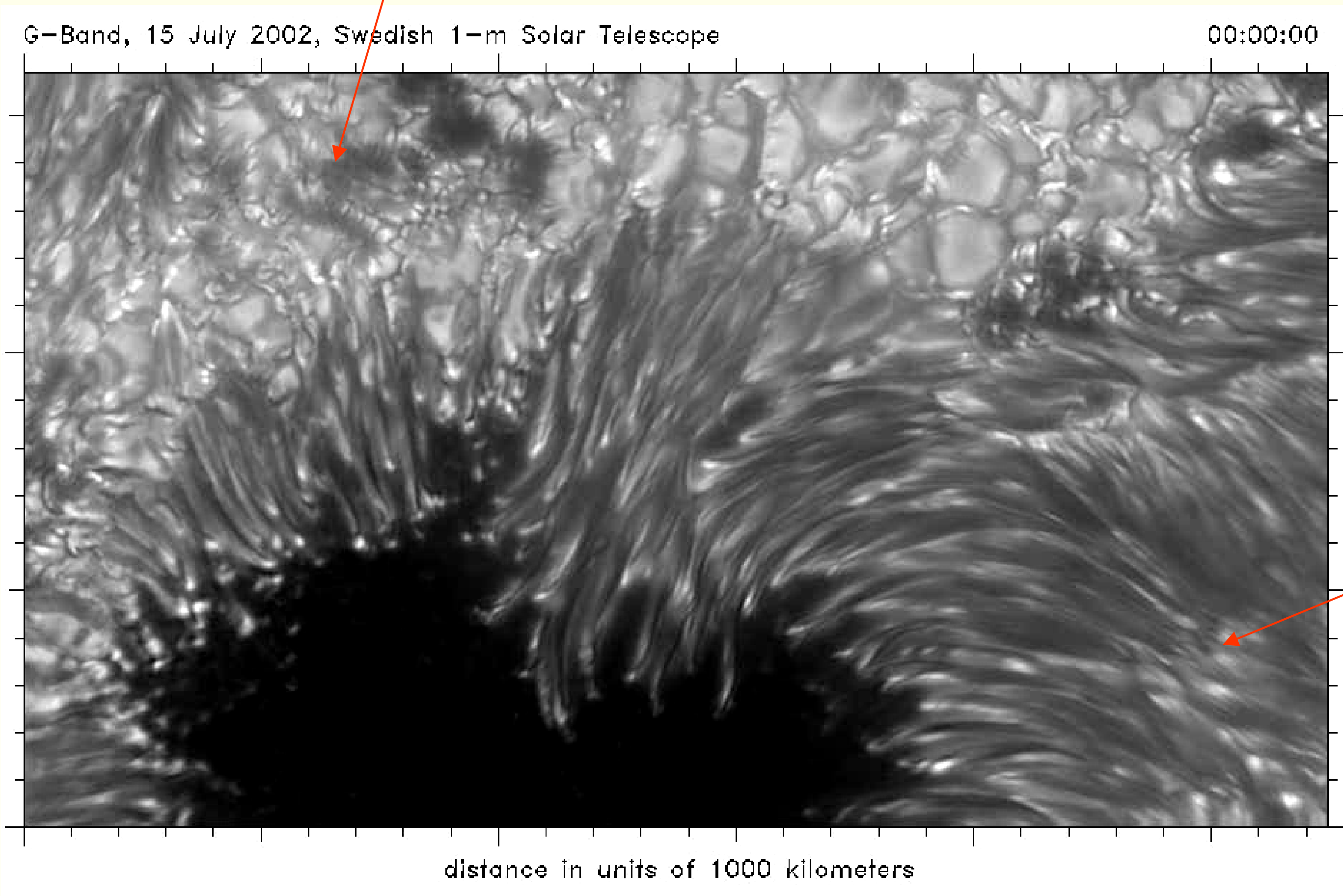




One theory is that the large magnetic field in the sunpots affects the convection of hot matter from the solar interior, so that it will not reach the surface.

