Last lecture (2)

- Plasma physics 2
- Solar activity

Today's lecture (3)

- Solar activity
- Magnetic reconnection ↔ solar flares
- Solar wind – basic facts

Today

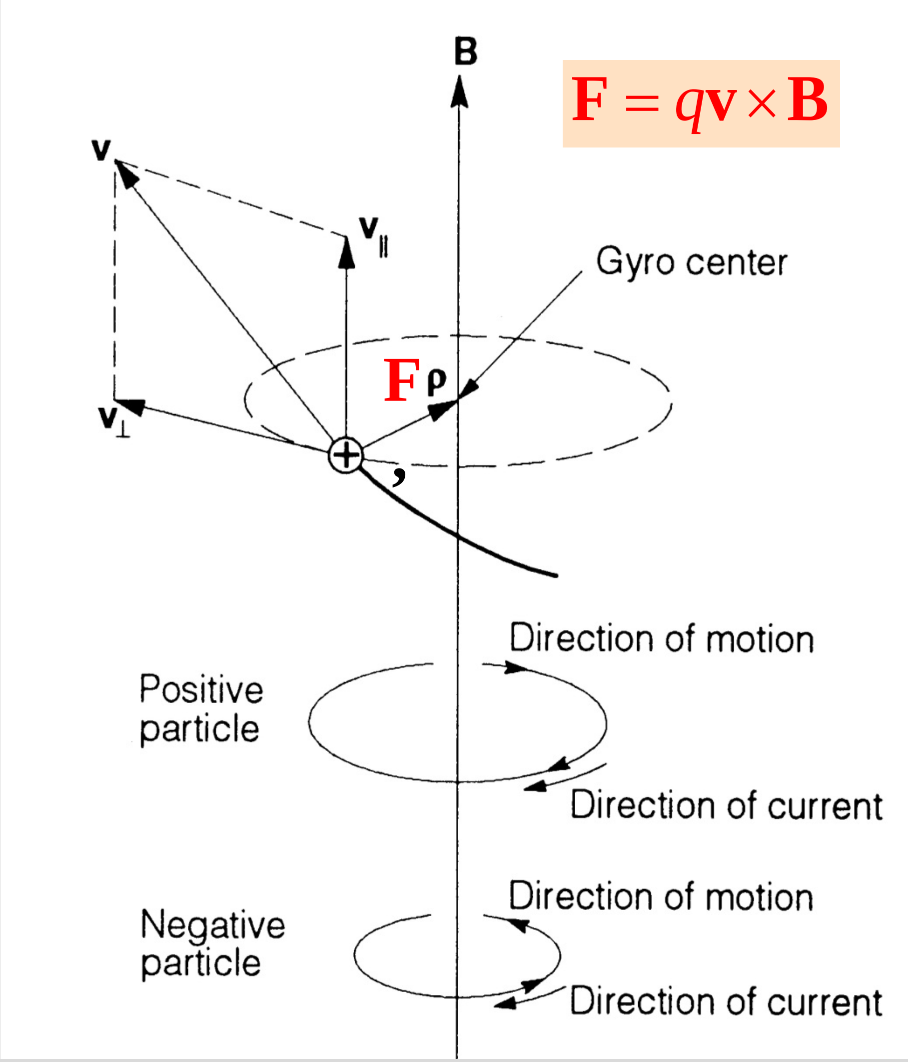
Activity	Date	Time	Room	Subject	Litterature
L1	31/8	13-15	V22	Course description, Introduction, The Sun 1, Plasma physics 1	CGF Ch 1, 5, (p 110-113)
L2	3/9	15-17	Q36	The Sun 2, Plasma physics 2	CGF Ch 5 (p 114-121), 6.3
L3	7/9	13-15	Q36	Solar wind, The ionosphere and atmosphere 1, Plasma physics 3	CGF Ch 6.1, 2.1-2.6, 3.1-3.2, 3.5, LL Ch III, Extra material
T1	10/9	15-17	Q36	Mini-group work 1	
L4	14/9	13-15	E2	The ionosphere 2, Plasma physics 4	CGF Ch 3.4, 3.7, 3.8
T2	17/9	8-10	Q31	Mini-group work 2	
L5	17/9	15-17	L52	The Earth's magnetosphere 1, Plasma physics 5	CGF 4.1-4.3, LL Ch I, II, IV.A
L6	21/9	13-15	L52	The Earth's magnetosphere 2, Other magnetospheres	CGF Ch 4.6-4.9, LL Ch V.
T3	24/9	16-18	Q36	Mini-group work 3	
L7	28/9	13-15	Q36	Aurora, Measurement methods in space plasmas and data analysis 1	CGF Ch 4.5, 10, LL Ch VI, Extra material
T4	1/10	15-17	V22	Mini-group work 4	
L8	5/10	13-15	M33	Space weather and geomagnetic storms	CGF Ch 4.4, LL Ch IV.B-C, VII.A-C
L9	6/10	8-10	Q36	Interstellar and intergalactic plasma, Cosmic radiation,	CGF Ch 7-9
T5	8/10	15-17	Q34	Mini-group work 5	
L10	12/10	13-15	Q36	Swedish and international space physics research.	
T6	15/10	15-17	Q33	Round-up.	
Written examination	28/10	8-13	Q21, Q26		

L = Lecture, T = Tutorial

Magnetized plasma

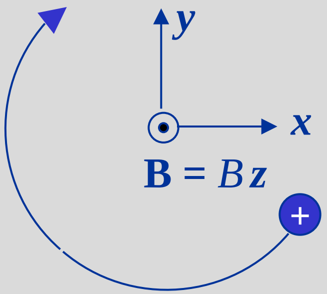
Extremely common in space.

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



Gyro motion

Consider a positively charged particle in a magnetic field.



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

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

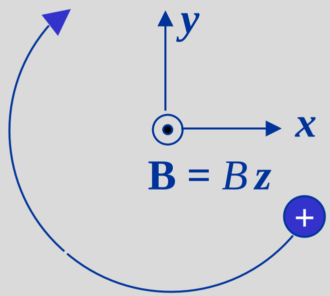
$$\begin{cases} m\dfrac{dv_x}{dt} = qv_yB \\[2ex] m\dfrac{dv_y}{dt} = -qv_xB \\[2ex] m\dfrac{dv_z}{dt} = 0 \end{cases} \Rightarrow$$

Constant velocity along $\mathbf{z}$

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

$$\Rightarrow$$

Gyro motion



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

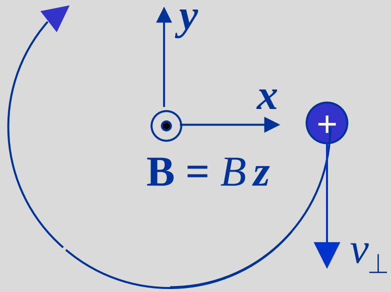
$\Rightarrow$

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

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 $v_{0x}, v_{0x} > 0$)

$$\begin{cases} v_y(0) = v_{0y}\cos\delta_y = -v_\perp & \Rightarrow\ v_{0y} = v_\perp, \delta_y = \pi \\ v_x(0) = v_{0x}\cos\delta_x = v_{0x}\cos\delta_x = 0 & \Rightarrow\ \delta_x = \dfrac{\pi}{2}, \dfrac{3\pi}{2} \end{cases}$$

and

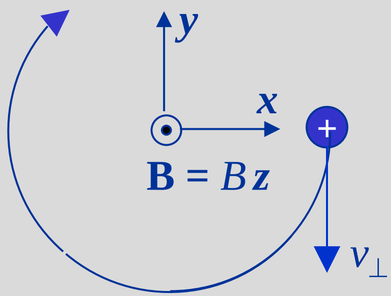
$$\begin{cases} x(0) = \dfrac{v_{0x}}{\omega_g}\sin\delta_x = x_0 & \Rightarrow\ \delta_x = \dfrac{\pi}{2},\ x_0 = \dfrac{v_{0x}}{\omega_g} \\ y(0) = \dfrac{v_\perp}{\omega_g}\sin\pi = 0 & \end{cases}$$

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



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

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

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

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

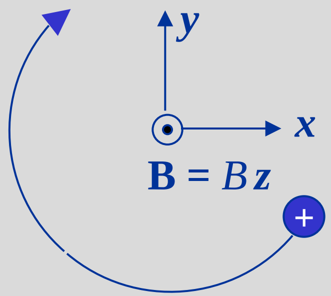
So

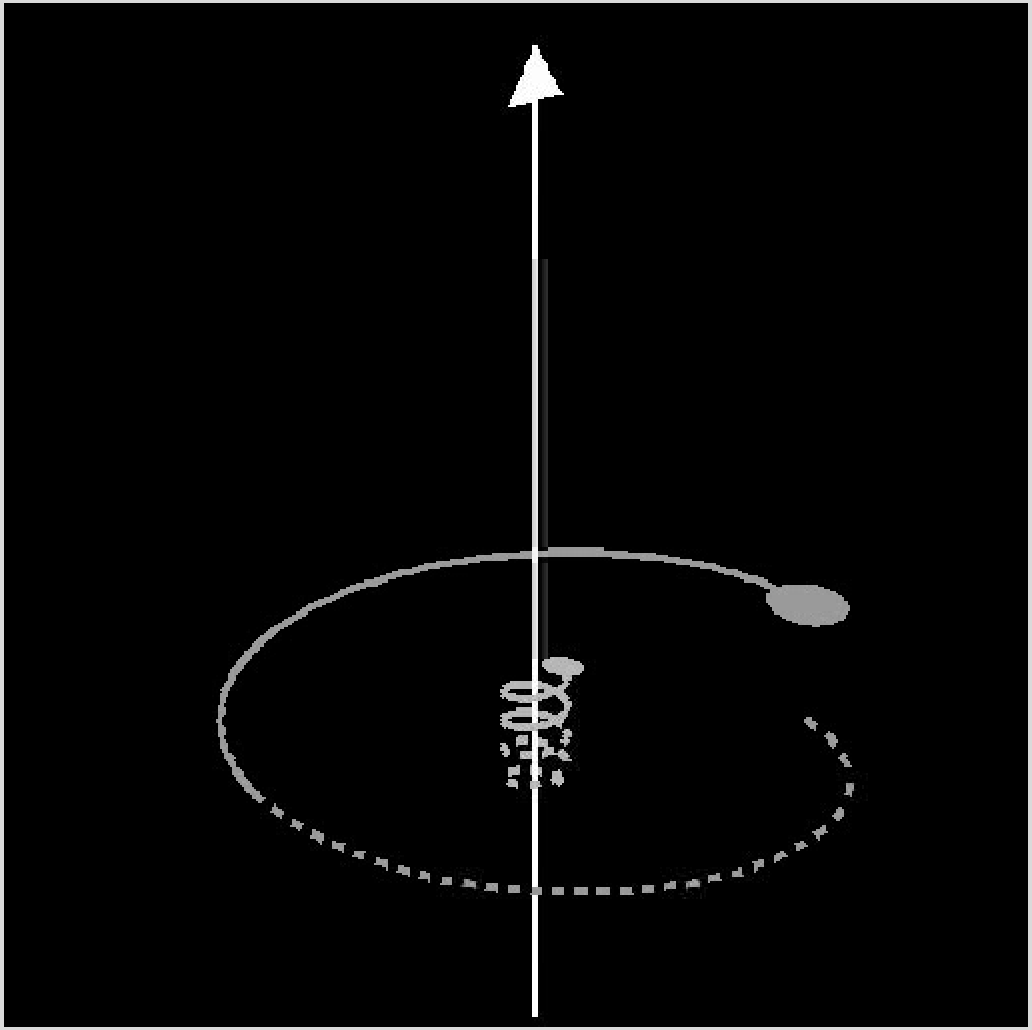
$$\begin{cases} x = \dfrac{v_\perp}{\omega_g} cos(-\omega_g t) \\ y = \dfrac{v_\perp}{\omega_g} sin(-\omega_g t) \end{cases}$$

and

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

Gyro motion





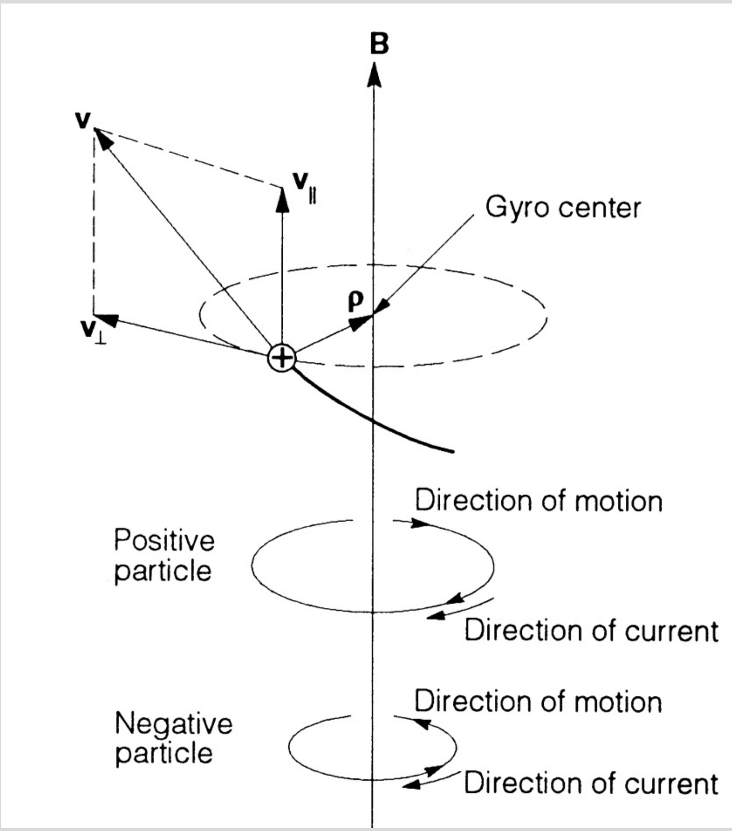
Then

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

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

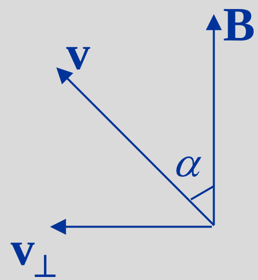
$$r_L = \frac{mv_\perp}{qB}$$

Gyro radius



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

Centripetal force: $$\mathbf{F} = \frac{mv_\perp^2}{\rho}\hat{\boldsymbol{\rho}}$$

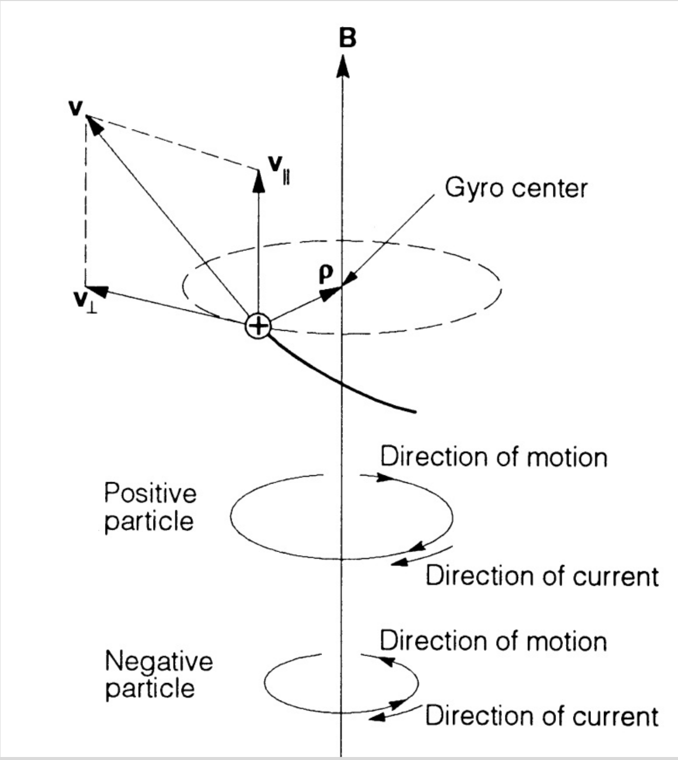


$$v_\perp = v \cdot \sin\alpha$$

$$\Leftrightarrow$$

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

Gyro frequency



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

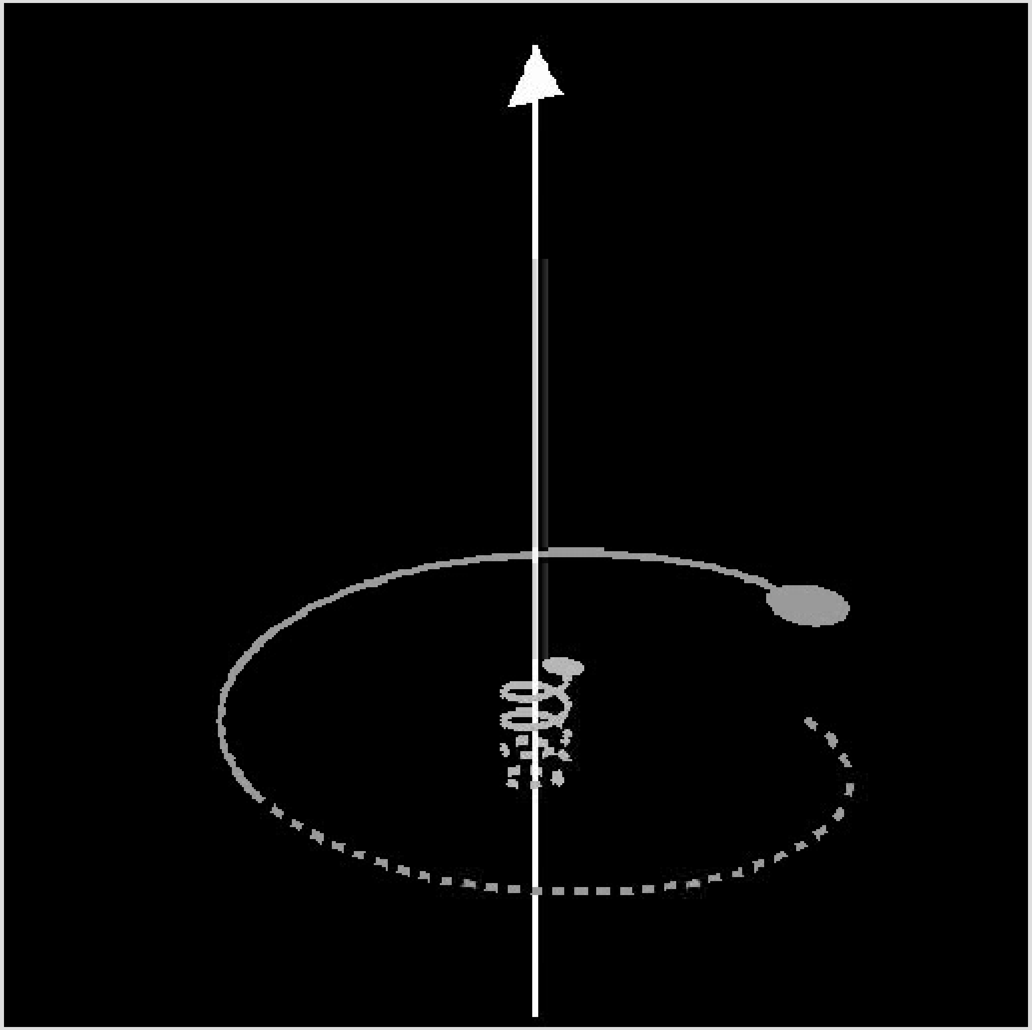
$$\omega\rho = v_\perp$$

$$\Rightarrow$$

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

$$\omega = 2\pi f$$

Gyro motion



Equipartion principle

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

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

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

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

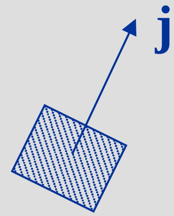
$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

Lorentz' force equation

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

Ohm's law

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



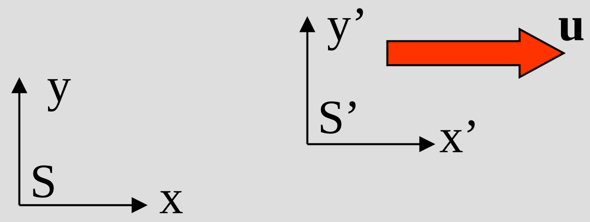
Energy density

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

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

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

Field transformations (relativistic)



Relativistic transformations
(perpendicular to the velocity $\mathbf{u}$*):*

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

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

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*

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

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

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

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

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

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

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

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

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

Frozen in magnetic flux *PROOF II*

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

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:

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

Frozen-in fields!