Sunpots, convection

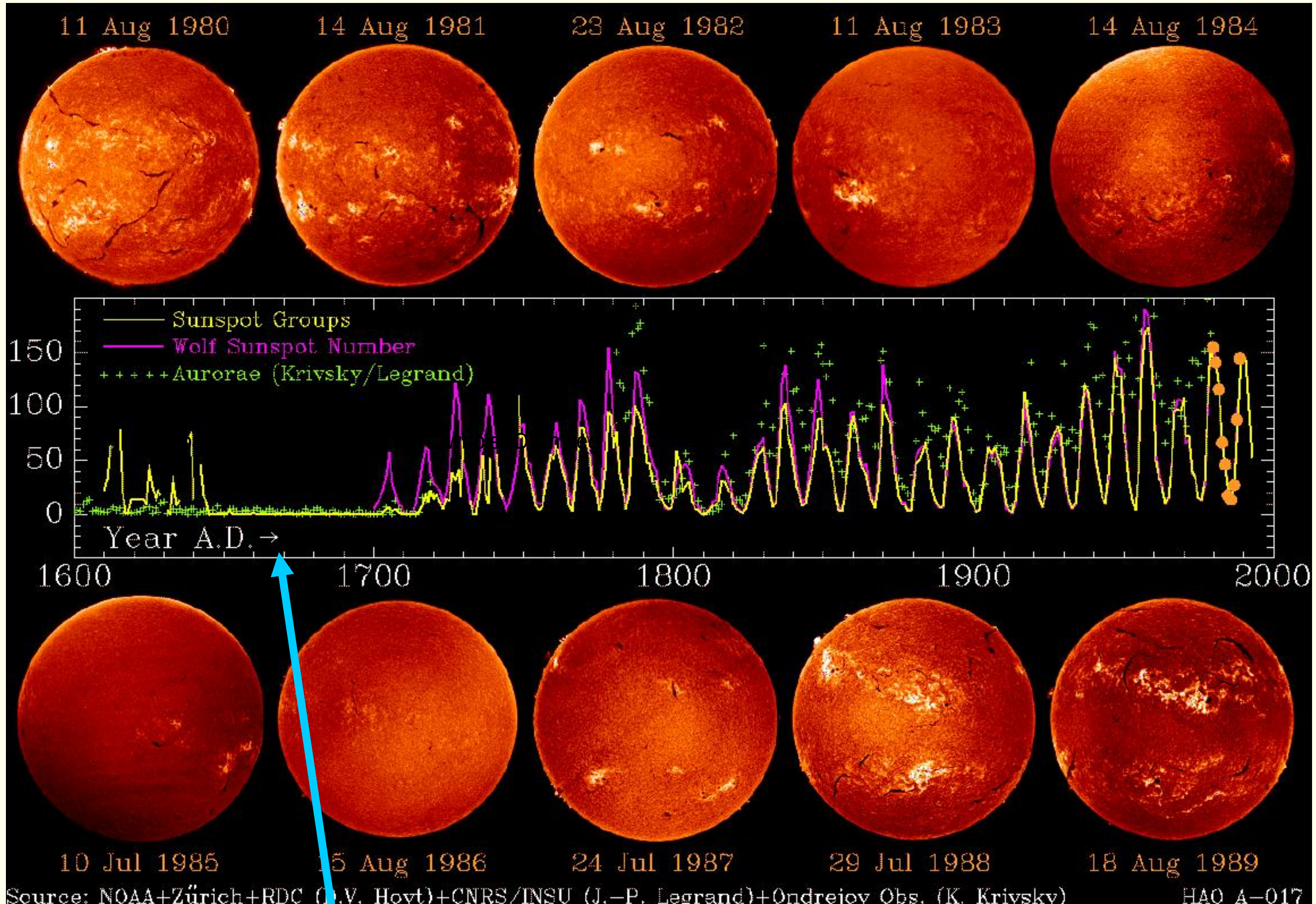
Convection cells (granulation)



Convection cell patter perturbed by magnetic field

Sunspot cycle (solar cycle)