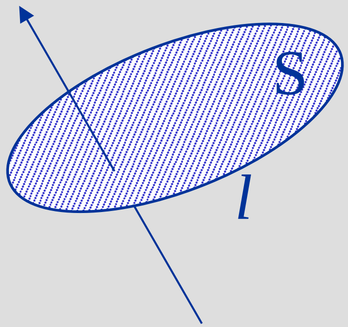
$$\mathrm{R_m} << 1 \Rightarrow \quad \frac{\partial \mathbf{B}}{\partial t} = \frac{1}{\mu_0 \sigma} \nabla^2 \mathbf{B}$$

Diffusion equation!

Frozen in magnetic flux *PROOF III*

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

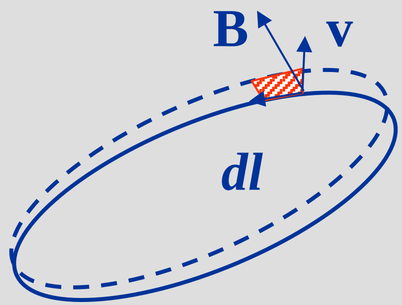
Consider the change of magnetic flux Φ through a surface S with contour l which follows plasma motion



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

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

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

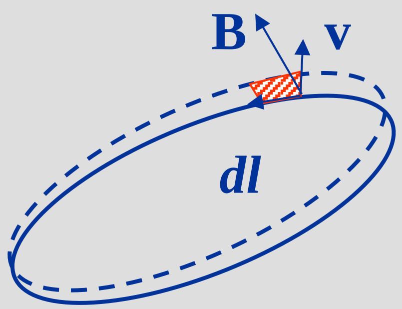


has an area of $(\mathbf{v} \cdot dt) \times d\mathbf{l}$

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

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

Frozen in magnetic flux *PROOF IV*



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

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

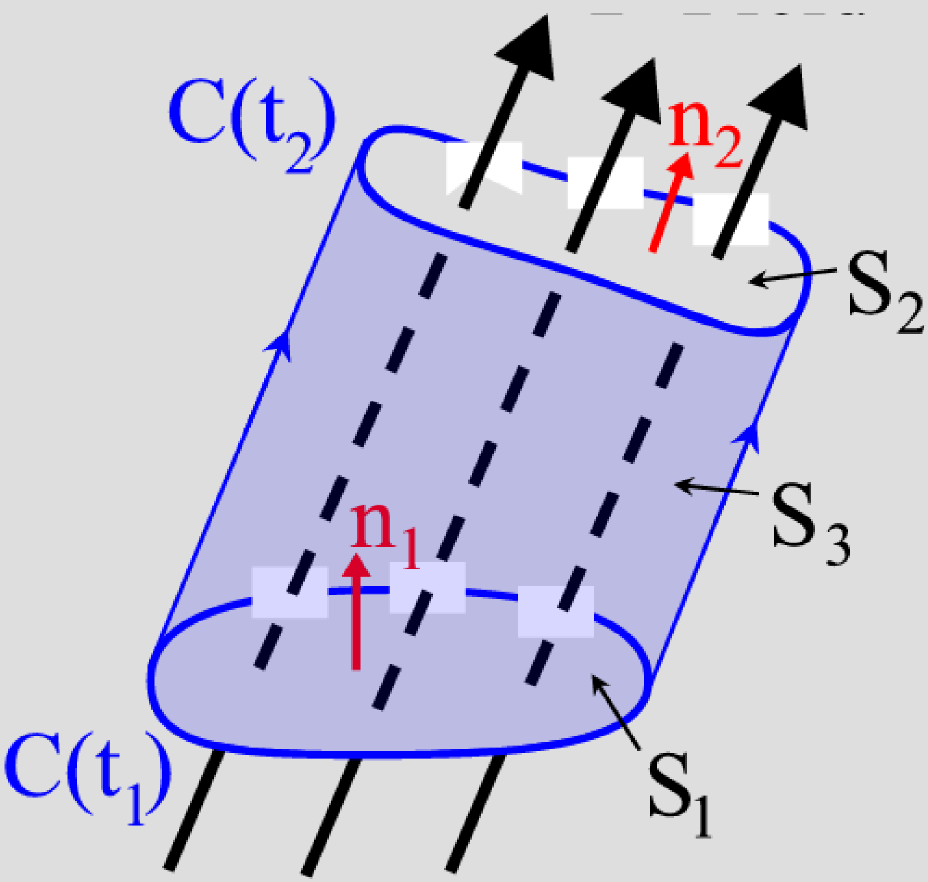
$$\because \frac{d\Phi}{dt} = \int_S \frac{\partial\mathbf{B}}{\partial t}\cdot d\mathbf{S} - \int_S \nabla\times(\mathbf{v}\times\mathbf{B})\cdot d\mathbf{S} =$$

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

★

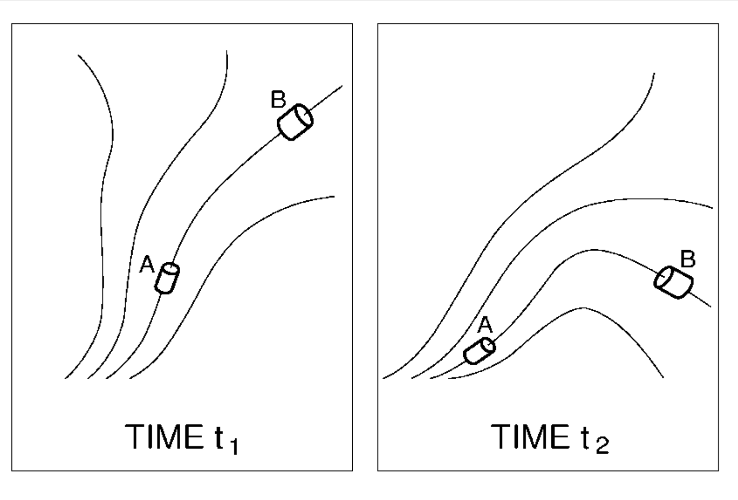
$$\because \frac{d\Phi}{dt} = 0$$

Frozen in magnetic field lines

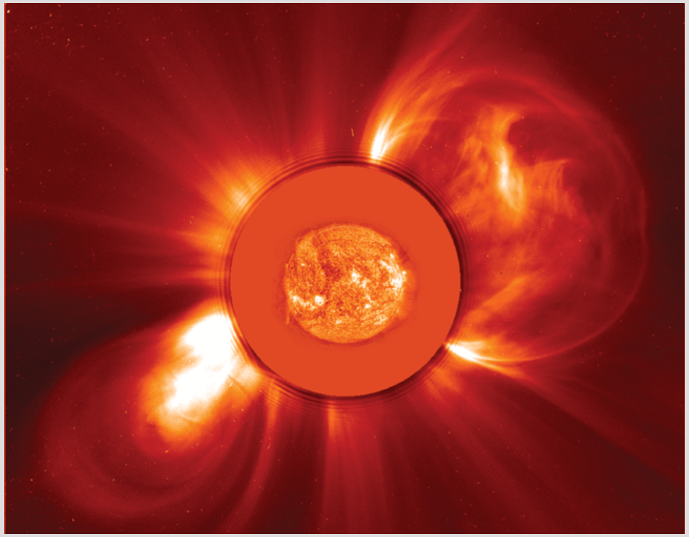


A *flux tube* is defined by following **B** from the surface S. Due to the frozen-in theorem the flux tube keeps its identity and the plasma in a flux tube stays in it for ever.

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



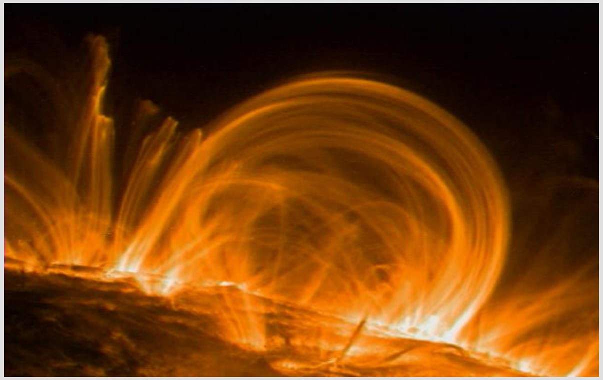
Magnetized plasma



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.

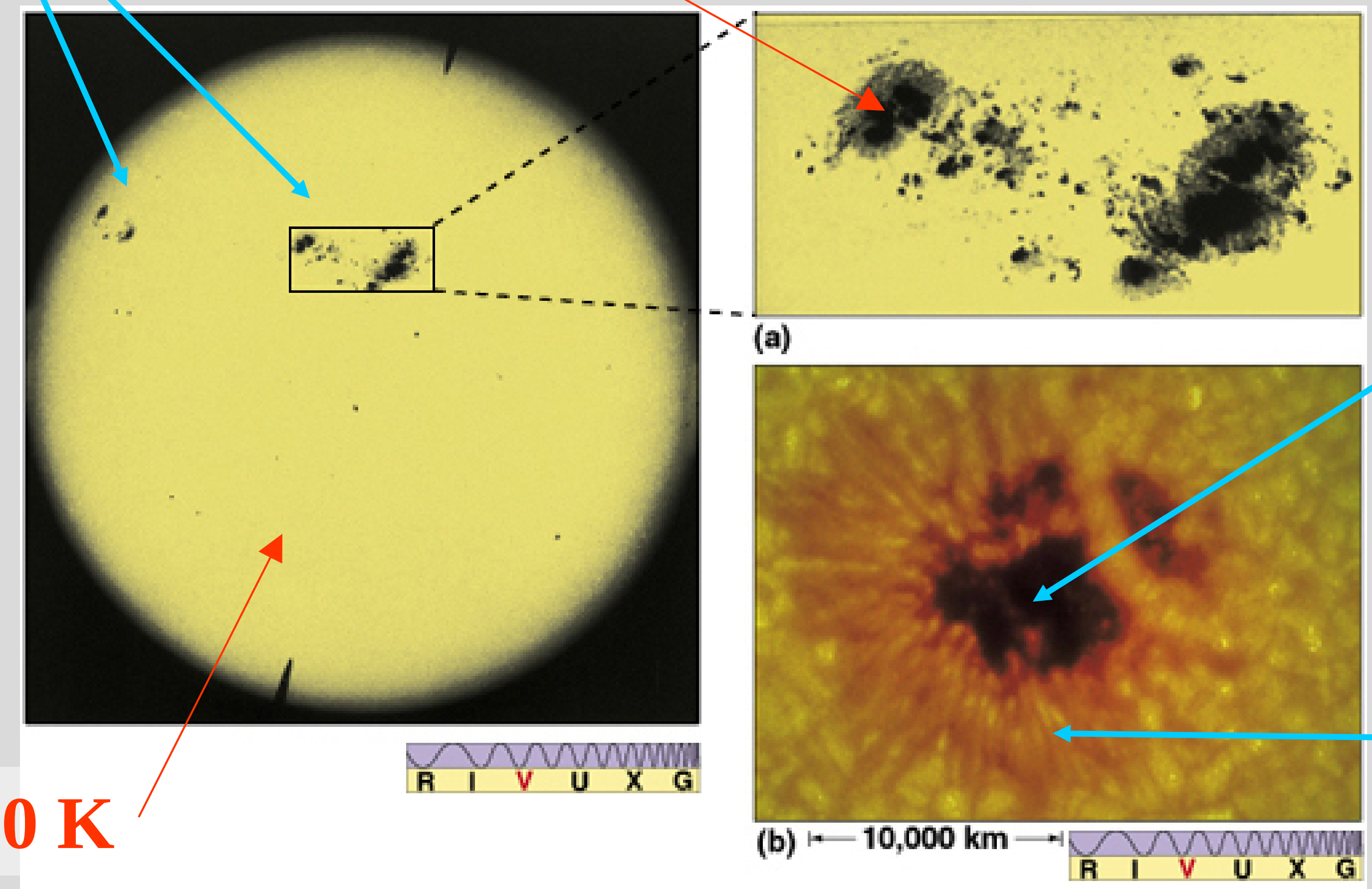


Coronal loop

Sunspots

Often seen in pairs

~4000 K



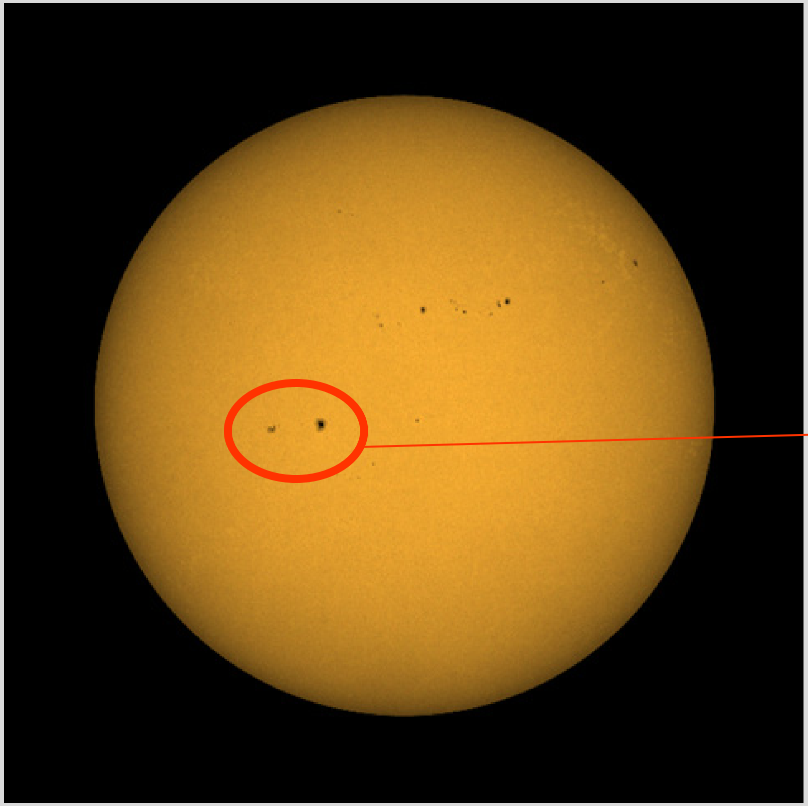
Umbra

Penumbra

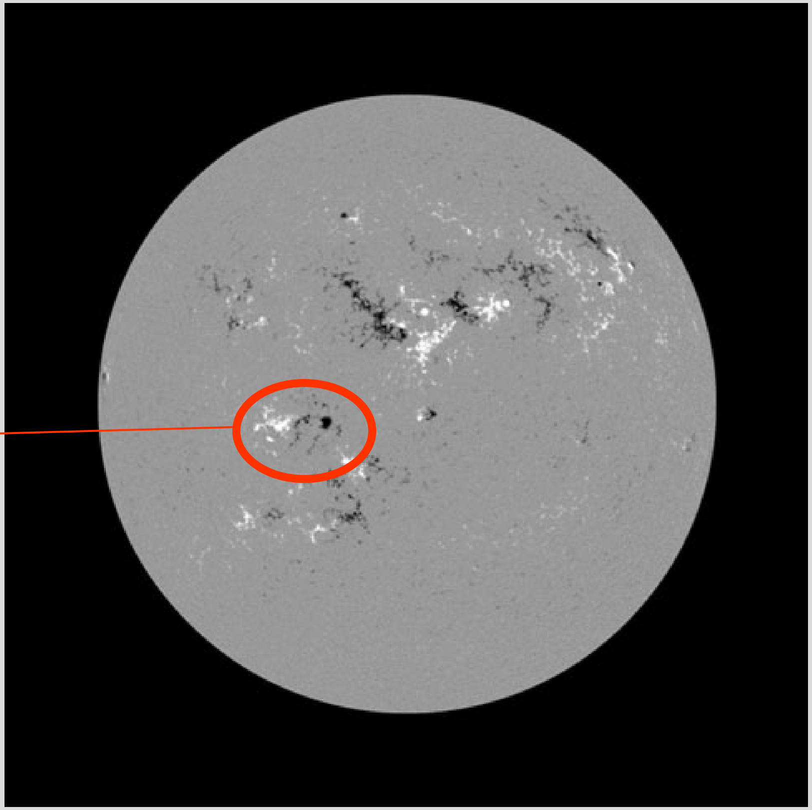
~6000 K

Sunspots and magnetic fields

Visible light

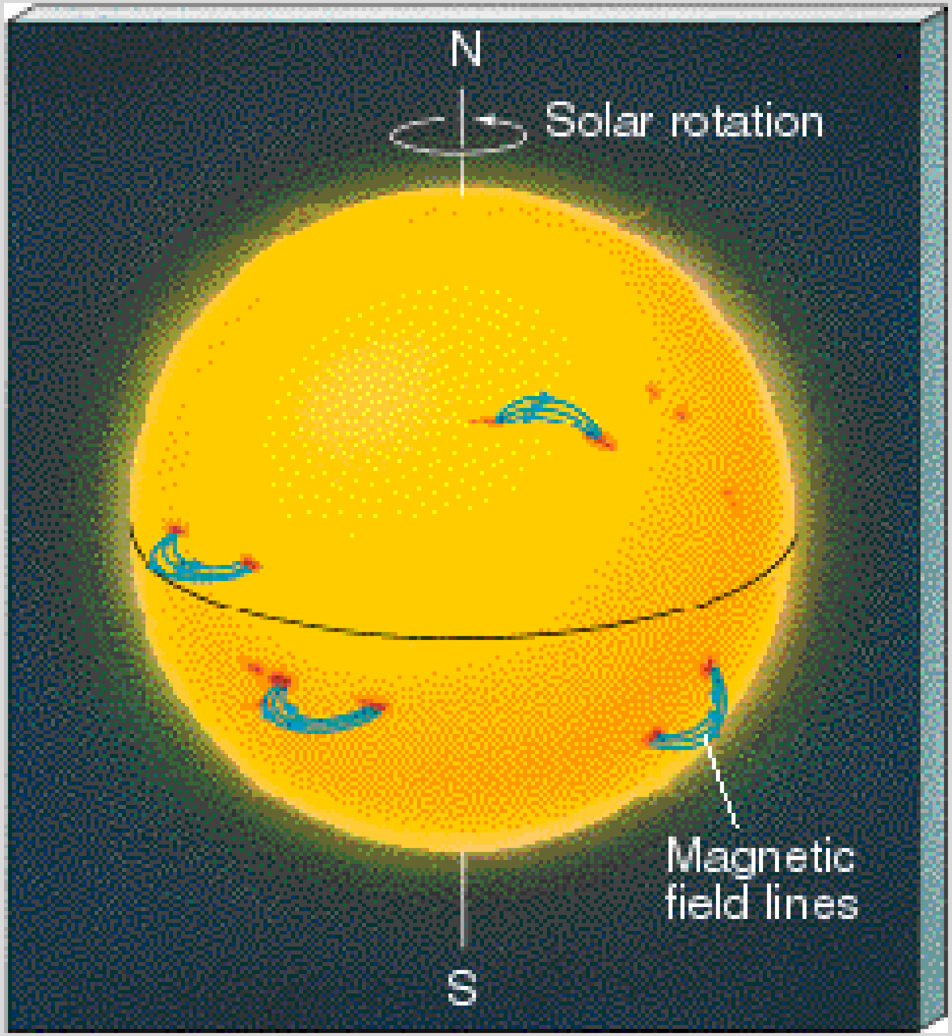


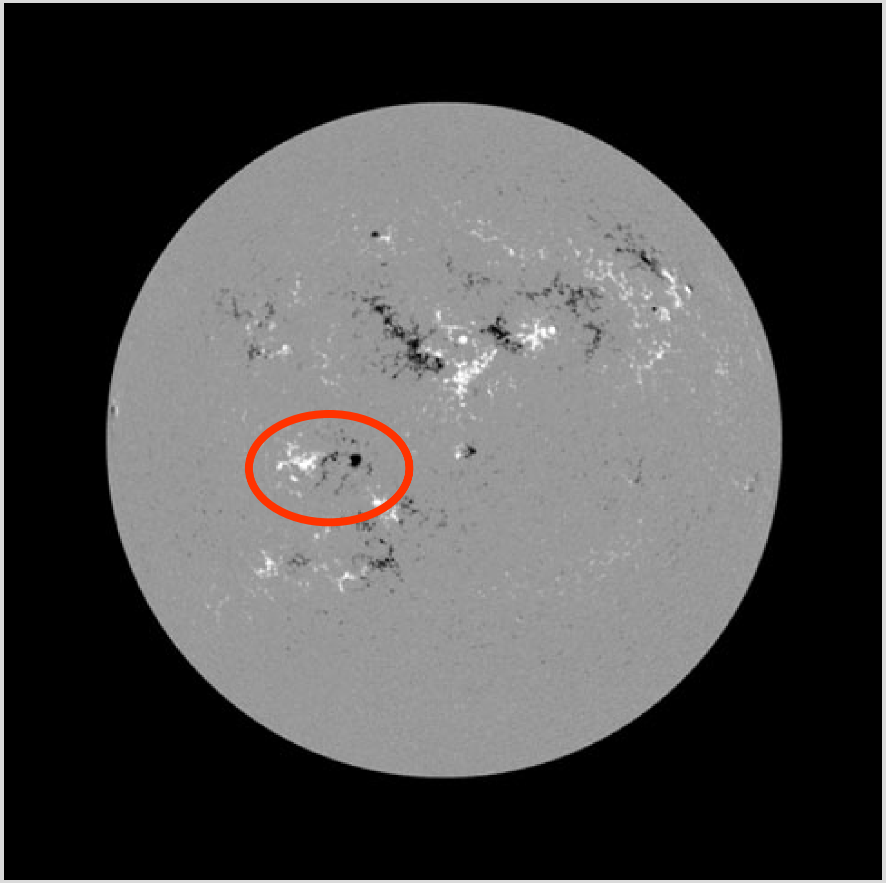
Magnetogram



Sunspots are associated with large magnetic fields

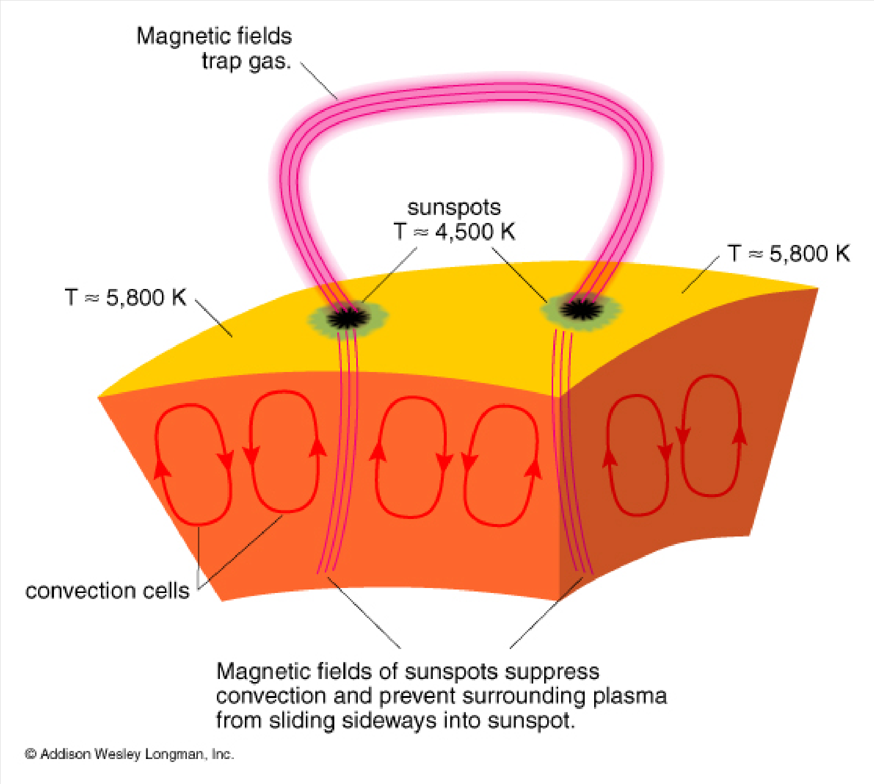
Sunspots and magnetic fields

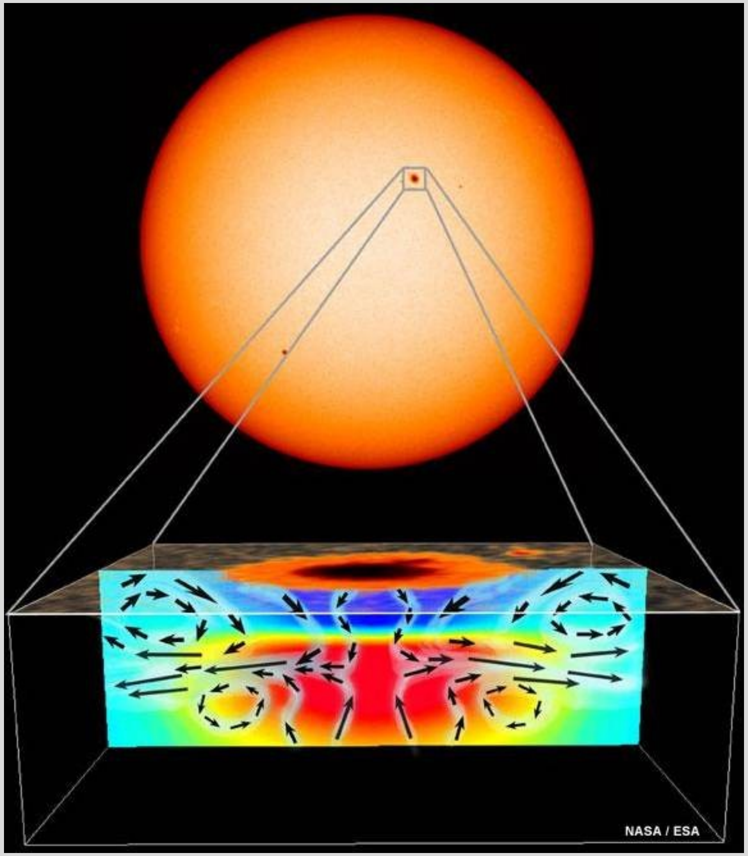




Sunspots and magnetic fields

Sunspots

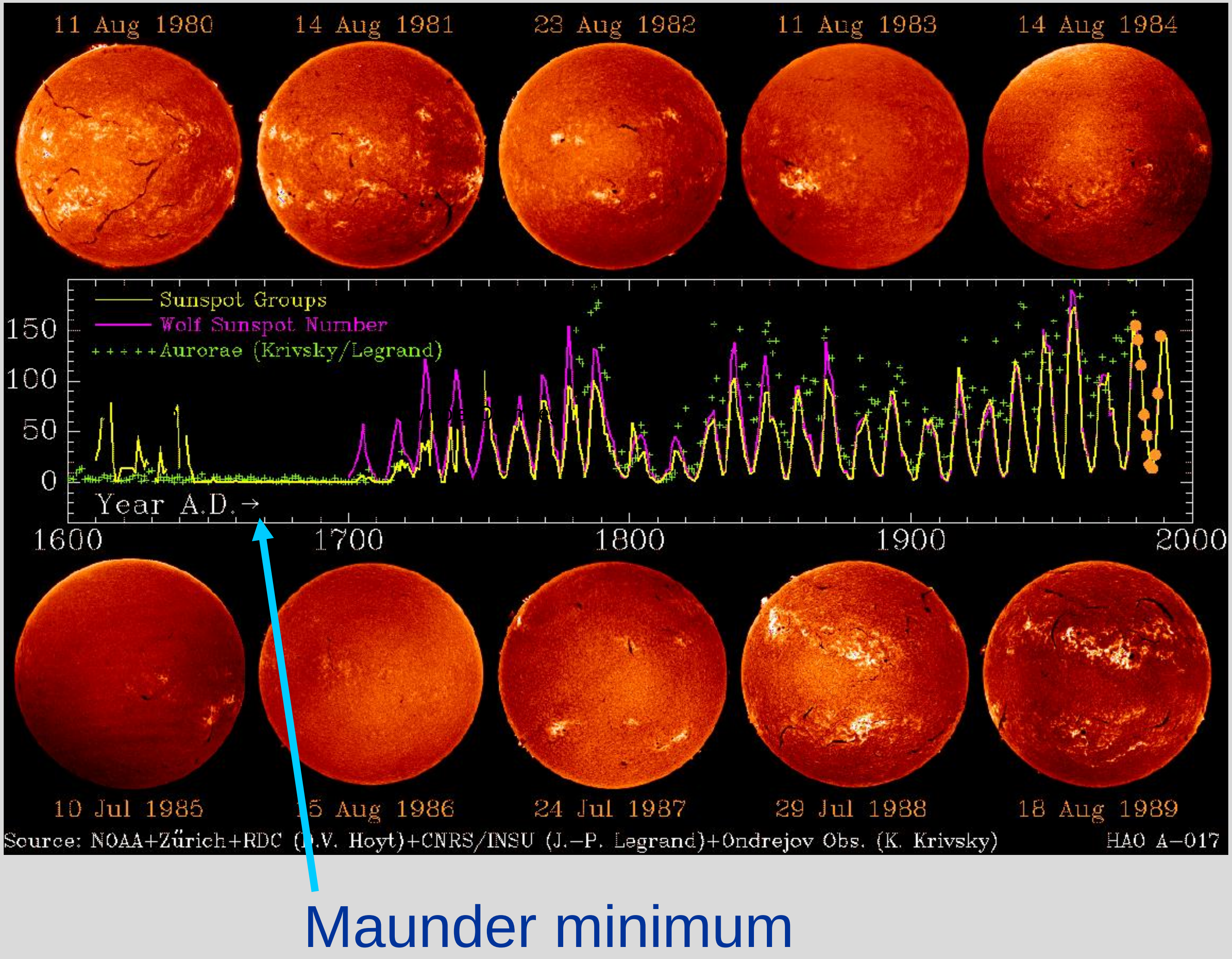




One theory is that the large magnetic field in the sunpots affects the convection of hot matter from the solar interior, so that it will not reach the surface.

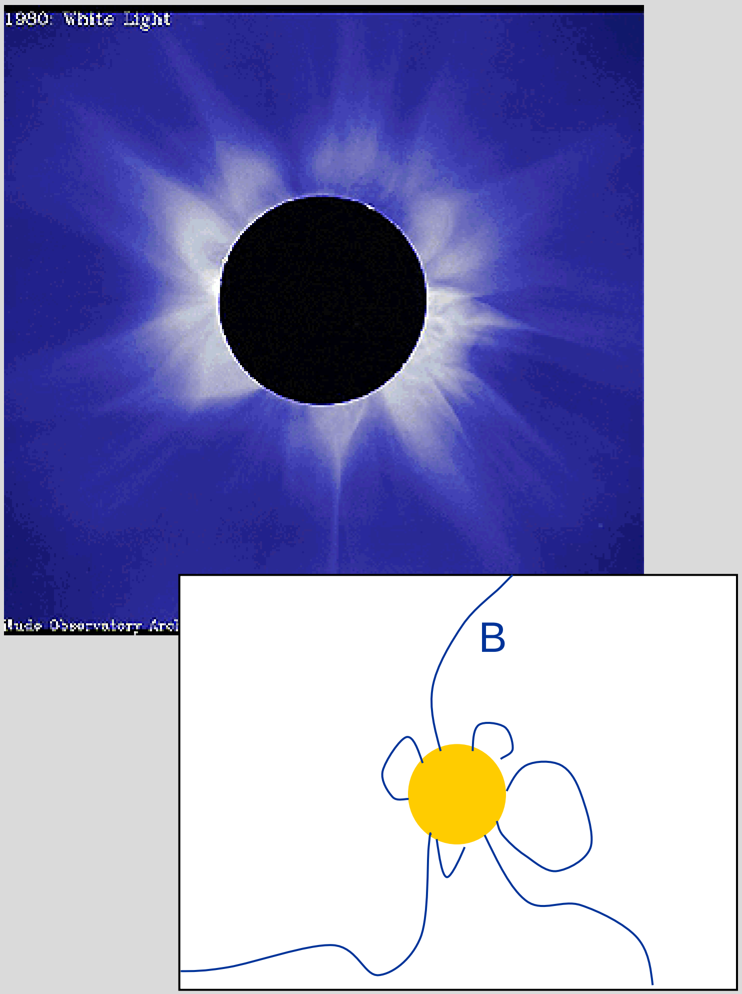
Sunspot cycle (solar cycle)

- 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.



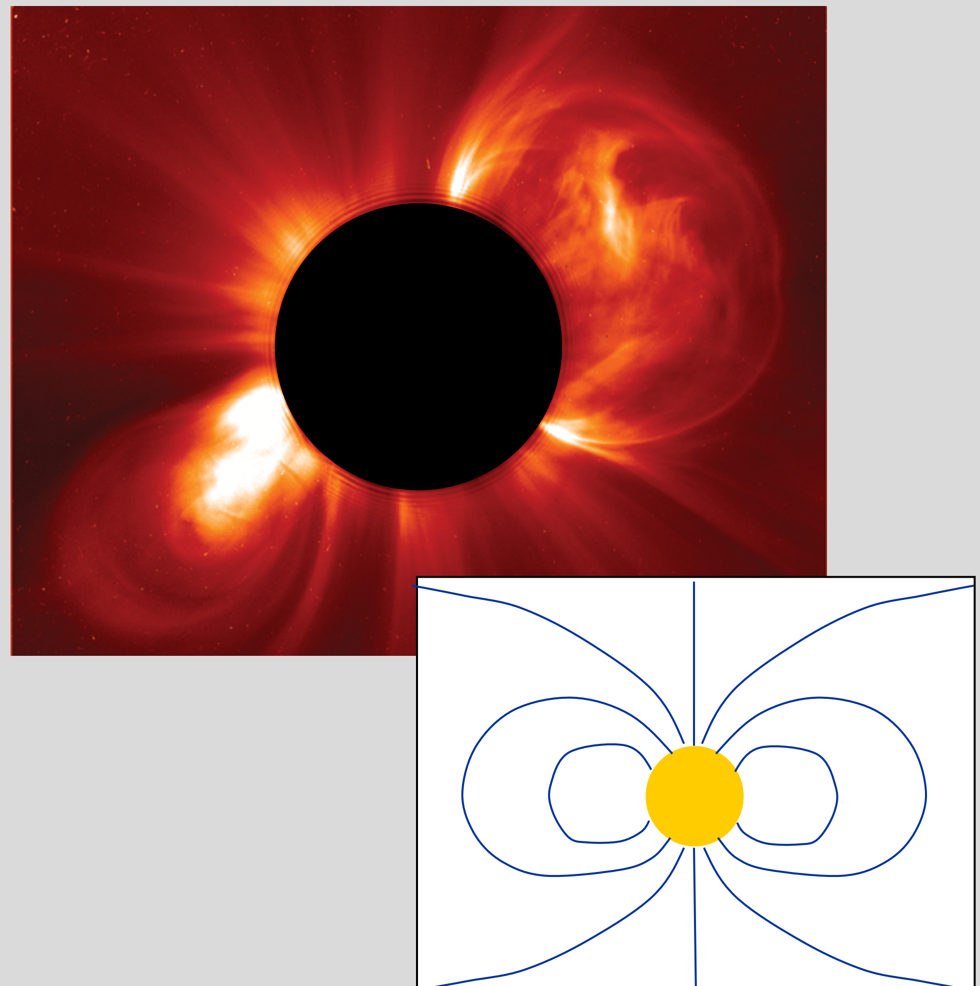
Solar magnetic field as organizing factor

Maximum



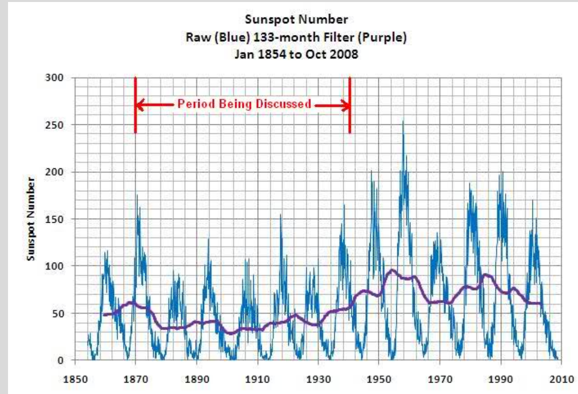
Maximum: weak, irregular magnetic field

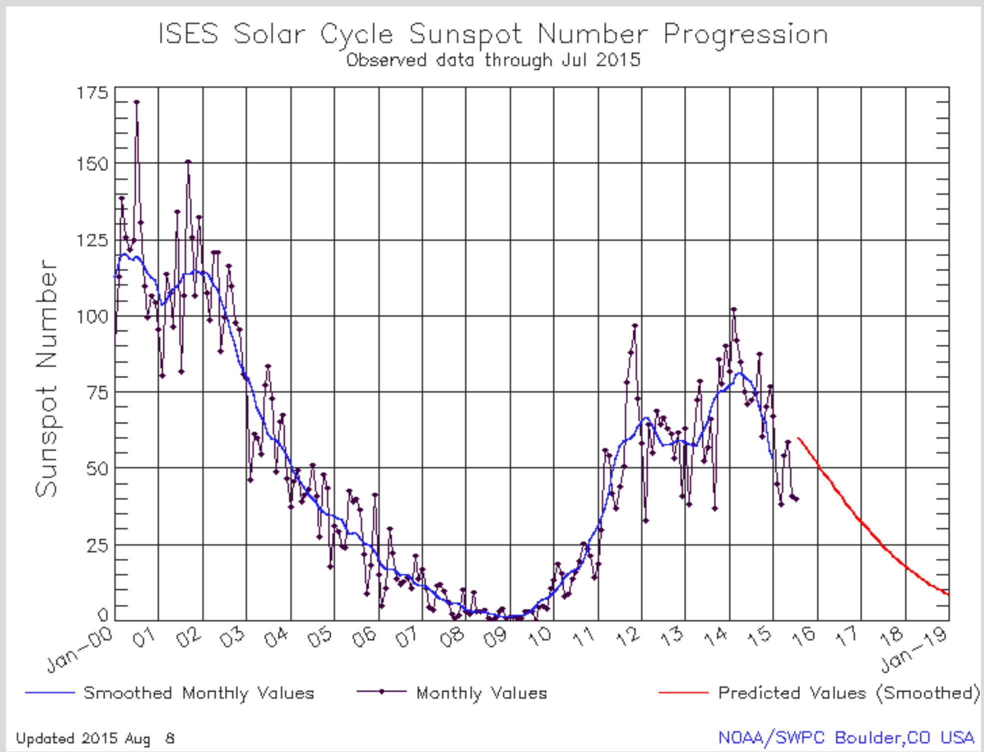
Minimum



Minimum: large, regular dipole-like field

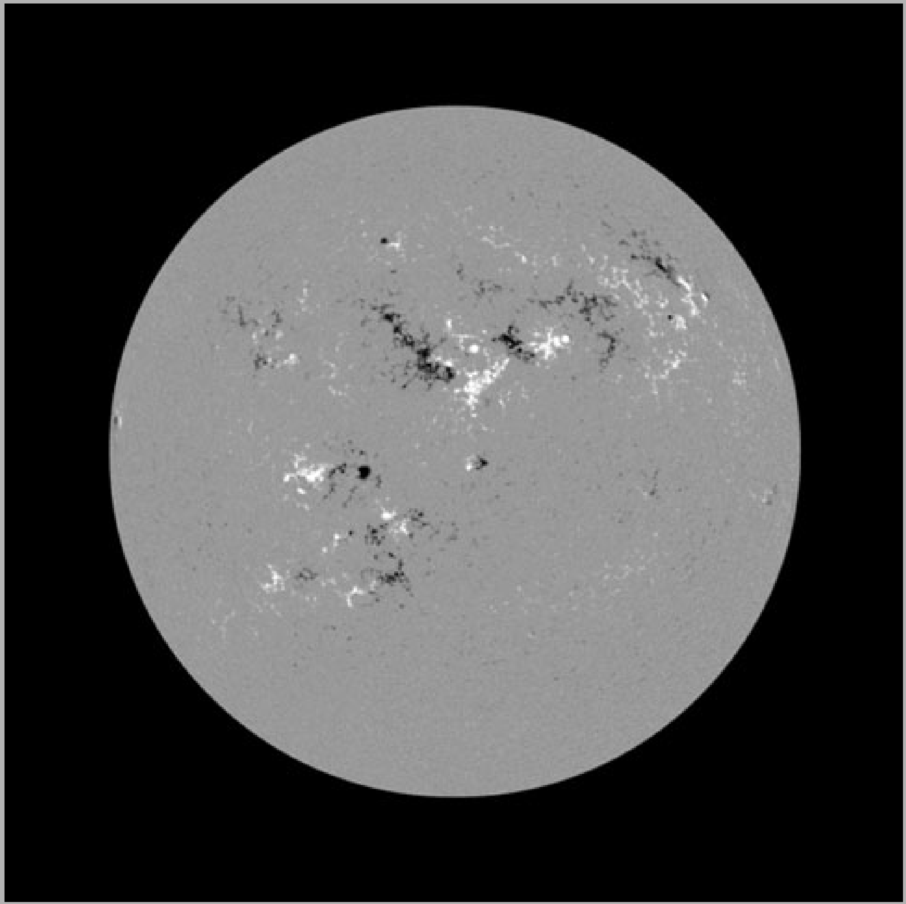
Where are we today?