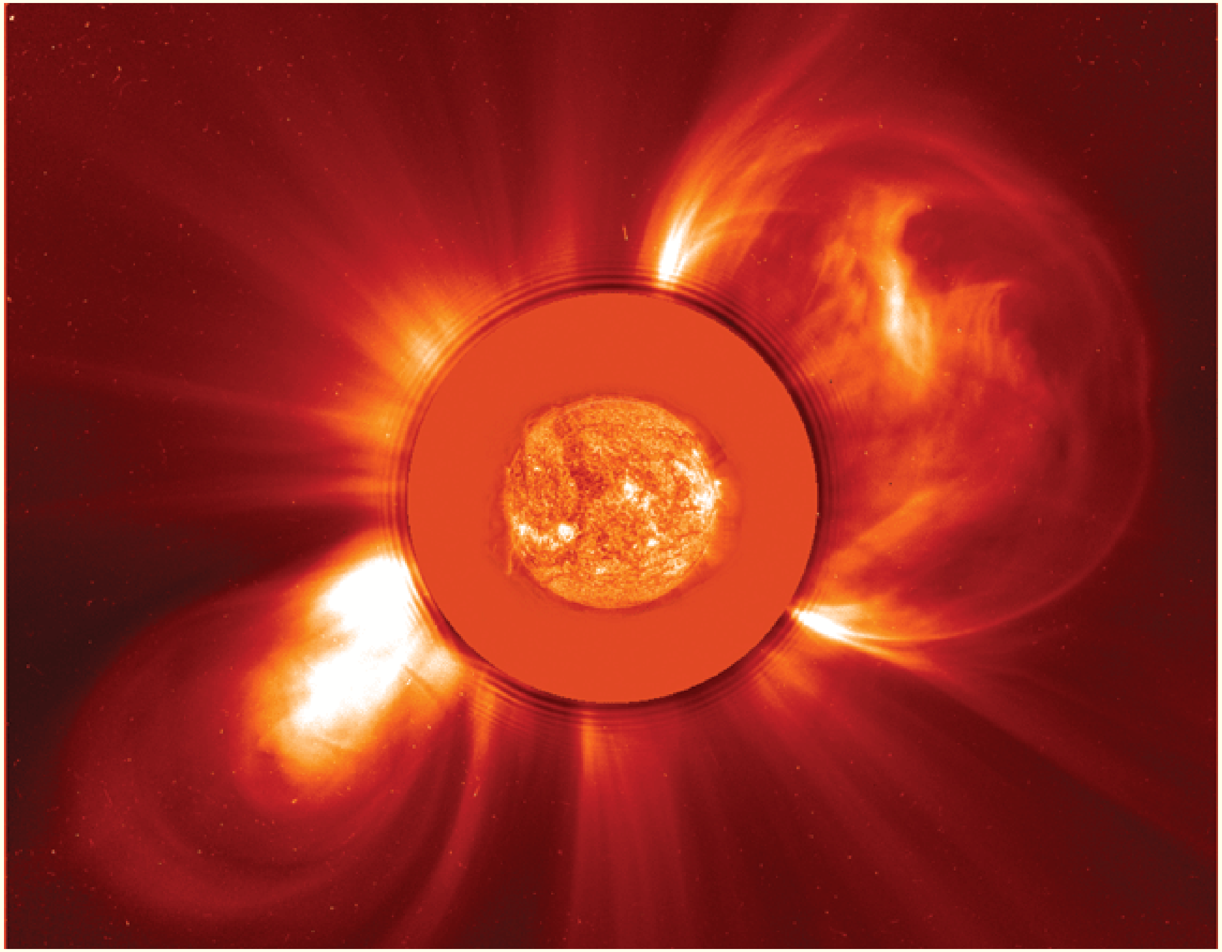
- T ≈ 11 ± 1 years
- The solar cycle is a manifestation of the changing solar magnetic field
- The Maunder minimum was associated with cold climate and no aurora.