Prediction by
National Weather
ServiceSpace Weather
Prediction Centre

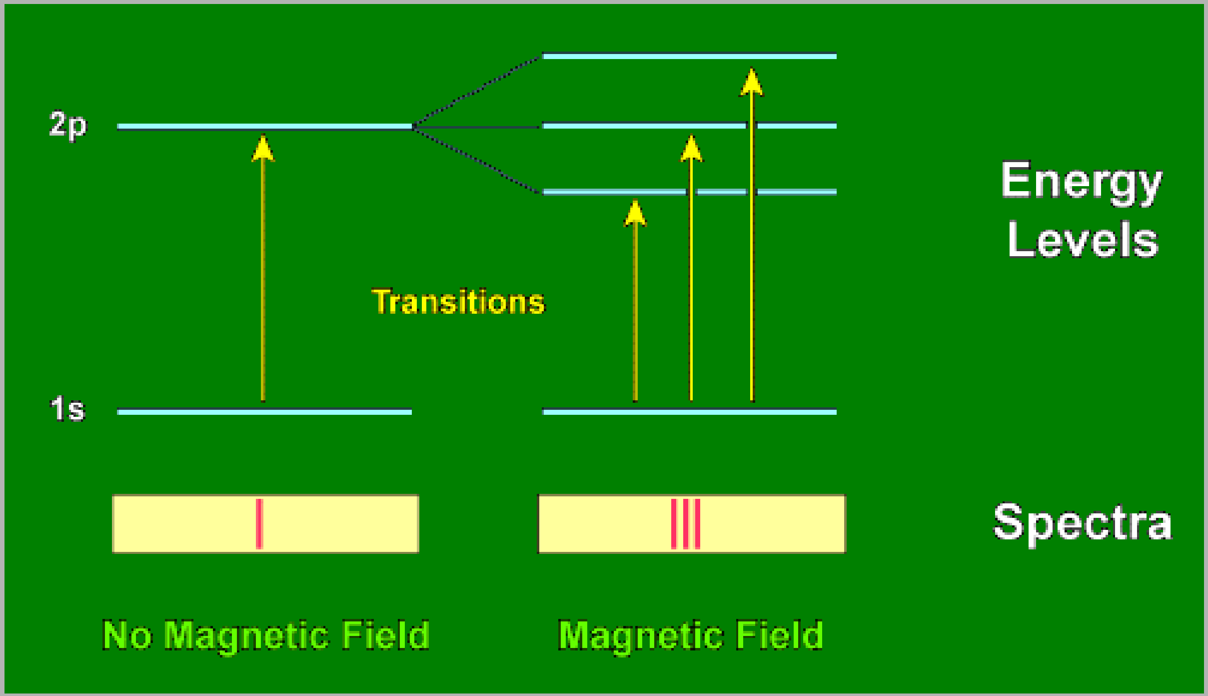
Think about this

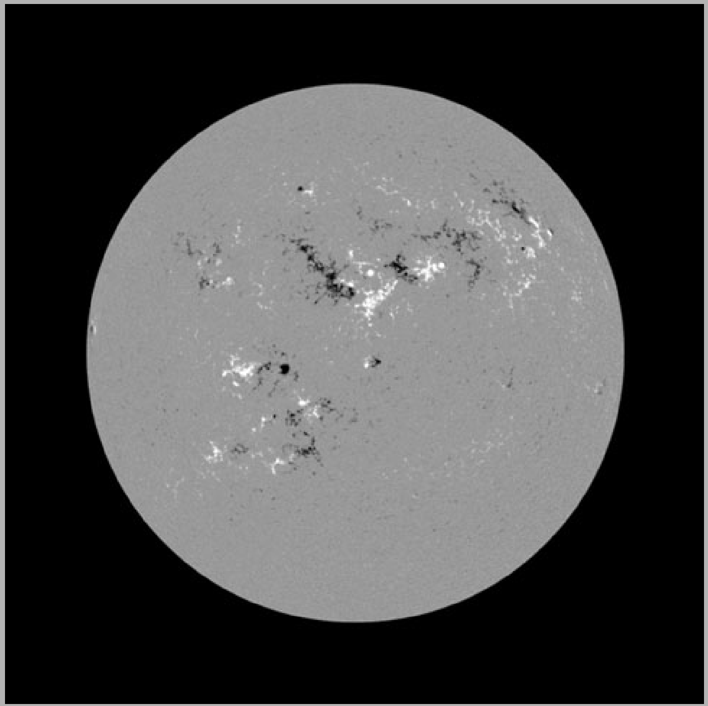


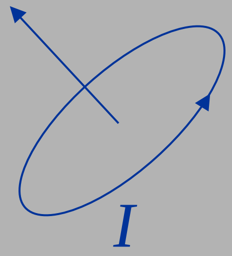
How can we measure the magnetic field on the solar surface???

Zeeman effect:

In the presence of a magnetic field electron orbits with different angular momentum will interact with B in slightly different ways. Thus the energy levels will split up. The larger B, the larger split.







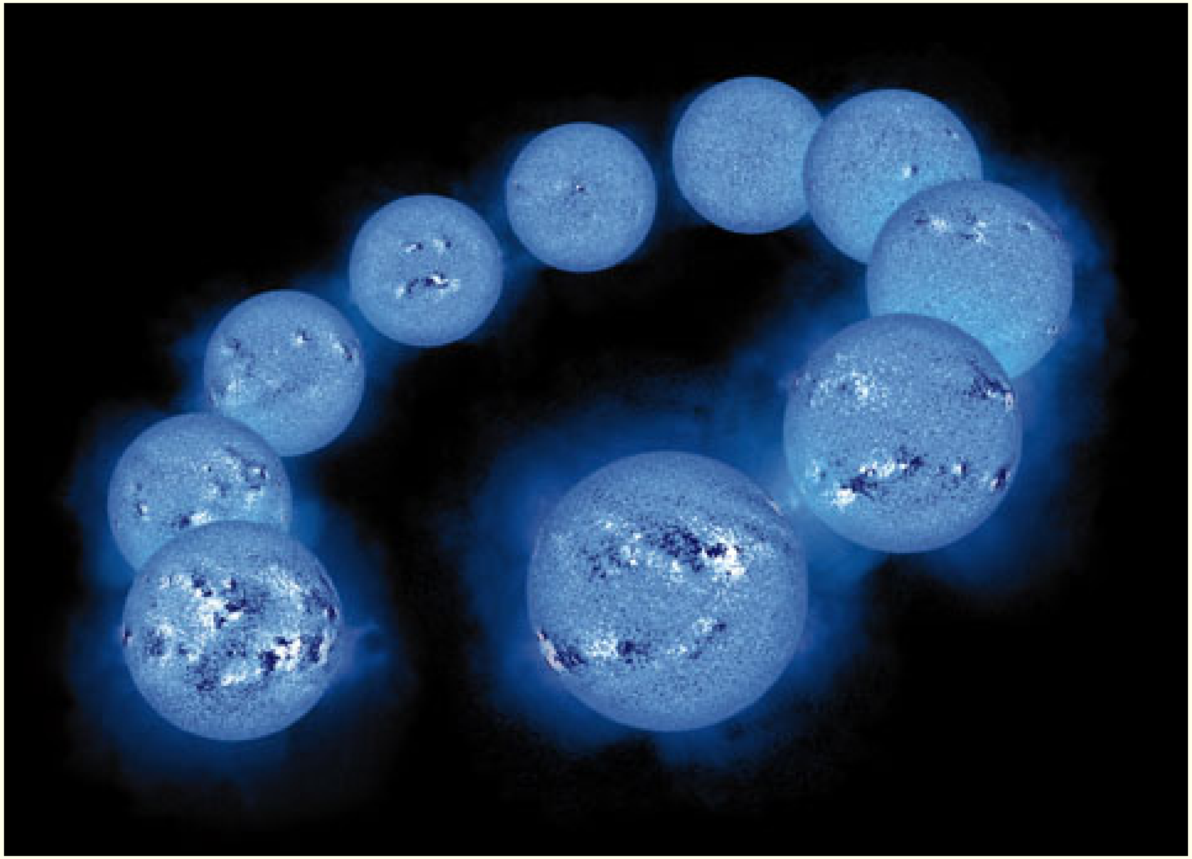
$$W = -\boldsymbol{\mu} \cdot \mathbf{B}$$

$$\mu = IA$$

Solar activity in general

On the solar surface there are various dynamical irregularities and structures.

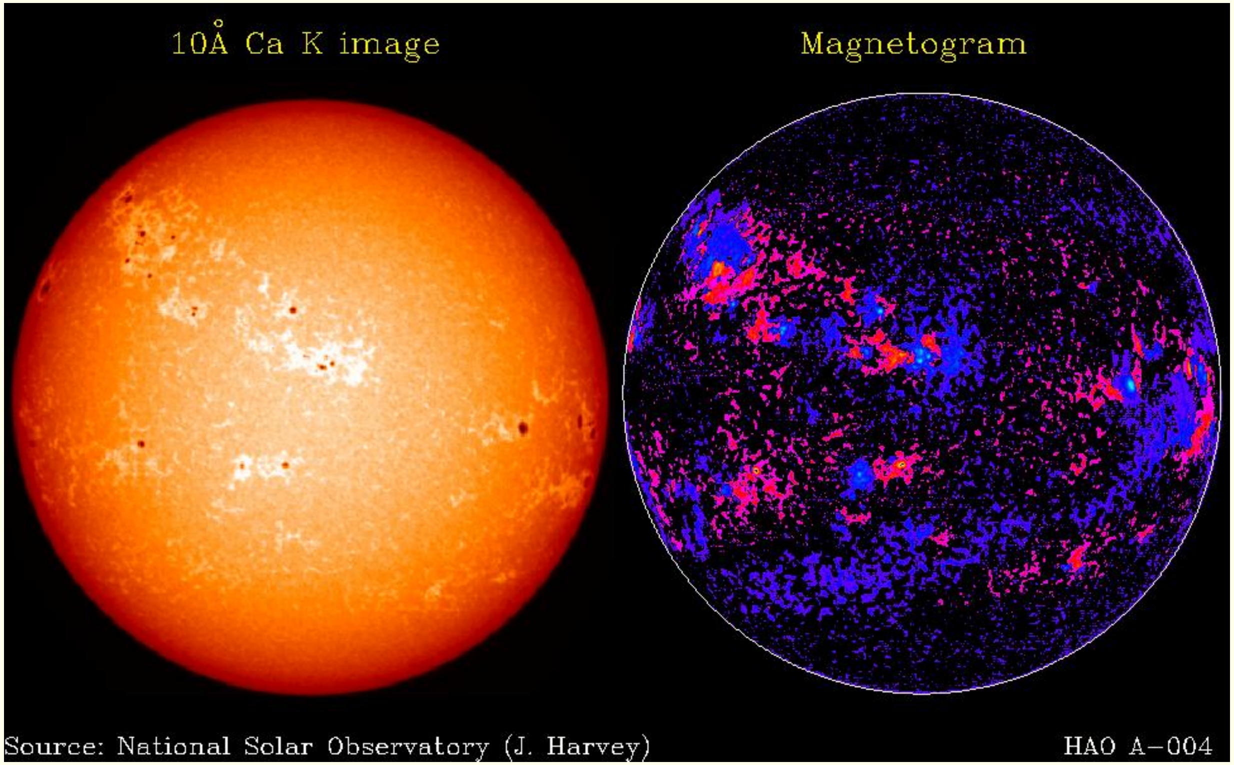
These are given the general name ”solar activity” or ”active regions”.



Magnetograms during a solar cycle

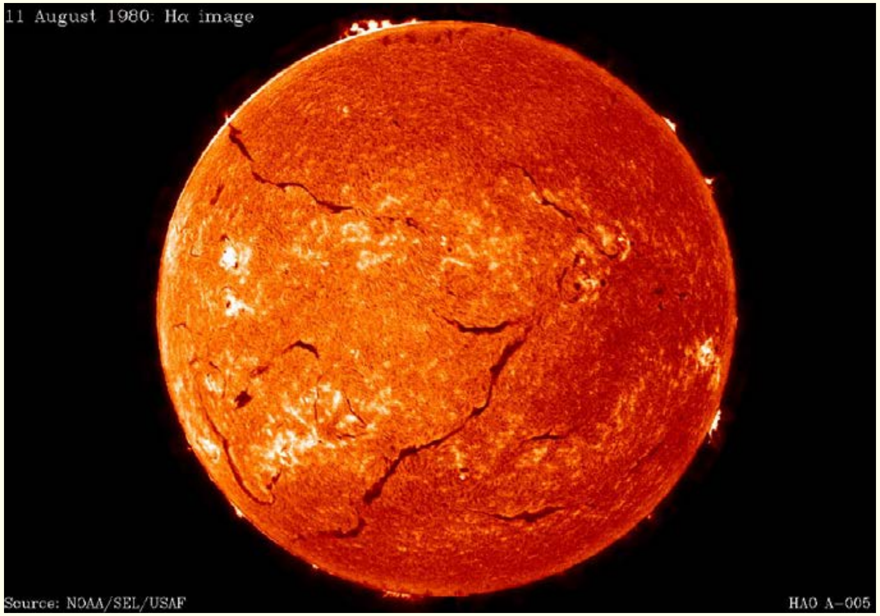
Active regions

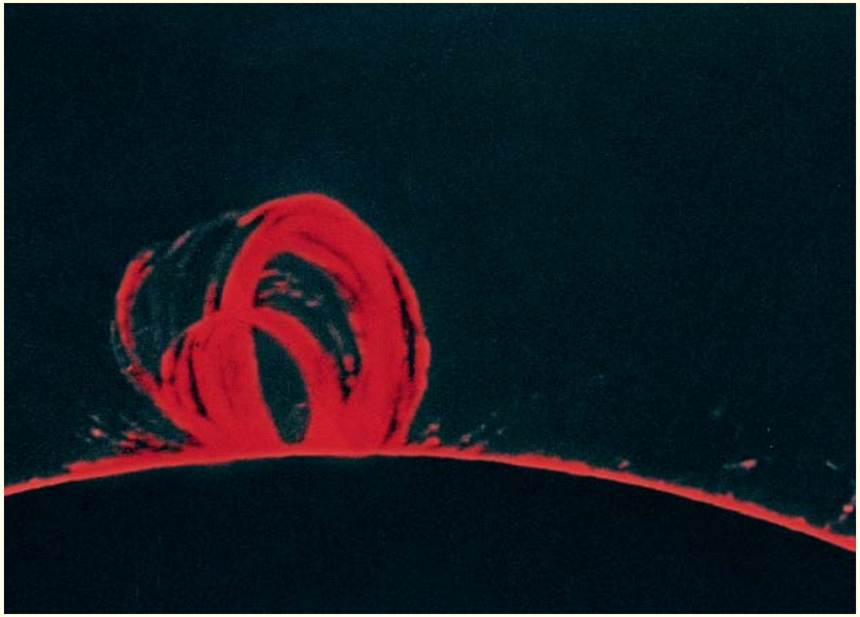
- Sunspots:
  B ~ 100 – 400 mT
- Plages:
  B ~ 10 – 50 mT
- Rest of solar surface:
  B ~ 0,1 – 0,3 mT



Prominences

When viewed from above they are called “filaments”





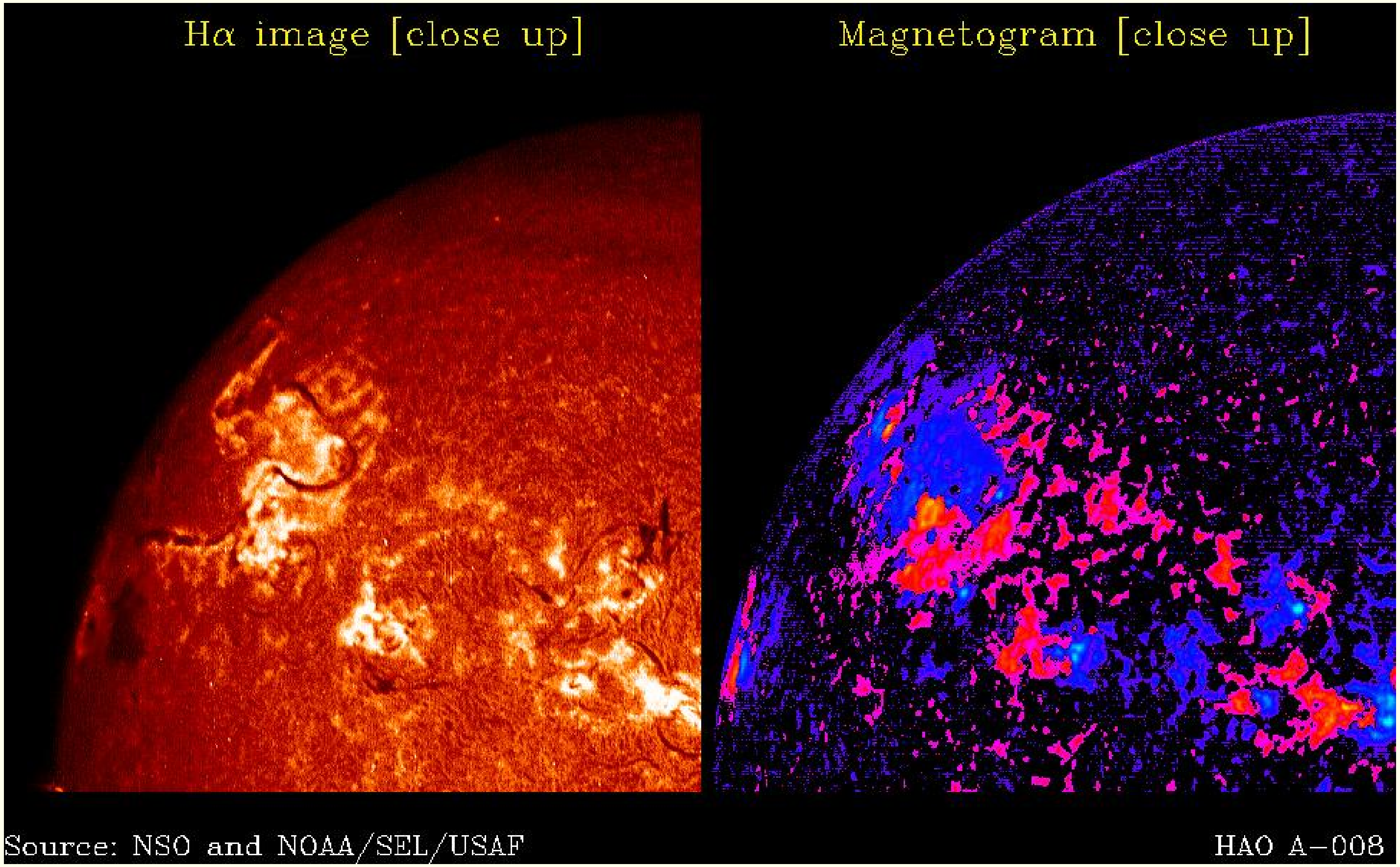
Viewed from the side: prominences

Possibly they are hotter plasma, their lower density to give them buoyancy,

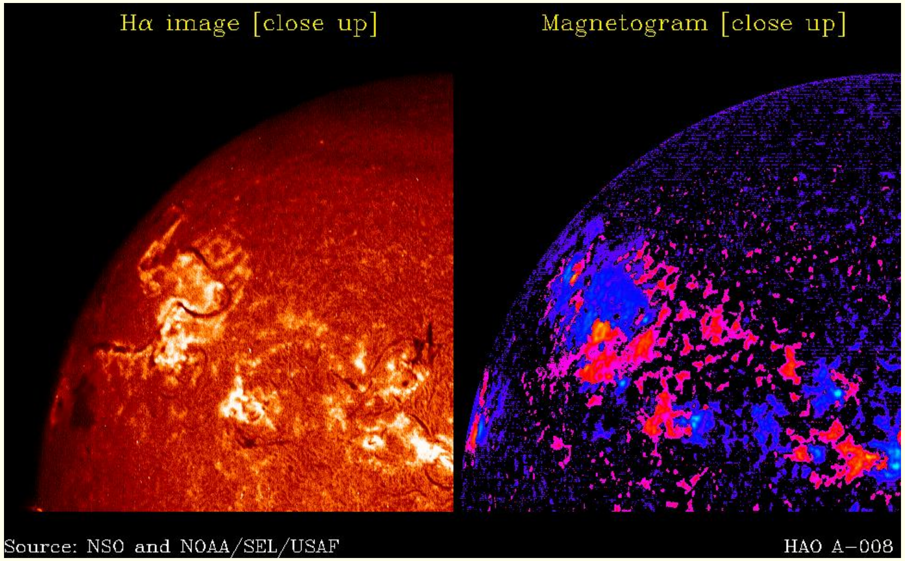
But most theories consider them to be colder material, supported by magnetic field lines.