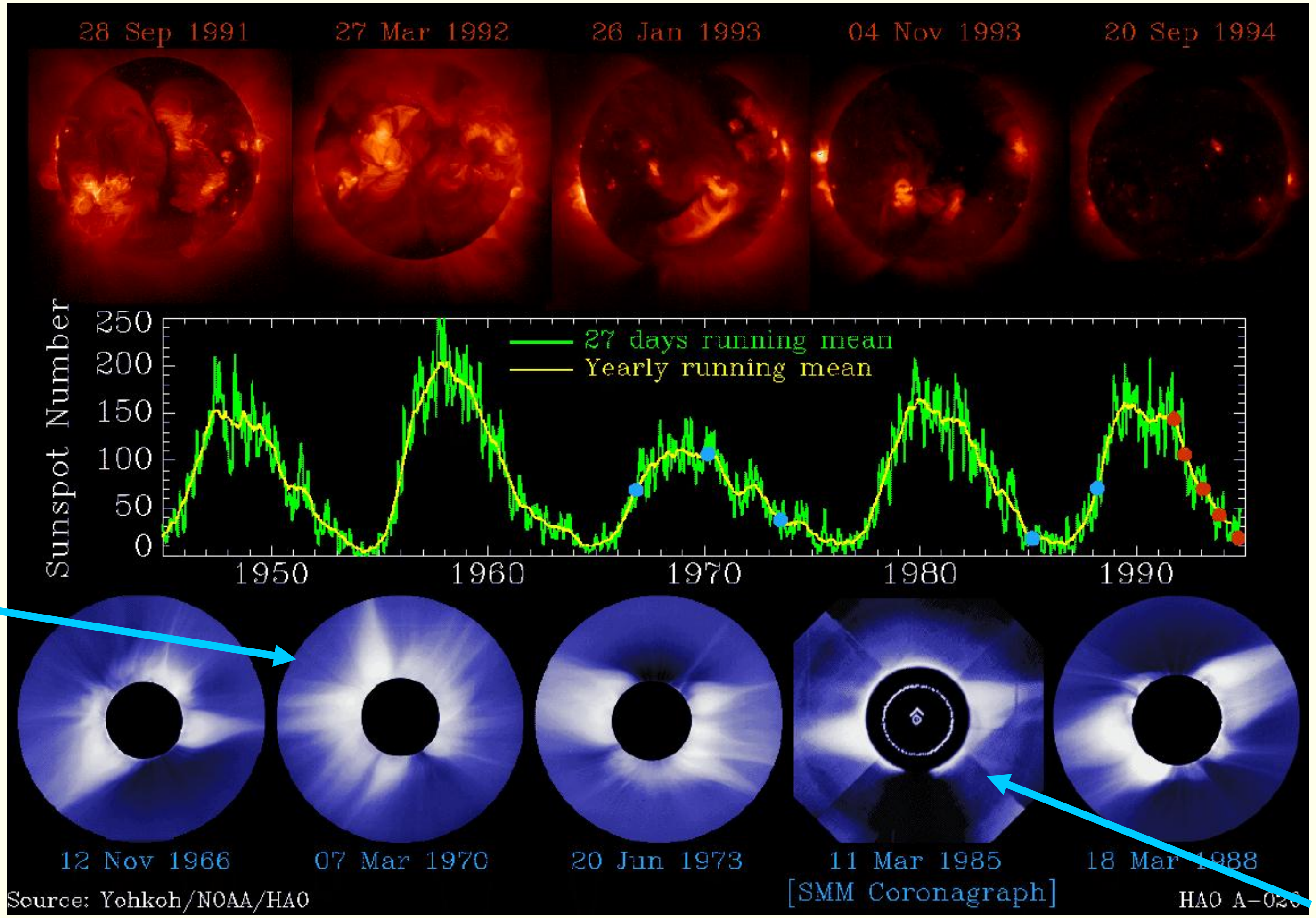
Maunder minimum

Solar magnetic field as organizing factor

Sun's dipole magnetic field



Solar magnetic field as organizing factor