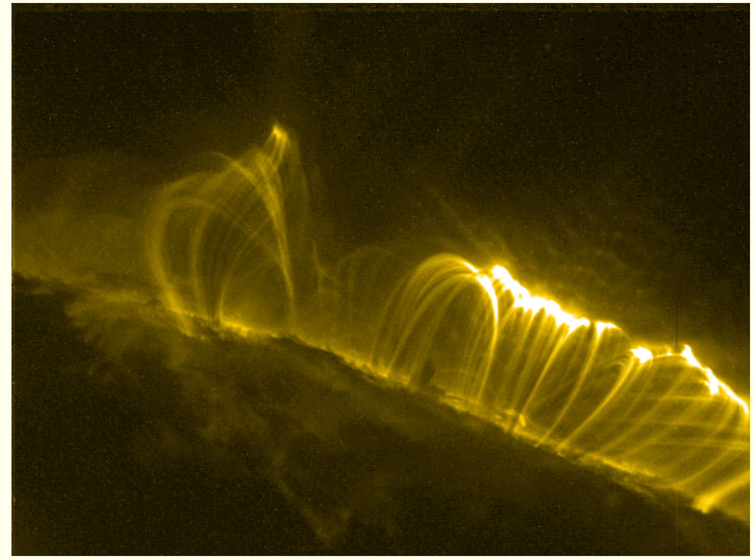
Prominences

Prominences are often observed at the border between regions of different magnetic polarity.

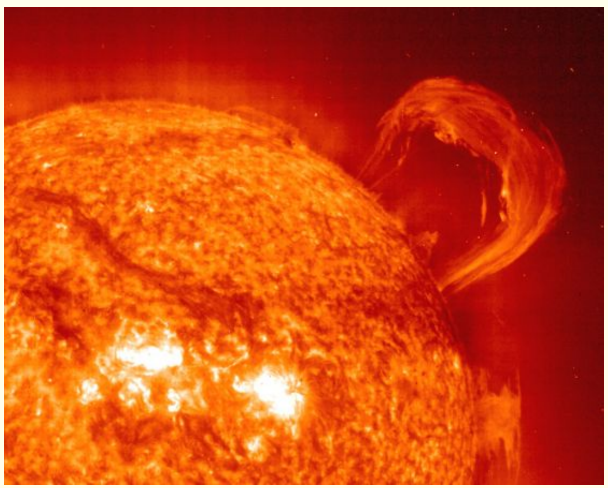


Prominences = filaments



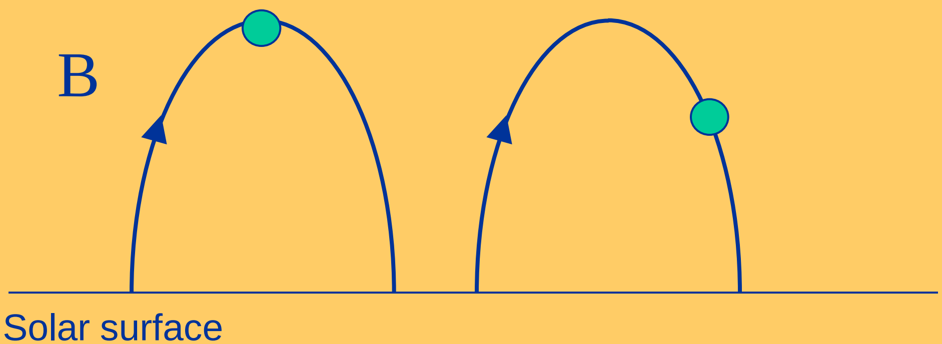


Interpretation: street of coronal loops along the border between polarities



Alternatively: one single, large loop makes up the prominence/filament.

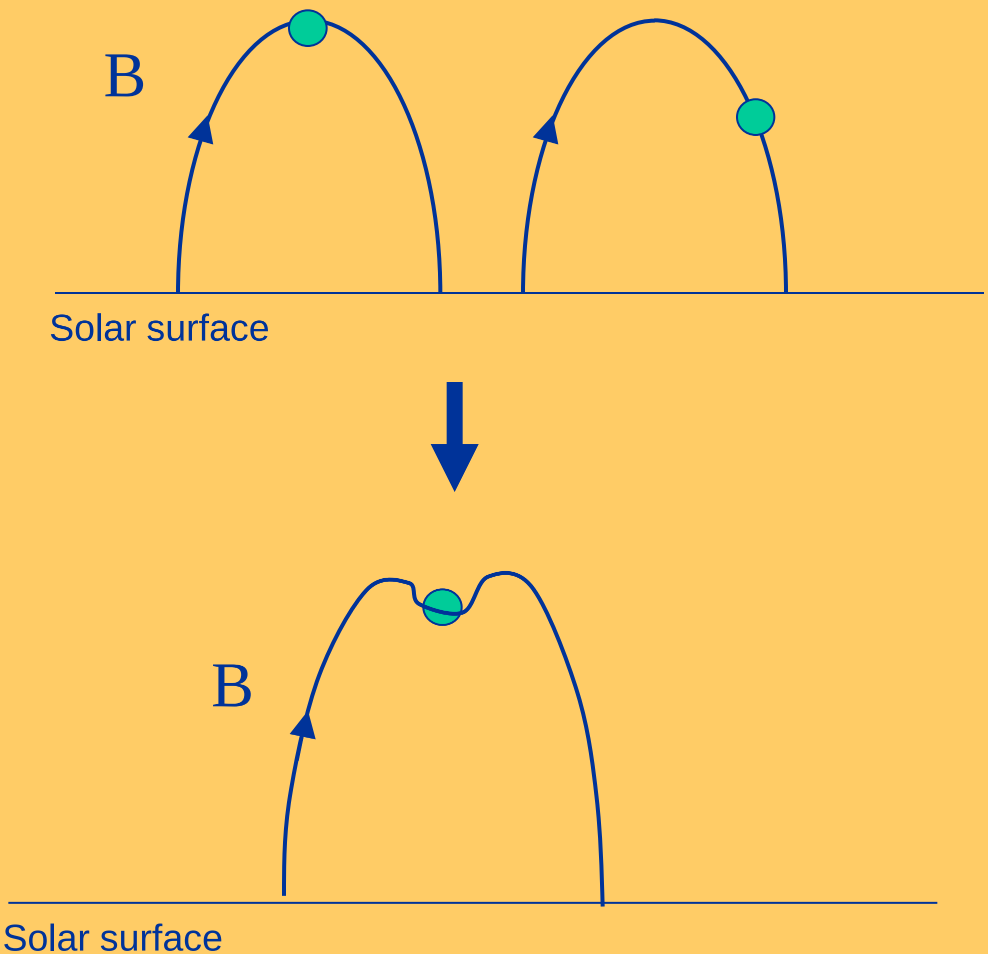
Think about this:

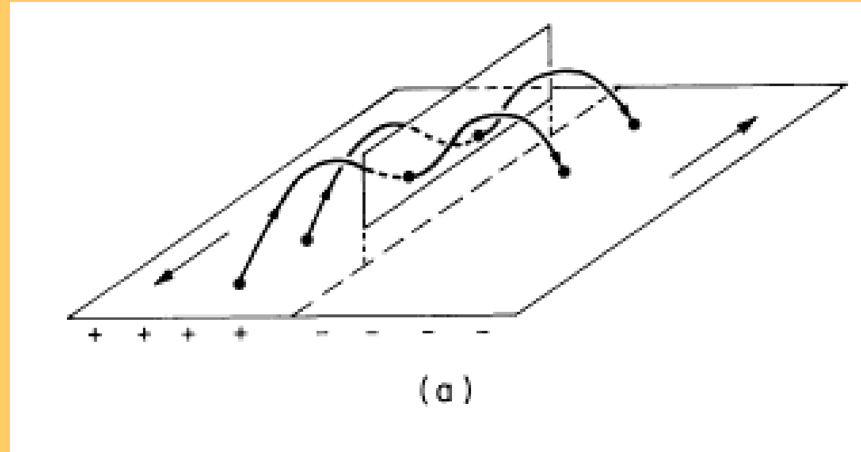


Plasma can only move along field lines. Due to gravity a plasma element at the top will ”fall down” from the top by the slightest disturbance.

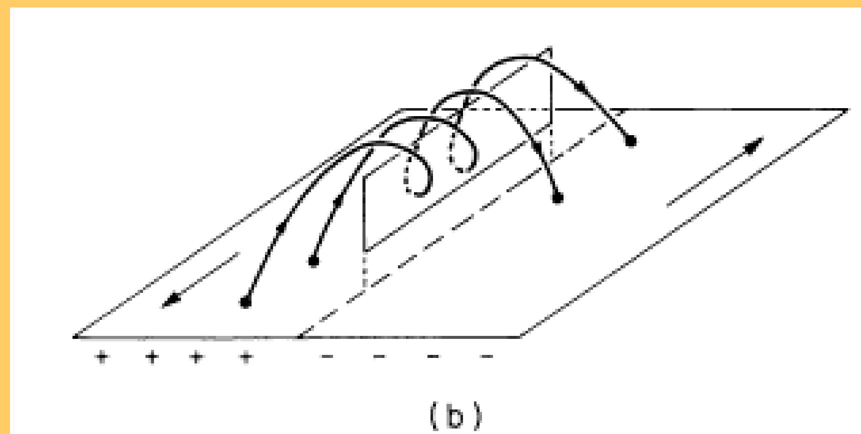
Can you think of a slight modification of the field line which may support the plasma element in a stable way?

Think about this:





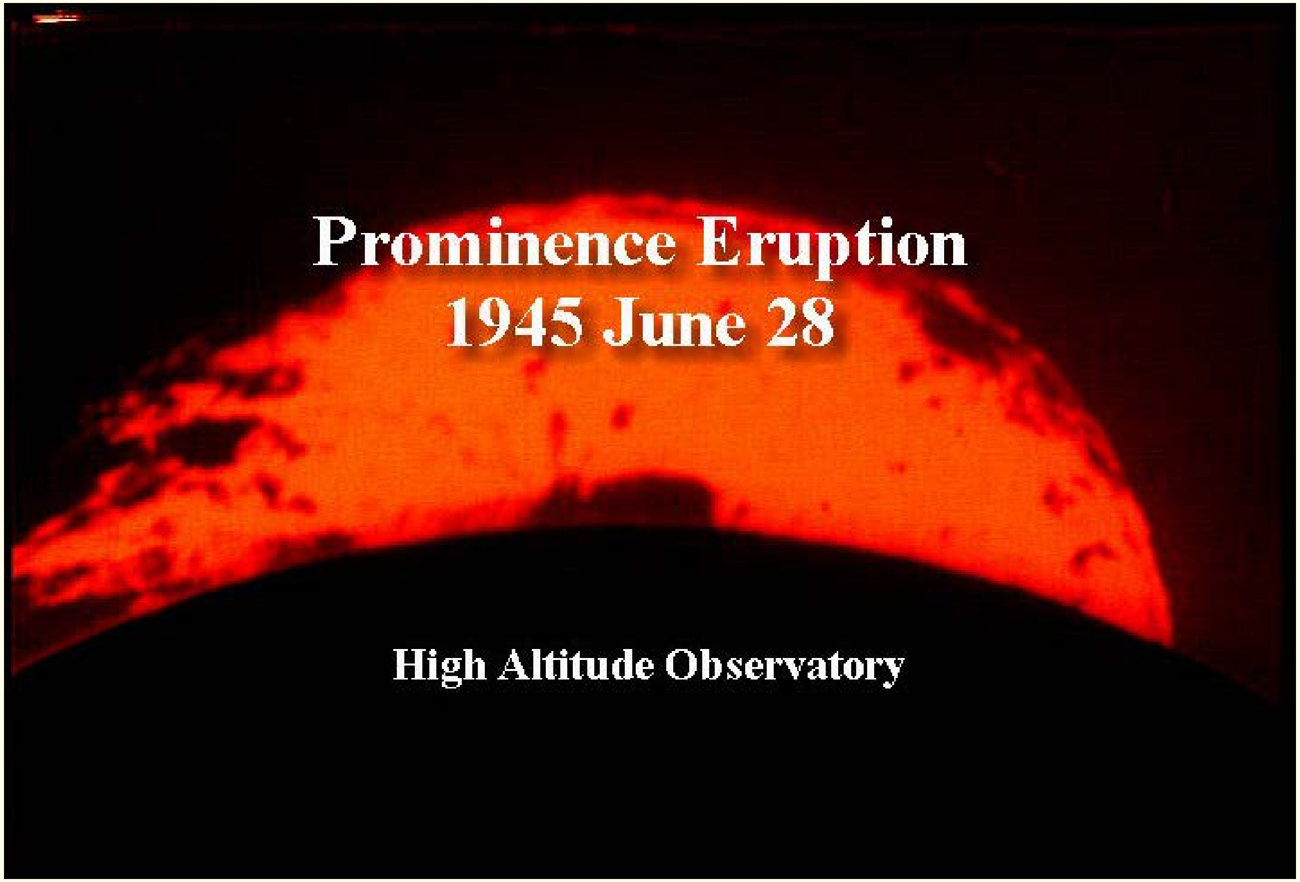
Kippenhahn-Schlüter model

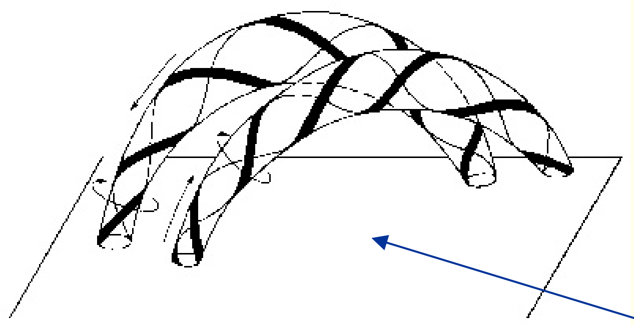


Kuperus-Raadu model

Erupting prominces

Sometimes the prominences may go unstable and release the energy stored in the magnetic fields.

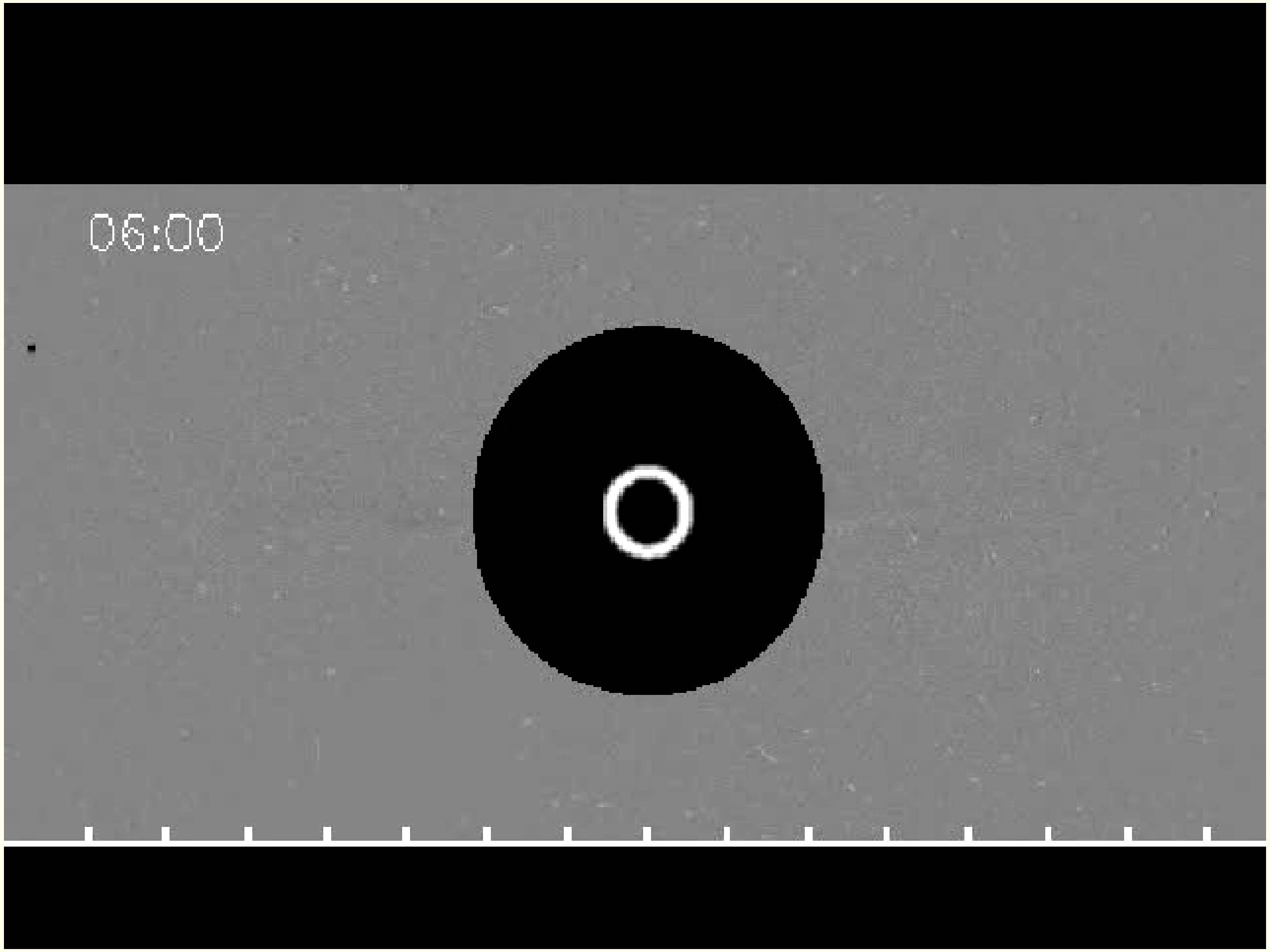




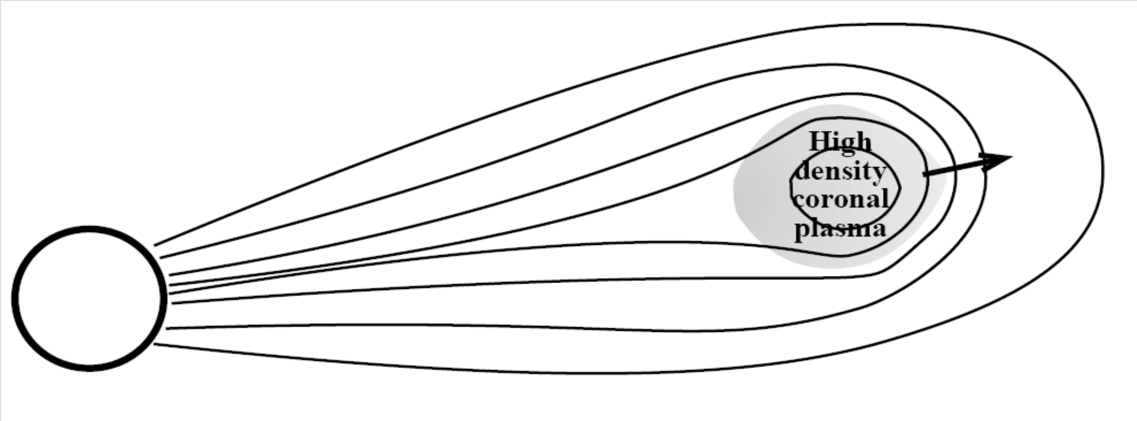
Twisted magnetic field lines store additional energy

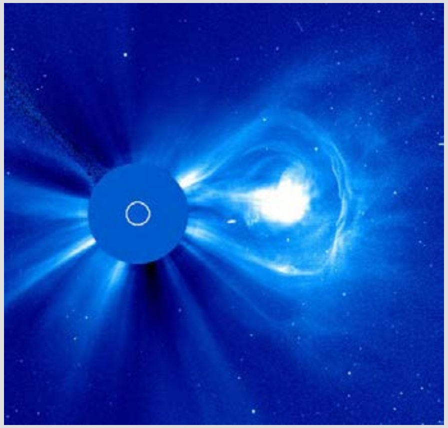
Coronal mass ejections – CME

- Often associated with ***prominences***, ***solar flares*** or "***helmet strea-mers***", but the exact mechanisms are not known
- May contain up to10^{13} kg matter
- May have velocities of up to 1000 km/s