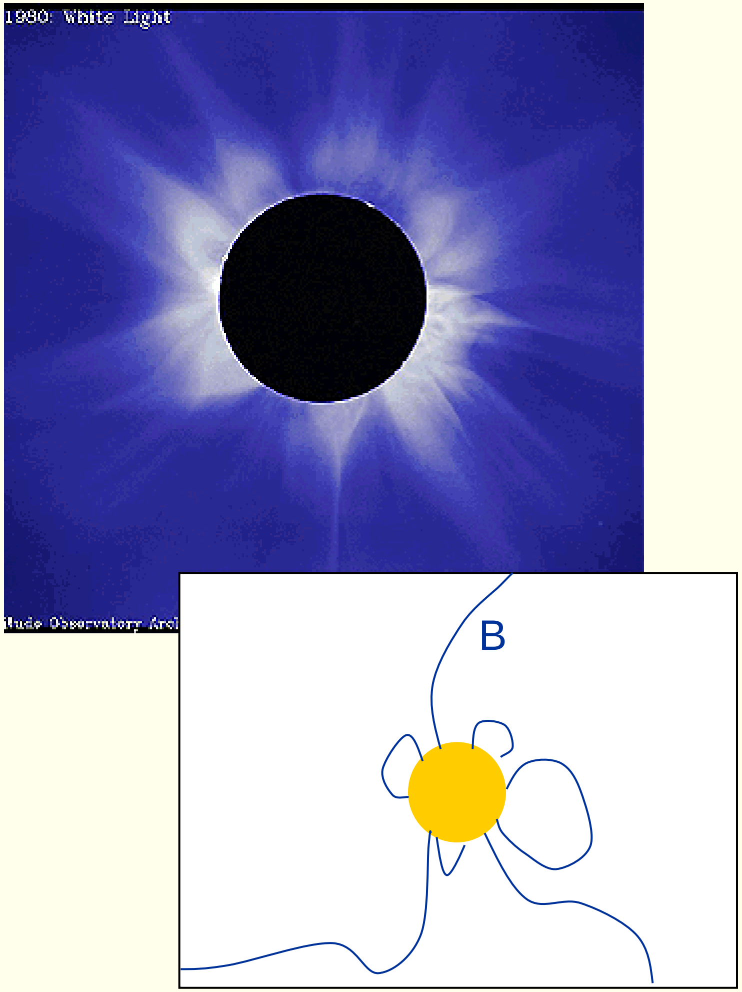
Maximum

Minimum

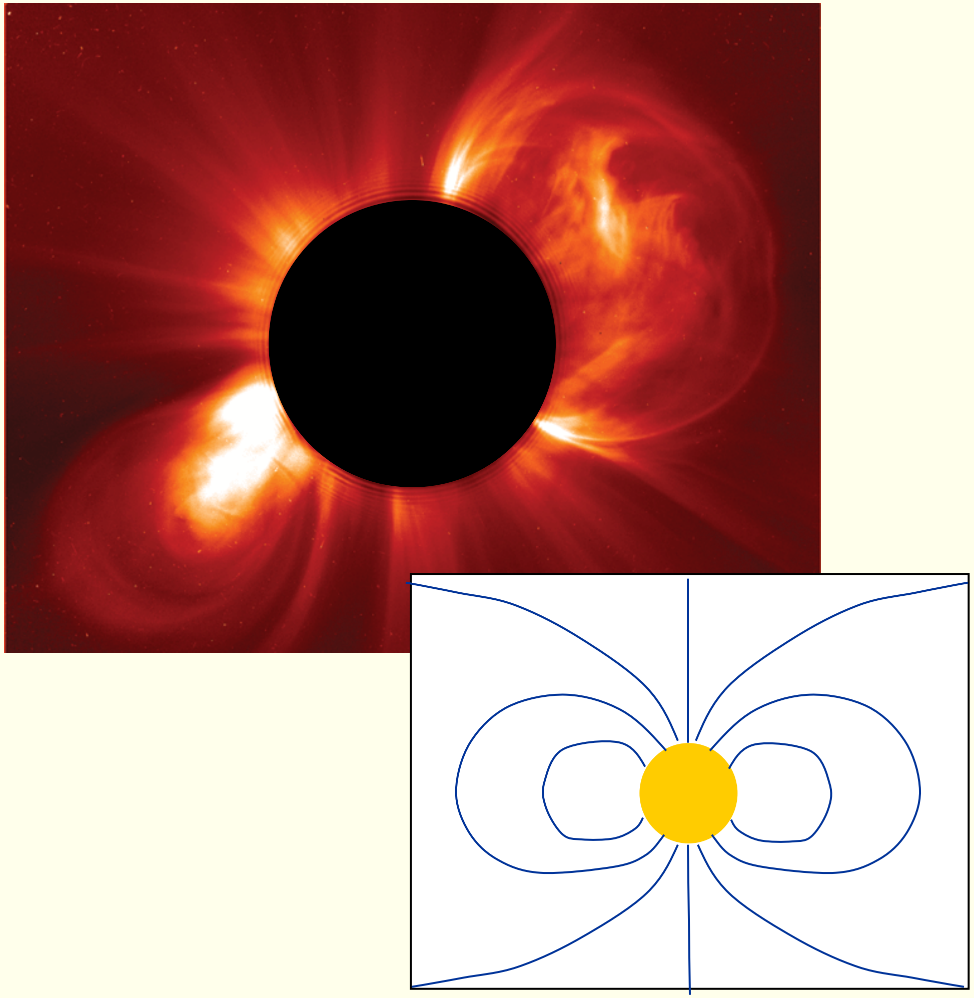
Solar magnetic field as organizing factor

Maximum

Minimum

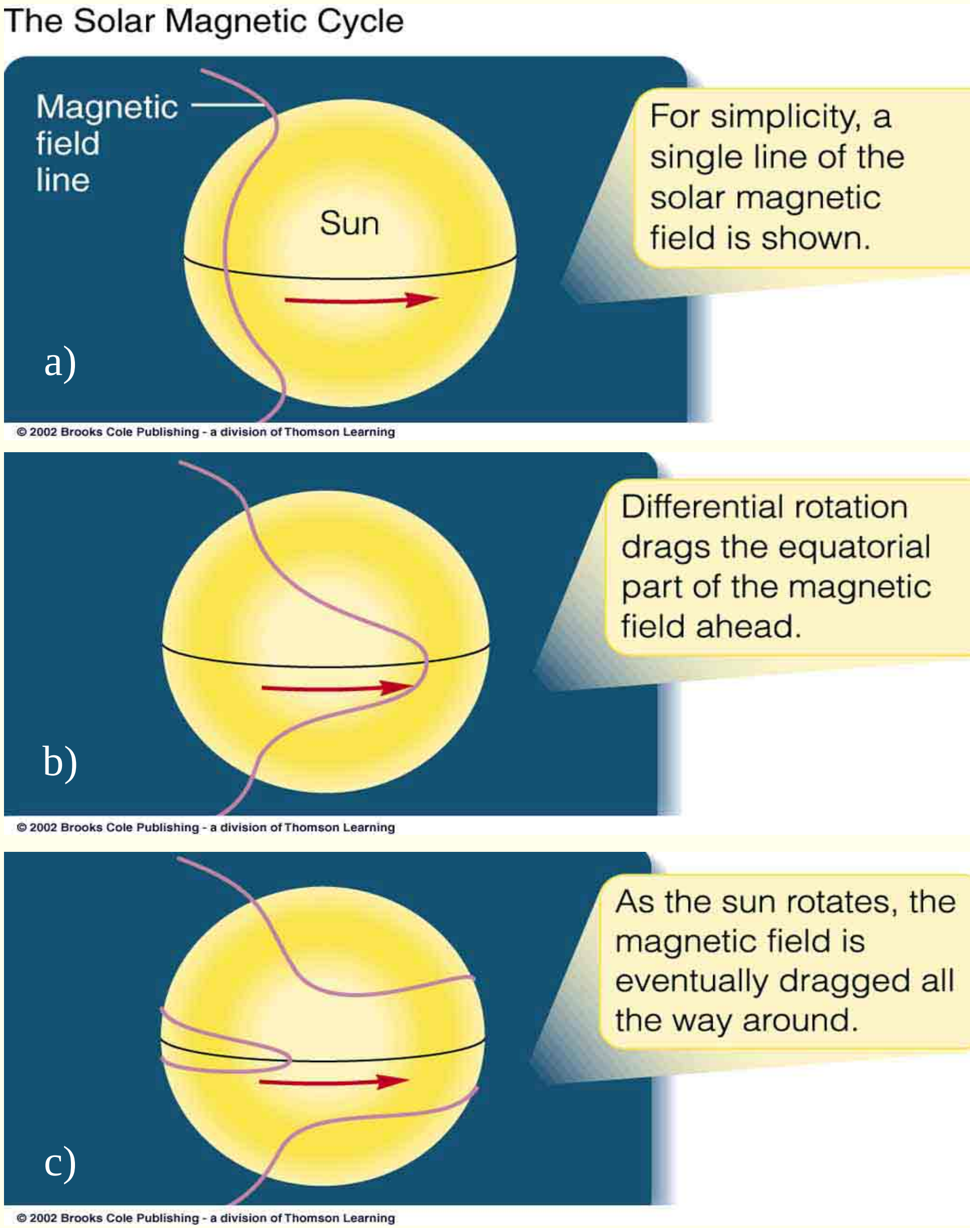


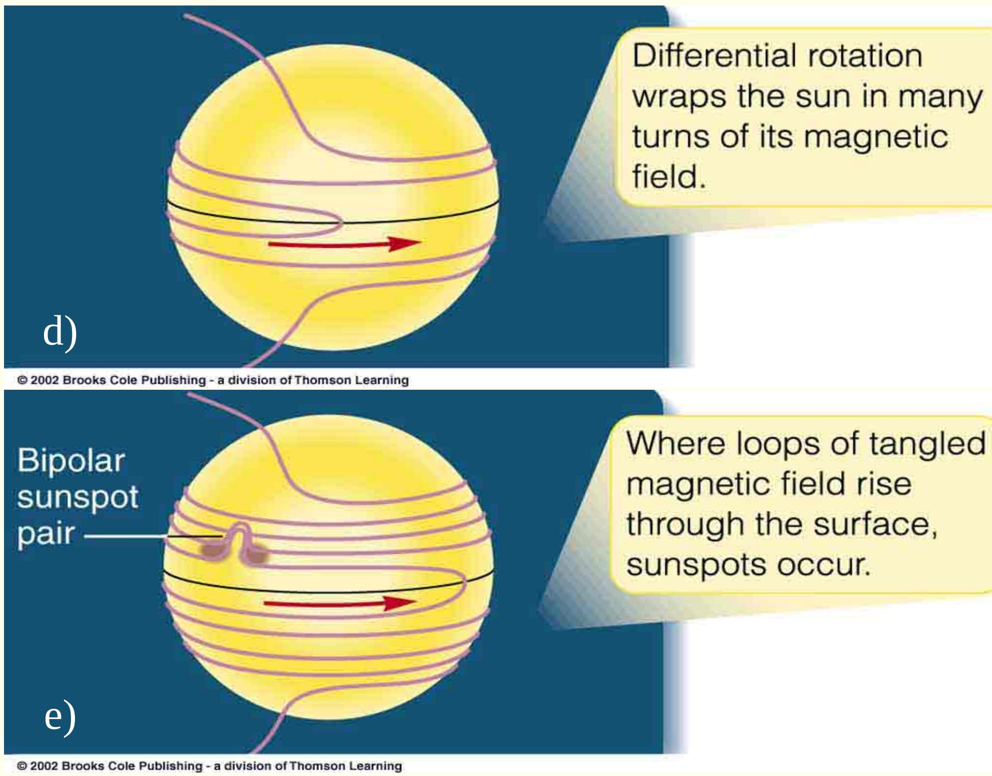
Maximum: weak, irregular magnetic field



Minimum: large, regular dipole-like field

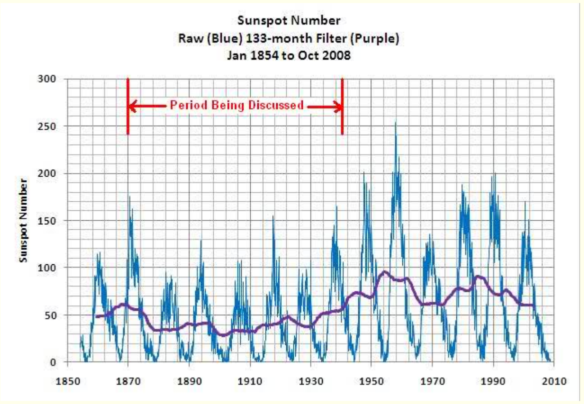
The Babcock Model