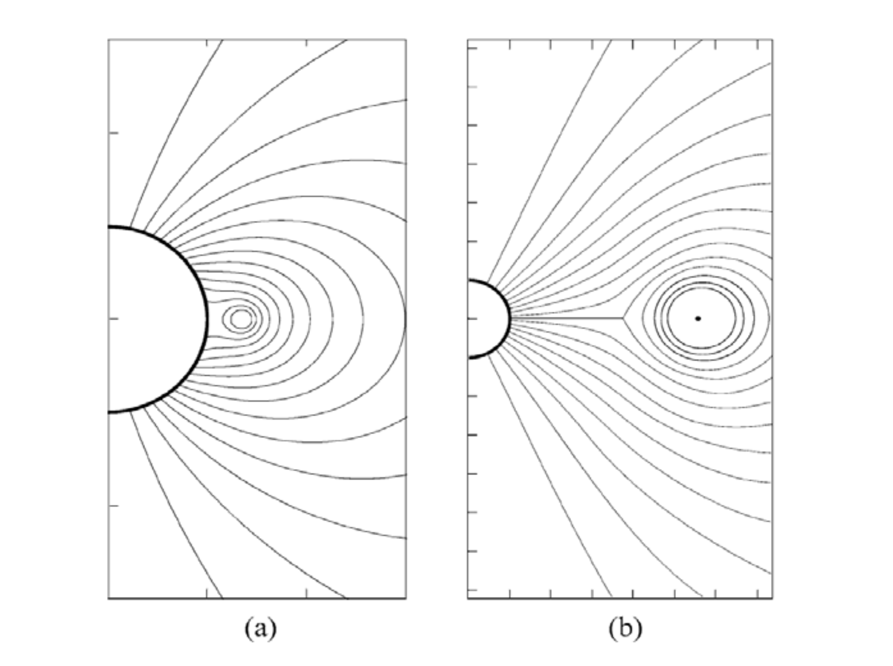


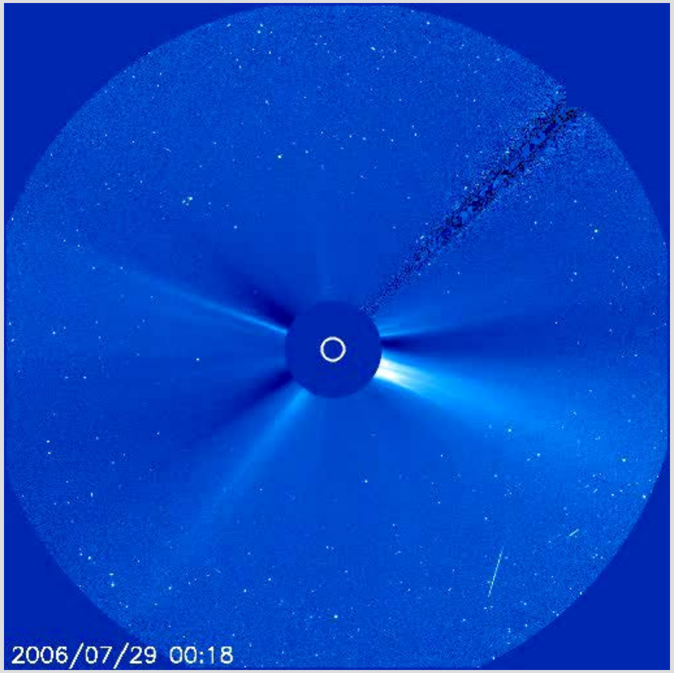
CME - magnetic connection to sun





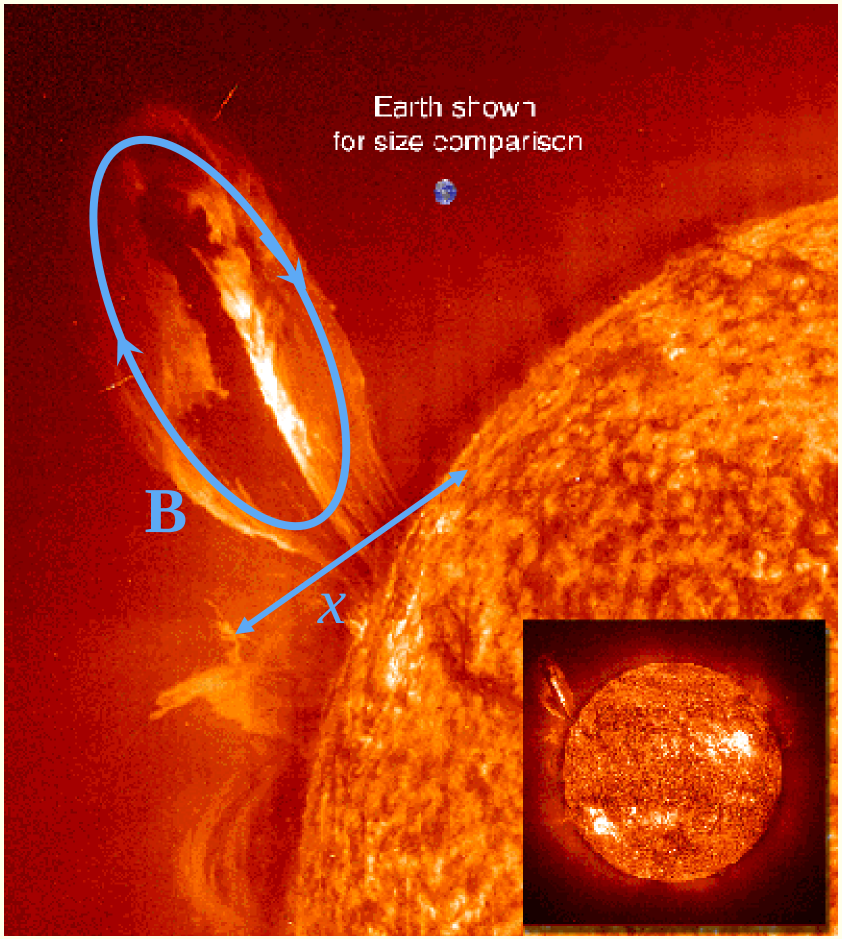
flux rope CME





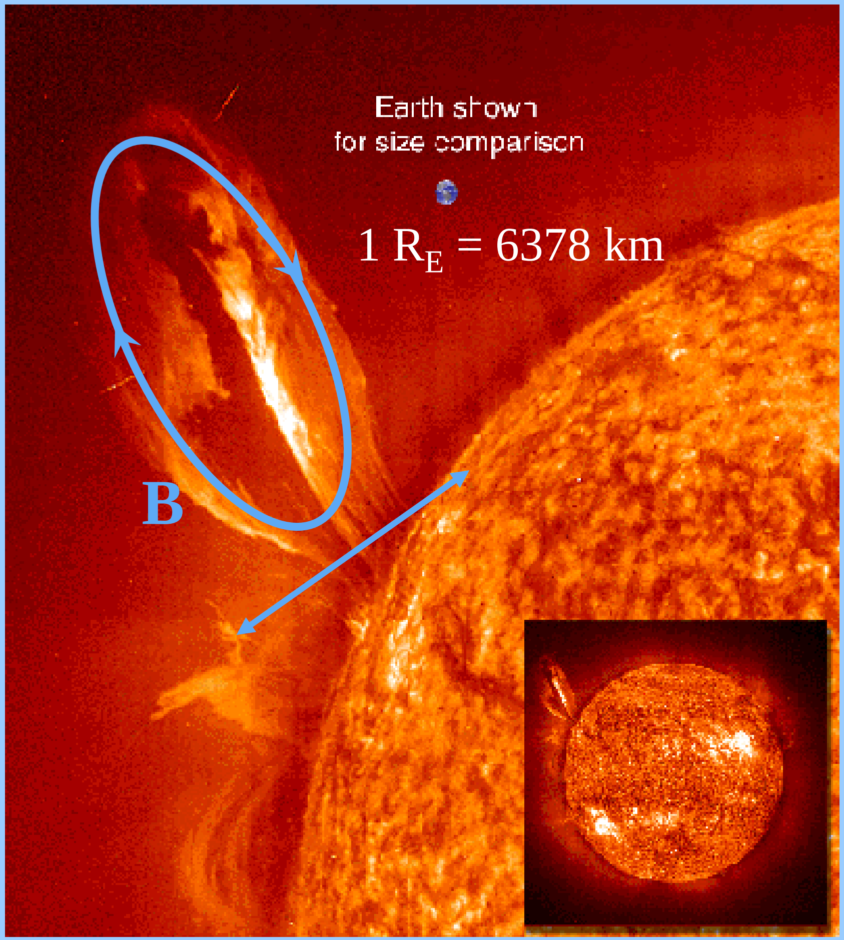
'smoke ring' CME

Coronal mass ejections



CME are sometimes called "magnetic clouds", because of their magnetic field configuration.

Coronal mass ejections



Estimate the kinetic energy of this CME!
(***Order of magnitude!***)

Suppose the density ρ of the plasma in the cloud is 1000 times denser than the plasma in the lower corona, which is $\rho \approx 10^{-18}$ kg/m^3

Suppose the CME velocity is v = 1000 km/s

Red	$W = 10^{12}$ J
Blue	$W = 10^{17}$ J
Yellow	$W = 10^{22}$ J
Green	$W = 10^{27}$ J

$r \approx 20\ \mathrm{R_E}$

$V_{CME} \approx 4\pi r^3/3 \approx 4\pi \cdot 20^3 \cdot (6378 \cdot 10^3)/3 \approx 9 \cdot 10^{24}\ \mathrm{m^3}$

$m_{CME} = V_{CME} \cdot \rho_{CME} = 9 \cdot 10^{24} \cdot 10^{-15} \approx 10^{10}\ \mathrm{kg}$

Maybe the cloud is not fully filled with matter, but I will assume that that is a relatively small correction.

$W_{CME} = m_{CME} v_{CME}^2 = 10^{10} \cdot (1000 \cdot 10^3)^2 \approx 10^{22}\ \mathrm{J}$

Yellow $W_{CME} = 10^{22}\ \mathrm{J}$

C.f. nuclear reactor: $P \approx 1\ \mathrm{GW}$.

In one year: $W \approx 10^{16}\ \mathrm{J}$

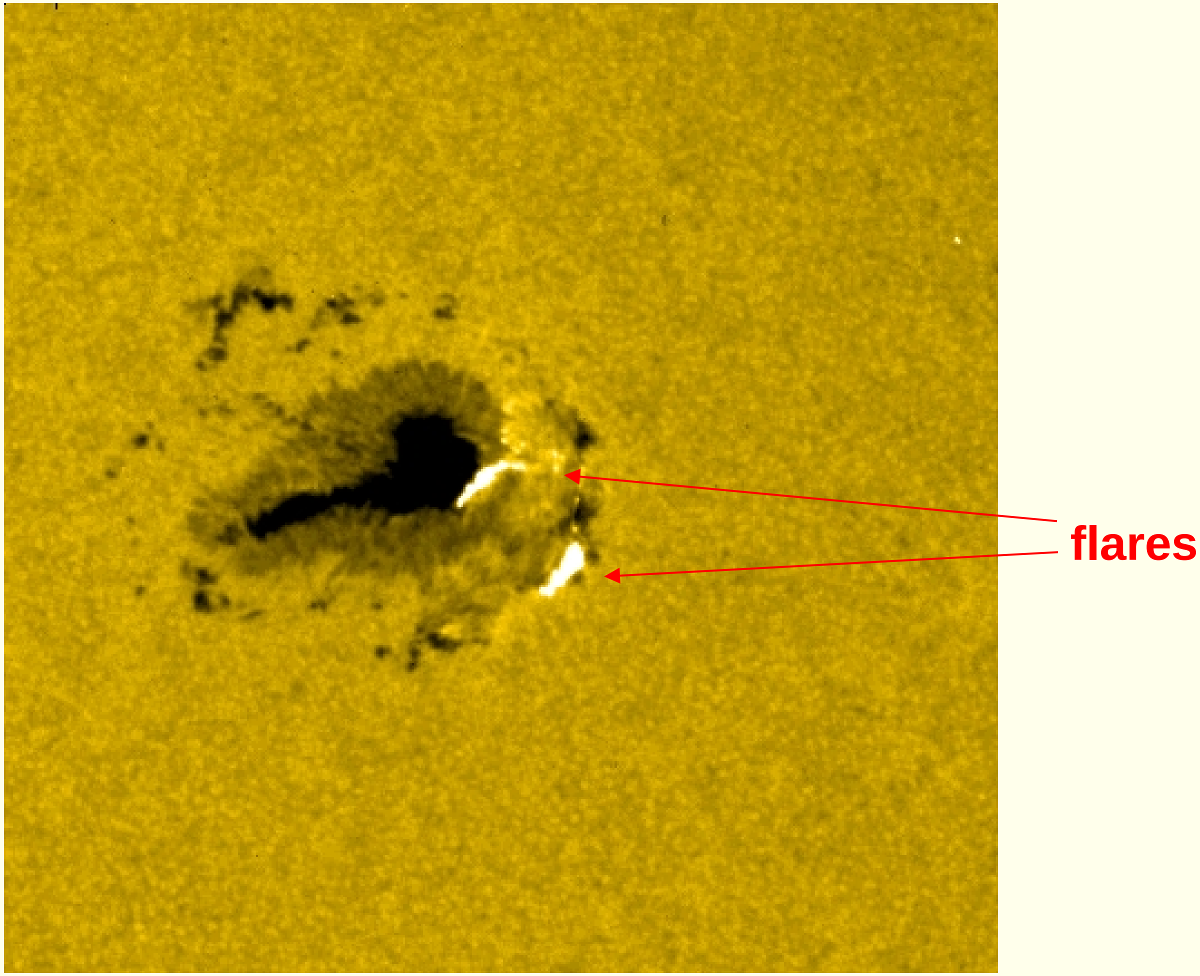
Solar flare

1972, August 07, Big Bear Solar Observatory

- Solar flares are explosive intensifications in X-ray, UV and visible light.
- Intensification in X-ray may be up to a factor 10^4
- Last for ~ 1 – 60 min.

Solar flares

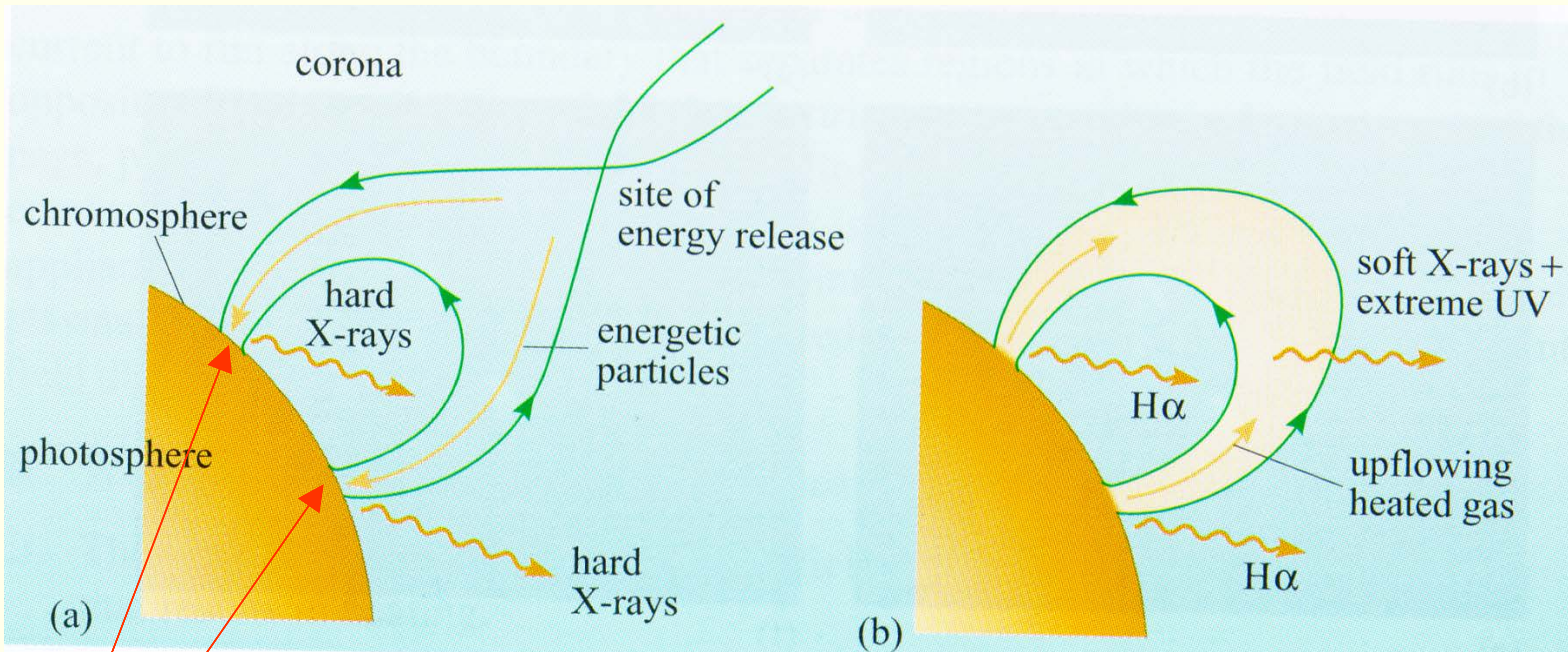
Size of solar flares is comparable to sunpots.



Solar flare

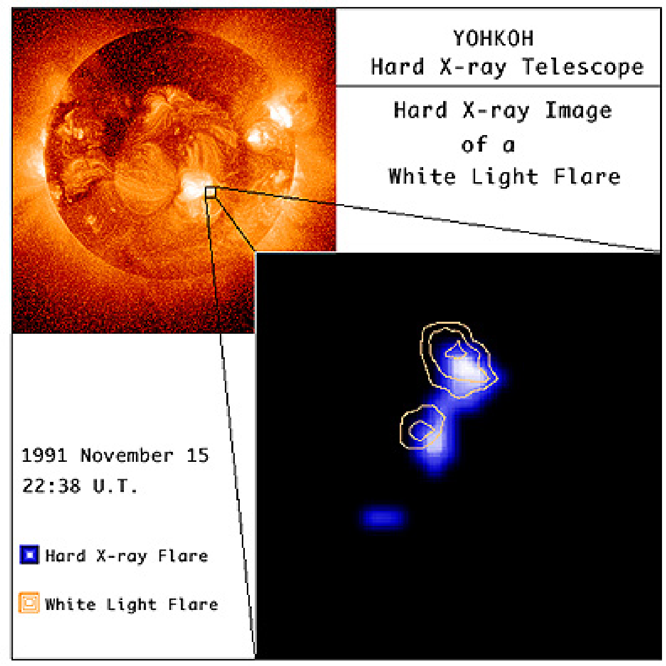

POST-FLARE LOOPS
H-alpha Observations from LaPalma
June 26, 1992
08:10 - 08:55 UT

Solar flare mechanism

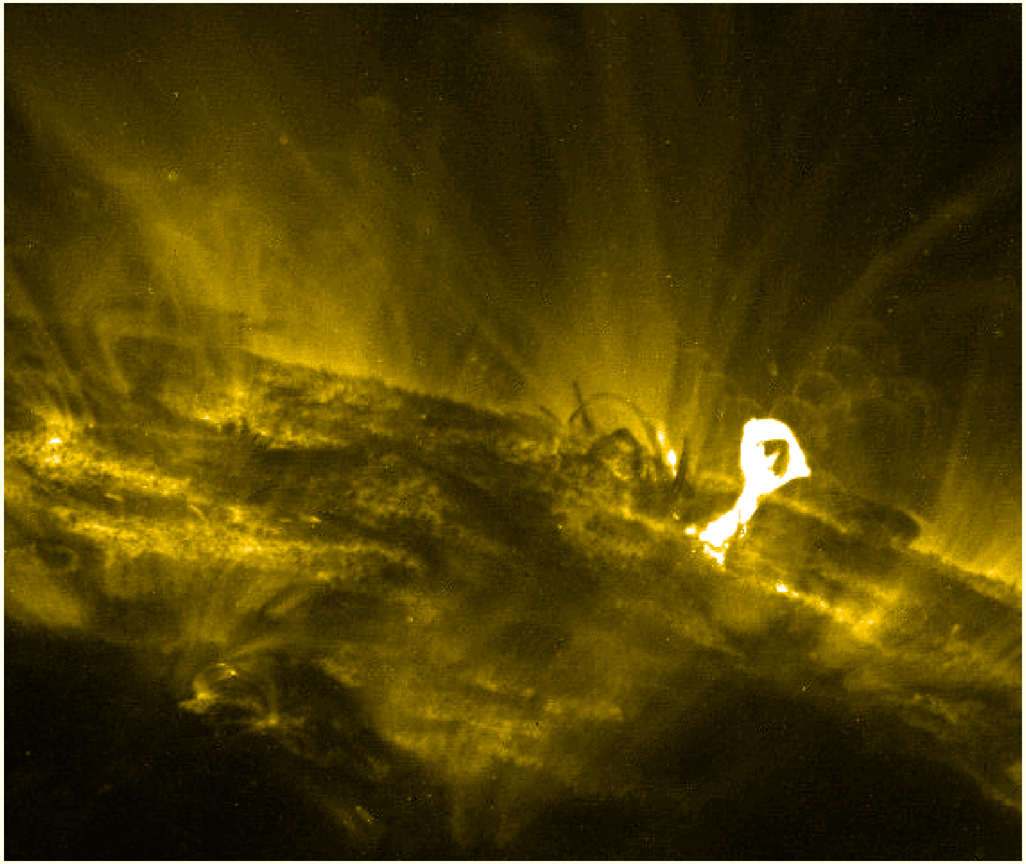


Electrons are accelerated, collide with solar surface (photosphere) and emit bremsstrahlung (X-rays).