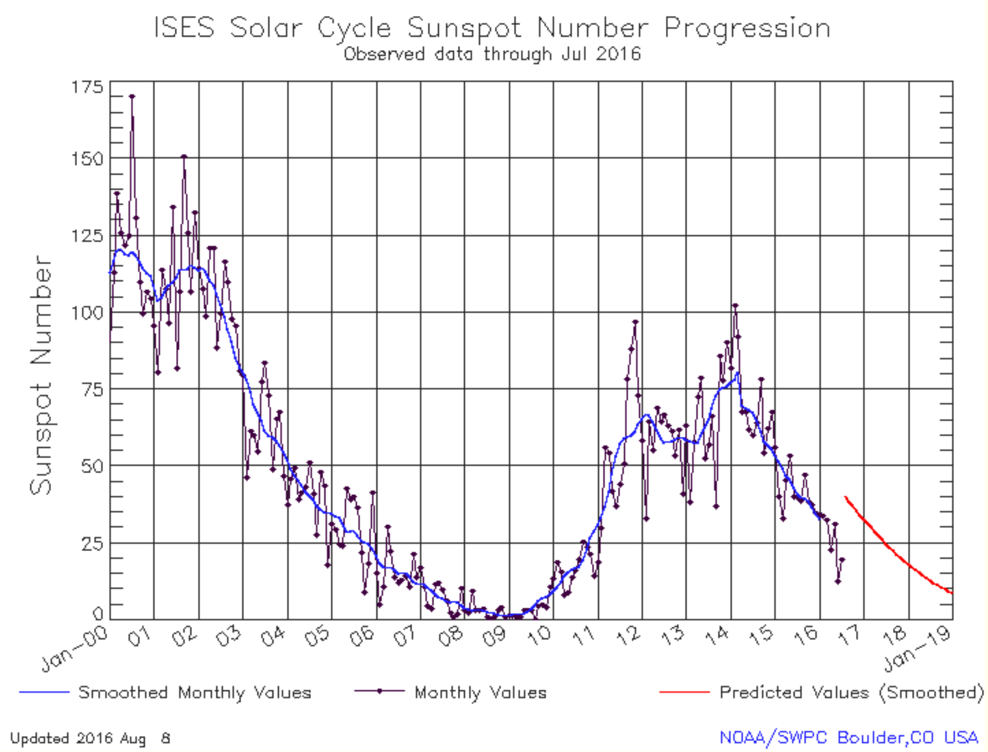




Eventually, the magnetic field lines become so contorted and tense that the field resets, but with the whole field flipped…
Why? No-one really knows…

Where are we today?





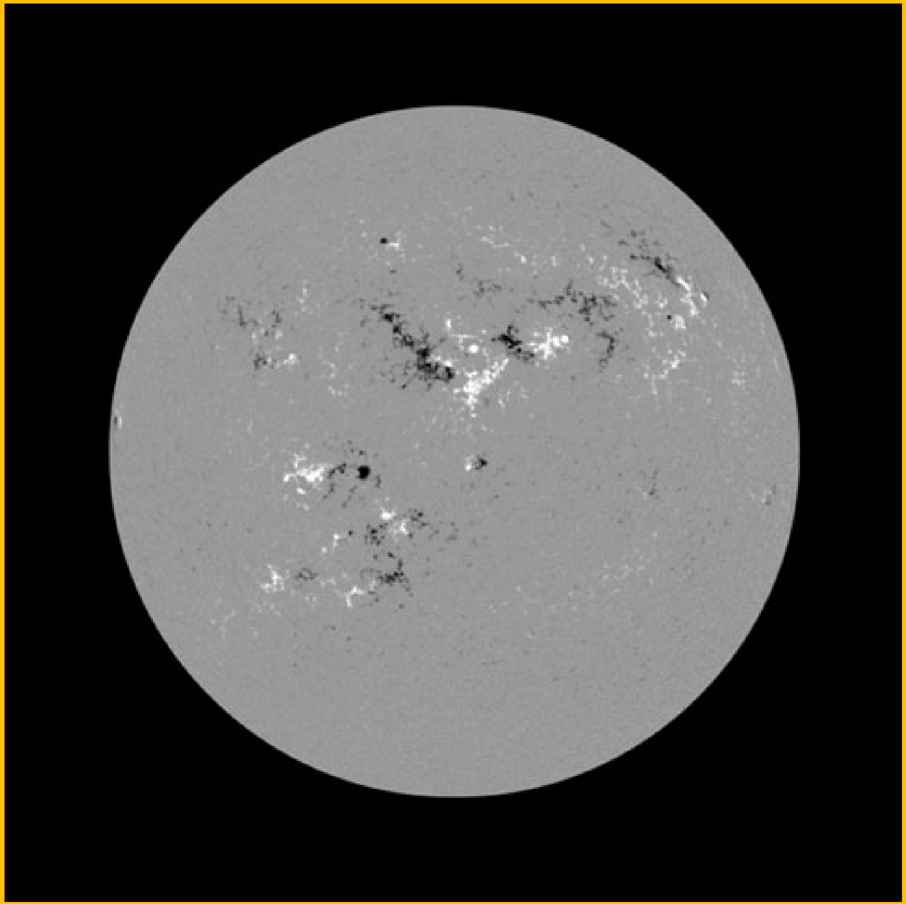
Prediction by
National Weather
ServiceSpace Weather
Prediction Centre

Last Minute!

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

Think about this



How can we measure the magnetic field on the solar surface???