Solar flare observations

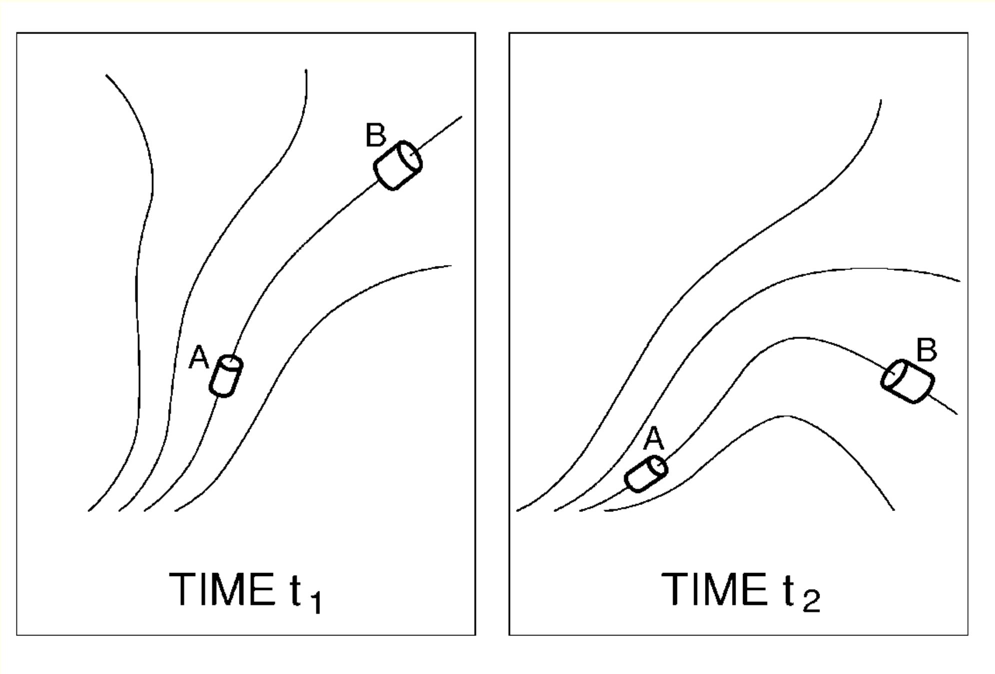


(a) double signature of x-ray emissions at foot of flare



(b) coronal loop filled with hot gas

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.

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:

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

Magnetic Reynolds number R_m:

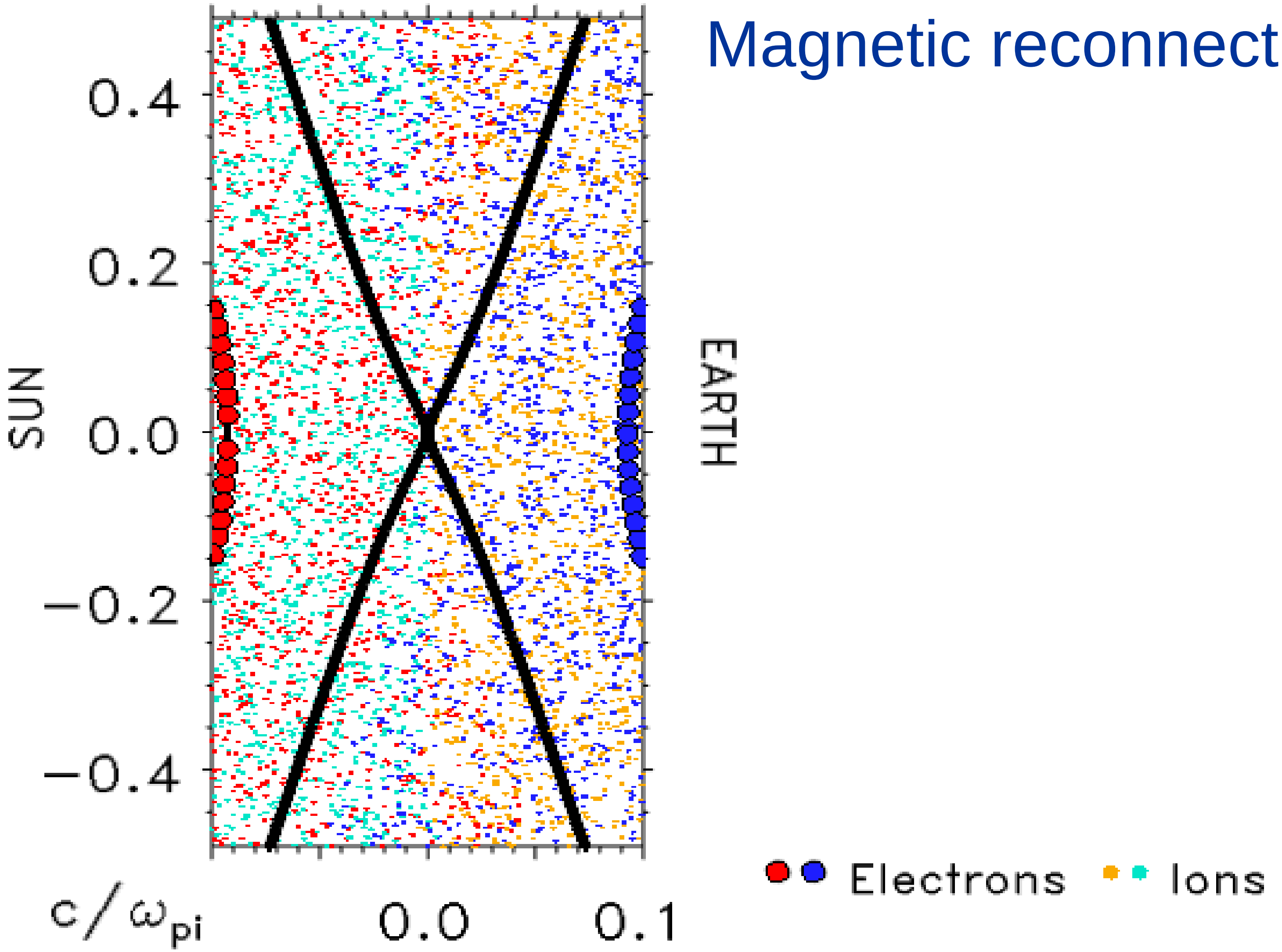
$$\mathrm{R_m} >> 1 \Rightarrow \quad \frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})$$

Frozen-in fields!

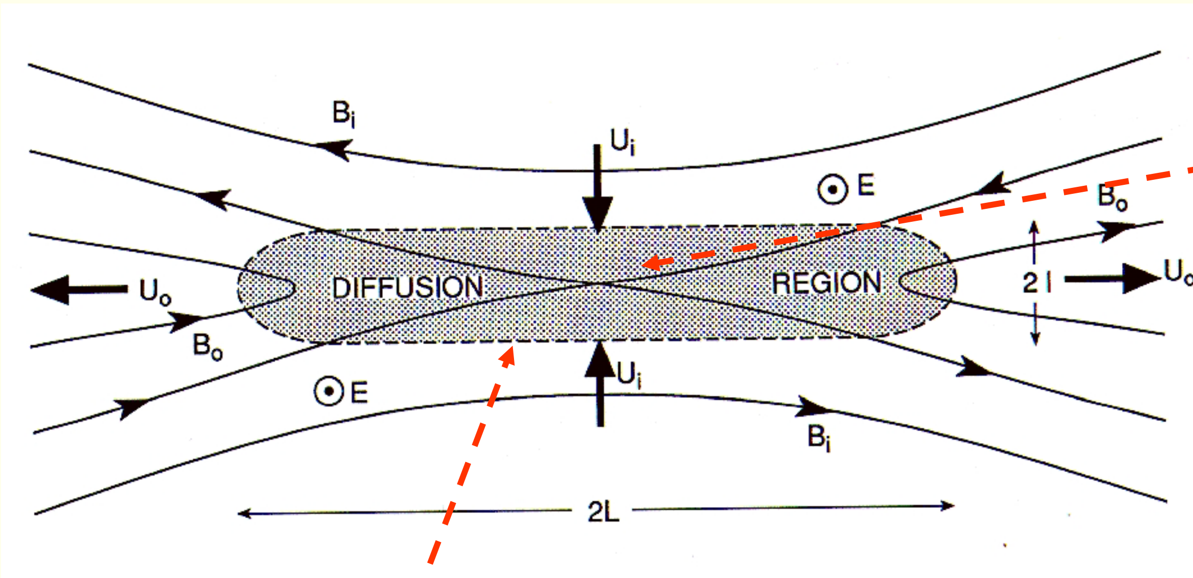
$$\mathrm{R_m} << 1 \Rightarrow \quad \frac{\partial \mathbf{B}}{\partial t} = \frac{1}{\mu_0 \sigma} \nabla^2 \mathbf{B}$$

Diffusion equation!

Magnetic reconnection



Reconnection



In ‘diffusion region’:

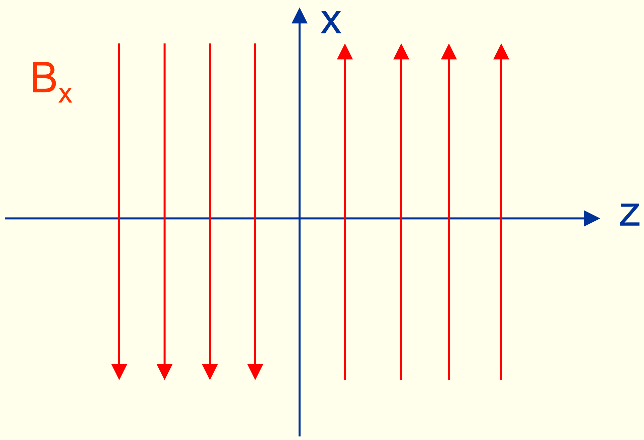
$R_m = \mu_0 \sigma l v \sim 1$

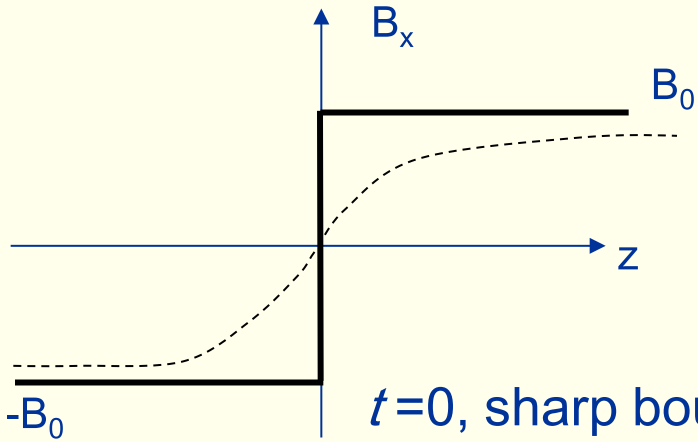
Thus: condition for frozen-in magnetic field breaks down.

A second condition is that there are two regions of magnetic field pointing in *opposite* direction:

- Field lines are “cut” and can be re-connected to other field lines
- **Magnetic energy is transformed into kinetic energy ($U_o >> U_i$)**
- **Plasma from different field lines can mix**

Reconnection in 1D





t =0, sharp boundary

$$\frac{\partial \mathbf{B}}{\partial t} = \frac{1}{\mu_0 \sigma} \nabla^2 \mathbf{B} \longrightarrow \frac{\partial B_x}{\partial t} = \frac{1}{\mu_0 \sigma} \frac{\partial^2 B_x}{\partial z^2}$$

Diffusion equation! Has solution

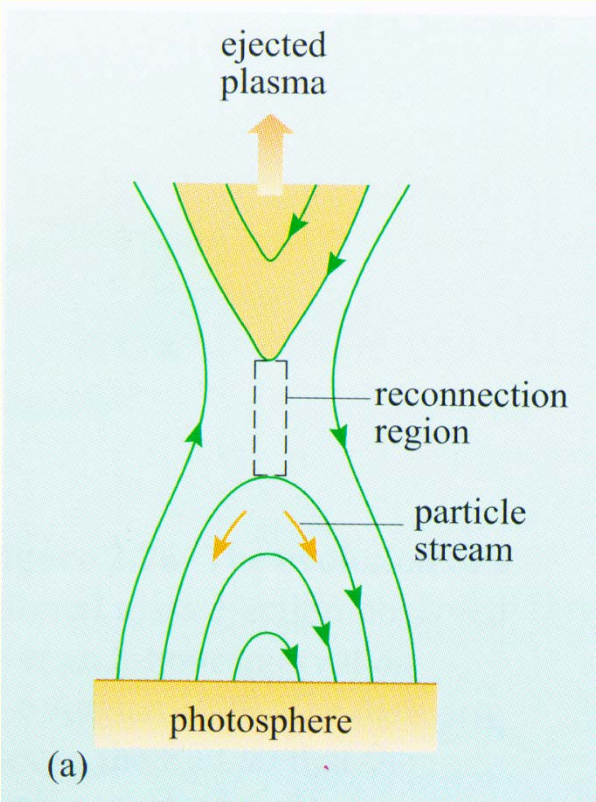
$$B_x(z,t) = B_0 erf\left(\left[\frac{\mu_0 \sigma}{4t}\right]^{1/2} z\right)$$

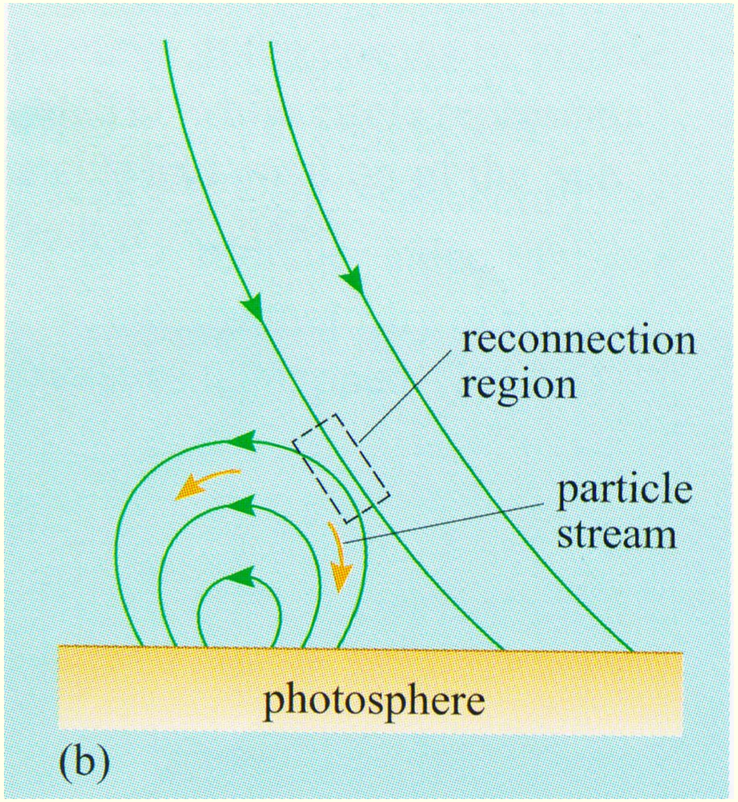
The total magnetic energy then decreases with time:

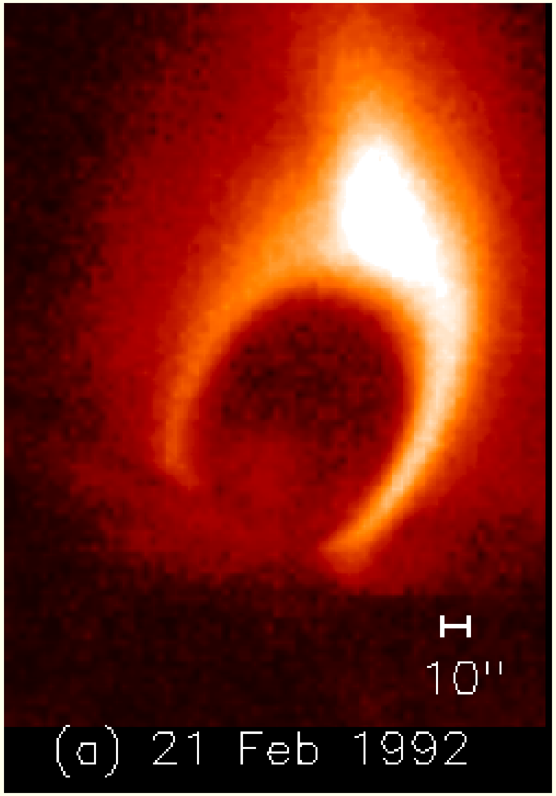
$$W_B = \int_{-\infty}^{\infty} \frac{B^2}{2\mu_0} dxdydz$$

The magnetic energy is converted into heat and kinetic energy in 2D

Solar flare
energization mechanism







Two possible reconnection geometries

Classification of flares

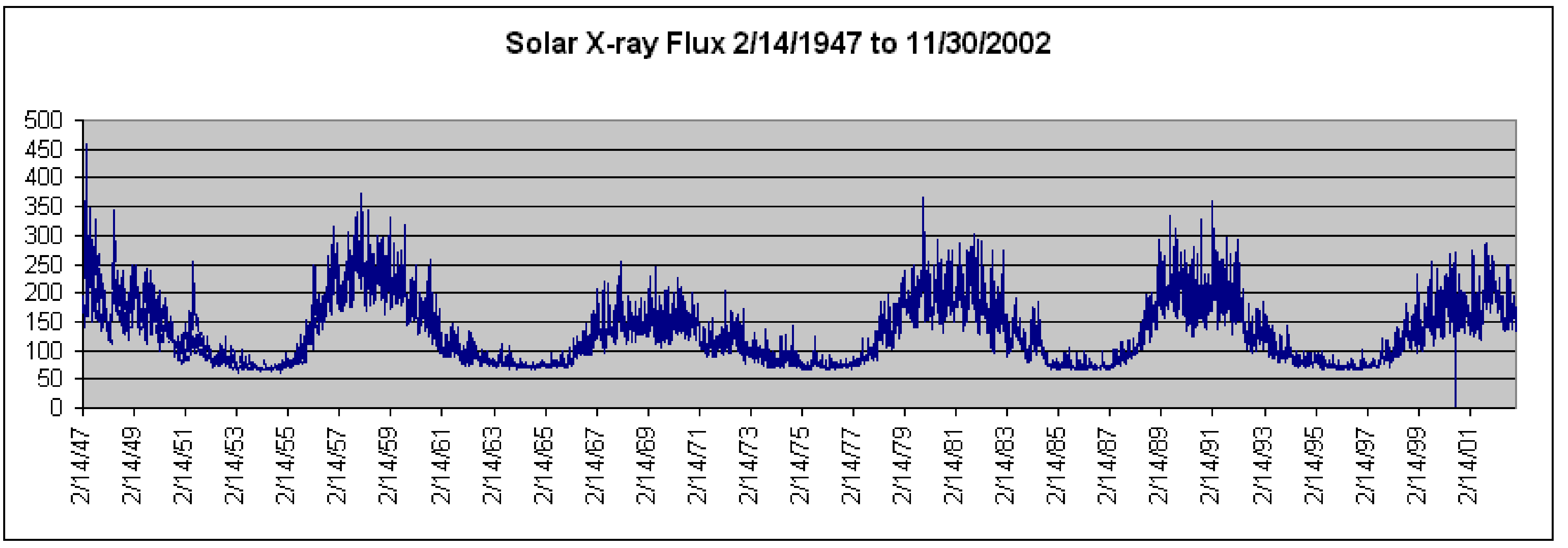
Old system

Denomination	Area $(°)^2$
S	< 2.0
1	2.1 – 5.1
2	5.2 – 12.4
3	12.5-24.7
4	> 24.7

New system

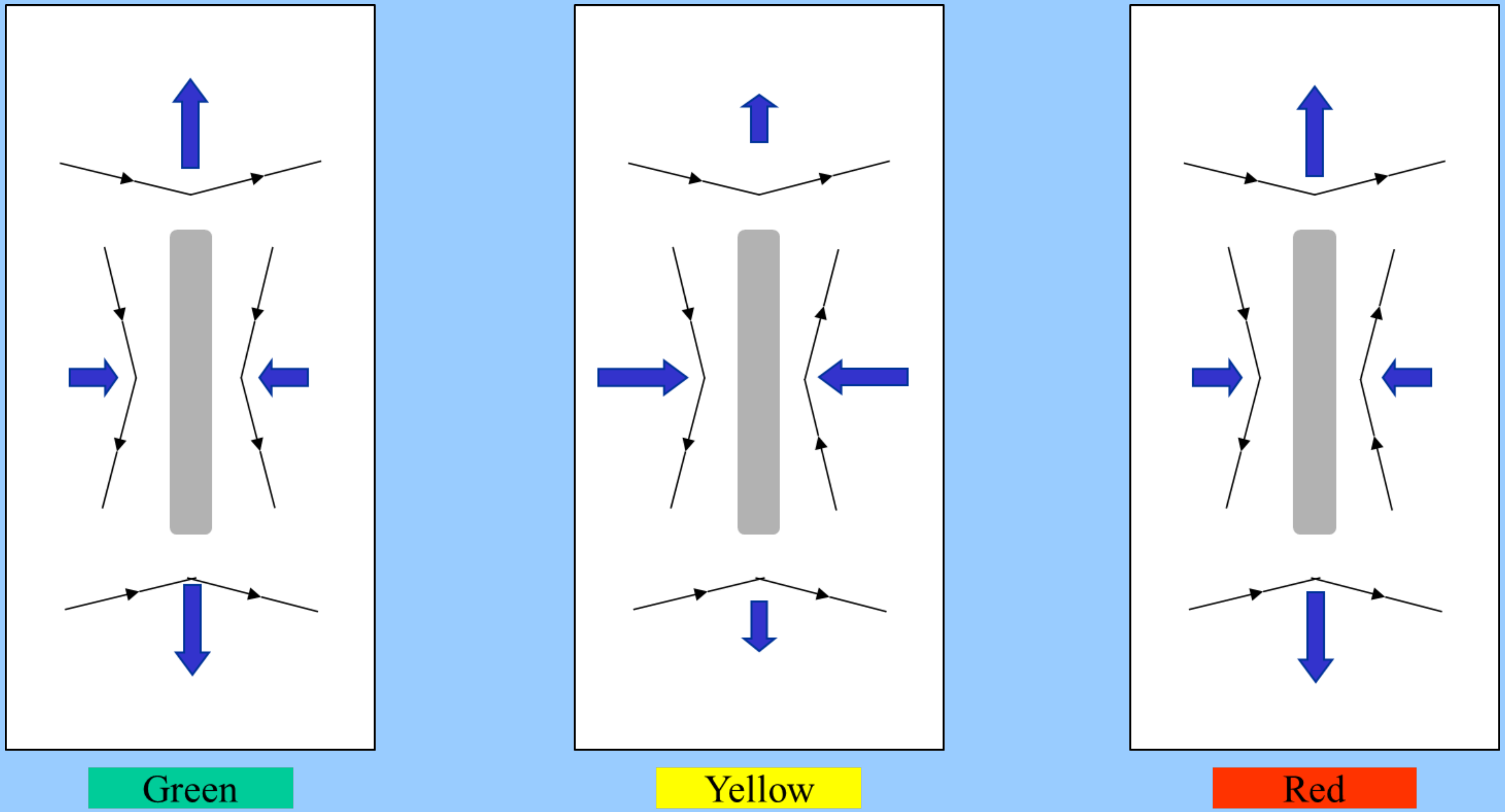
Denomination	Maximum flux of X-ray radiation (W/m^2) (near Earth 0.1-0.8 nm)
A*n*	$n \times 10^{-8}$
B*n*	$n \times 10^{-7}$
C*n*	$n \times 10^{-6}$
M*n*	$n \times 10^{-5}$
X*n*	$n \times 10^{-4}$

Recent X ray flux measurements

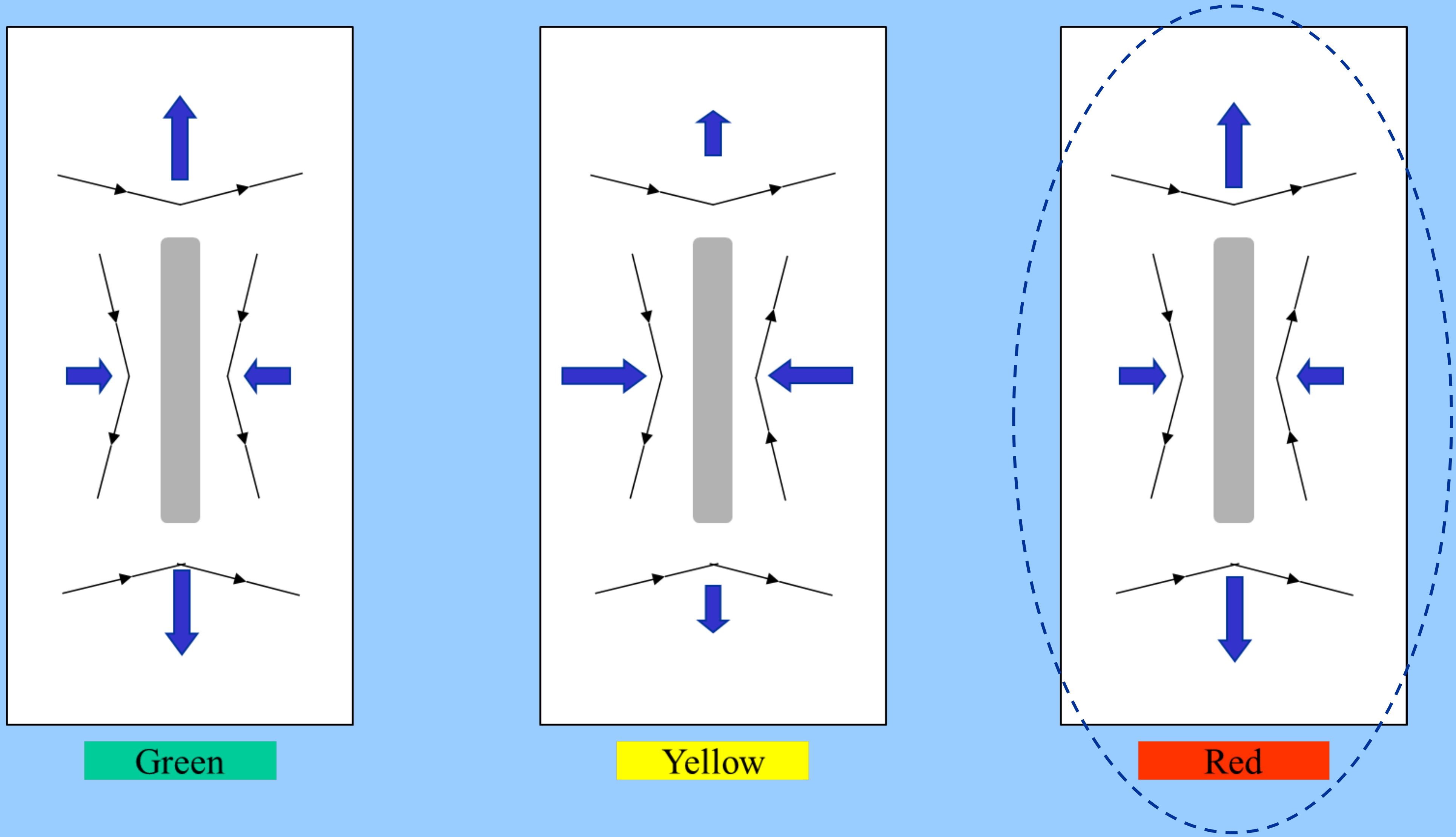


http://www.swpc.noaa.gov/ Space Weather Prediction Centre

Magnetic reconnection



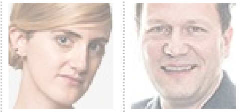
Magnetic reconnection



Think about this:

What determines the form of the spiral of the water from a rotating lawn sprinkler?

NIKLAS WAHLLÖF
"Så gott som allt upplevt – en frukost, ett bad och givetvis alla resor – är magiskt. Helt magiskt."



17° Stockholm

Sök DN.se

Solstorm på väg mot jorden

Publicerad i dag 14:04

Foto: TT I solens atmosfär sker hela tiden olika fenomen och explosioner. Då och då sker urladdningar av magnetisk energi vilket skapar flammor av ultraviolett ljus och moln som består av elektriskt ledande gas.

En solstorm är just nu på väg mot jorden och kan träffa atmosfären i kväll eller i morgon. Det kan innebära norrsken över stora delar av Sverige.

I solens atmosfär sker hela tiden olika fenomen och explosioner. Då och då sker urladdningar av magnetisk energi vilket skapar flammor av ultraviolett ljus och kan kasta ut moln som består av elektriskt ledande gas.

I folkmun kallas det för solstormar och just nu är en sådan på väg rakt mot jorden. Nyhetsbyrån AP skriver att det var det flera år sedan en solstorm i den här storleken senast riskerade att träffa jorden, men enligt astronomen Dan Kiselman innebär det ingen fara för oss människor.

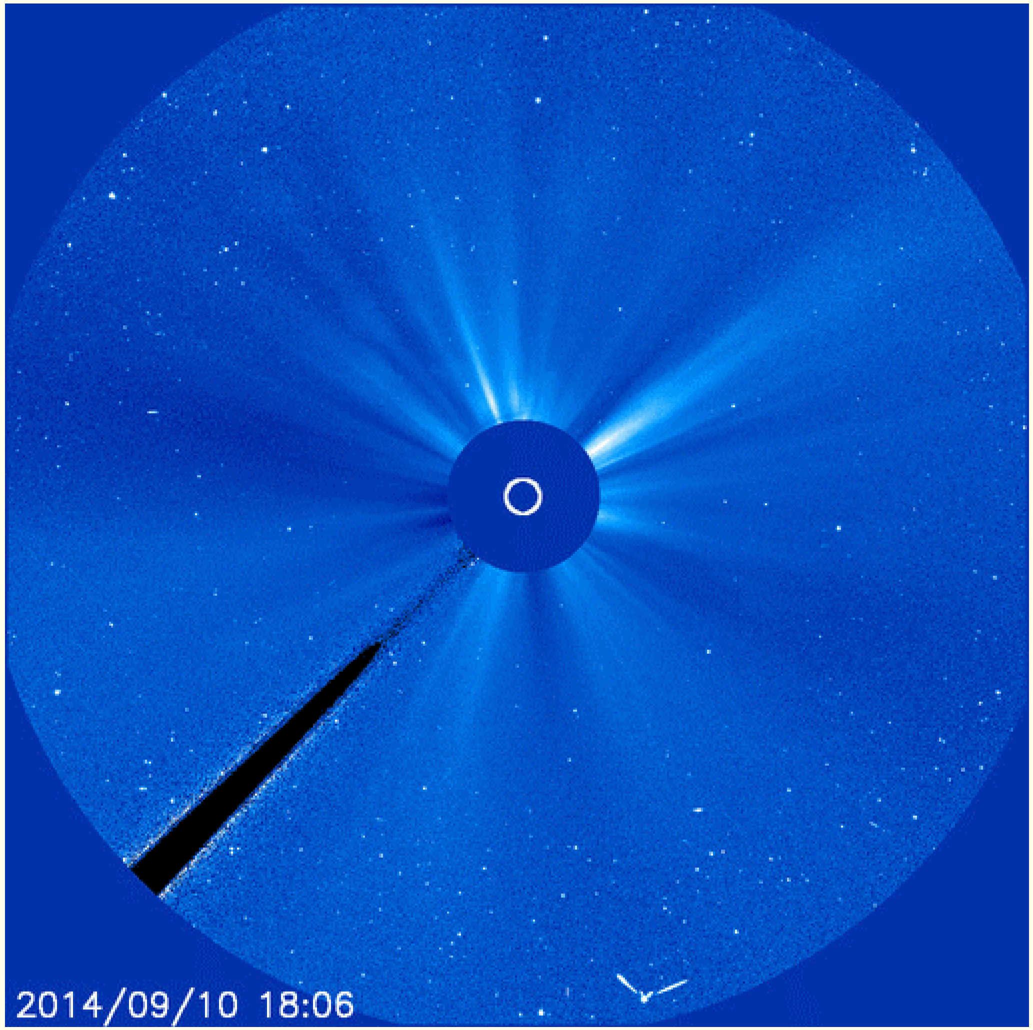
– **Det blir ingen** civilisationsomskakande händelse. Däremot kan det orsaka norrsken, säger han.

Enligt Dan Kiselman kan solstormar ge effekter på exempelvis kraftledningar men troligast är att vi bara märker av den här genom ett ljus på himlen. Norrsken är vanligt förekommande i de norra delarna av Sverige men i morgon och i övermorgon kan den som bor betydligt längre söderut se spännande fenomen på himlen nattetid.

Kan det synas ända ner mot Stockholmsområdet?

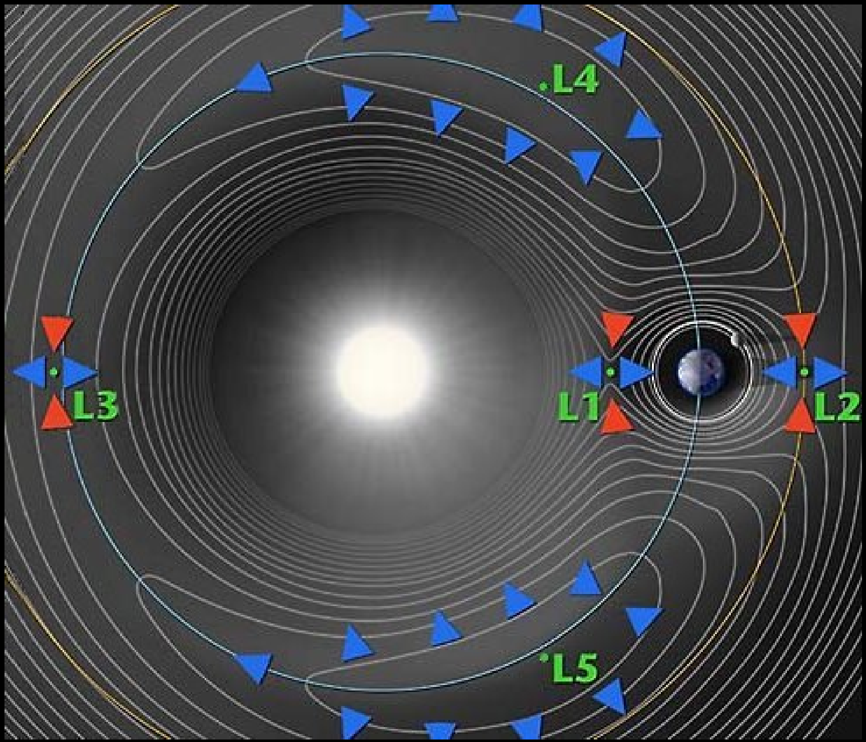
– Det är inte omöjligt. En extra titt på himlen skadar aldrig.

Coronal mass ejection, 2014-09-10



SOHO

(Solar and Heliospheric Observatory)

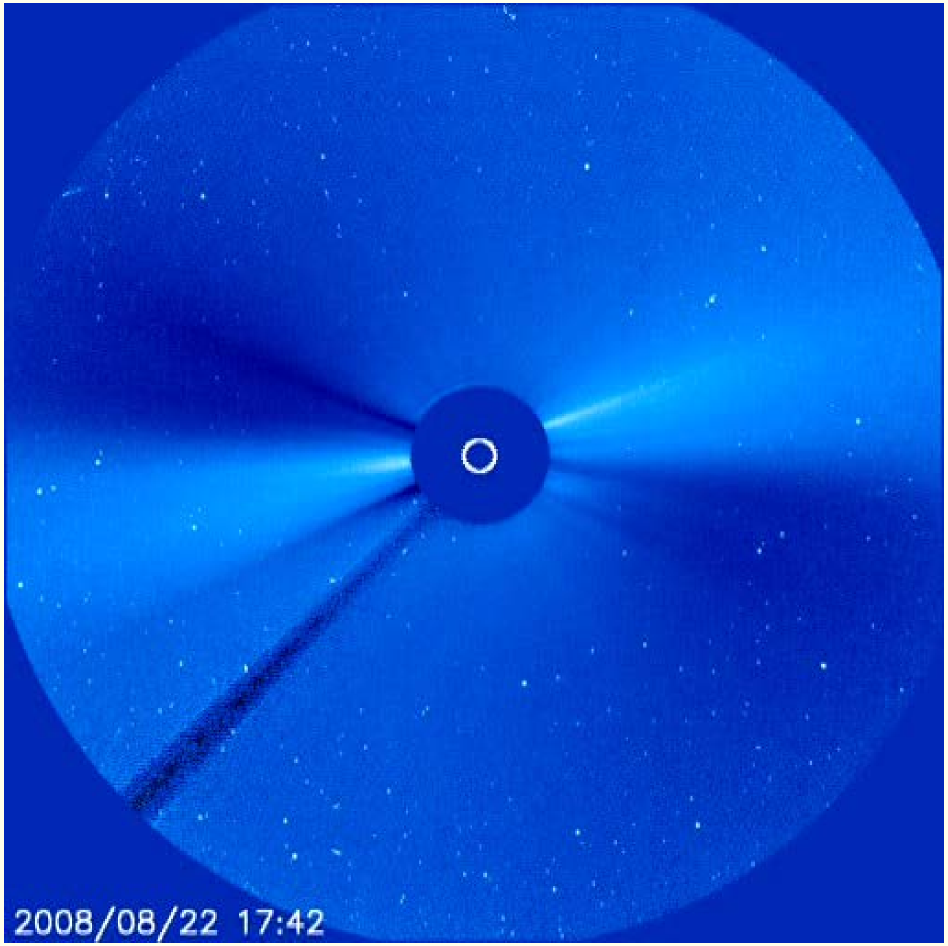


SOHO orbits the first Lagrange point

ESA - NASA collaboration

Solar wind

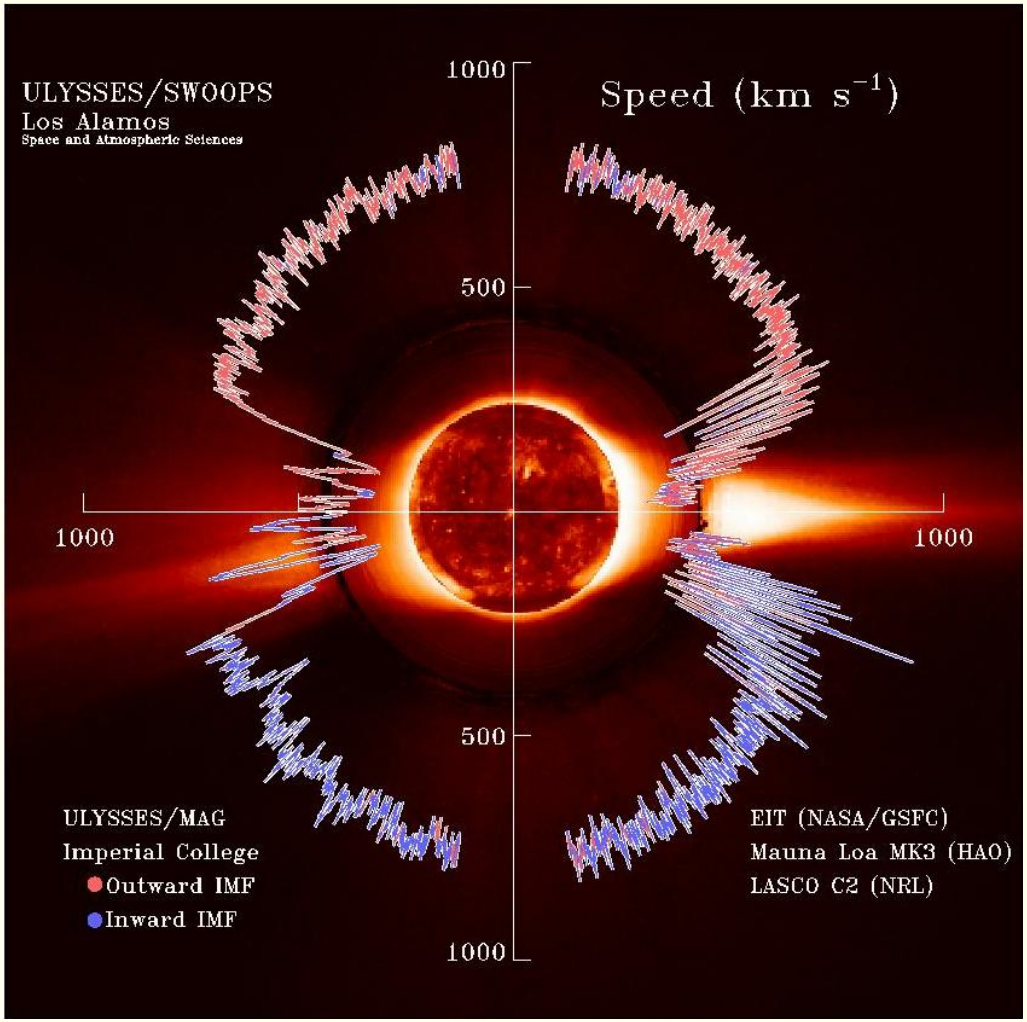
Corona continuously merges into solar wind



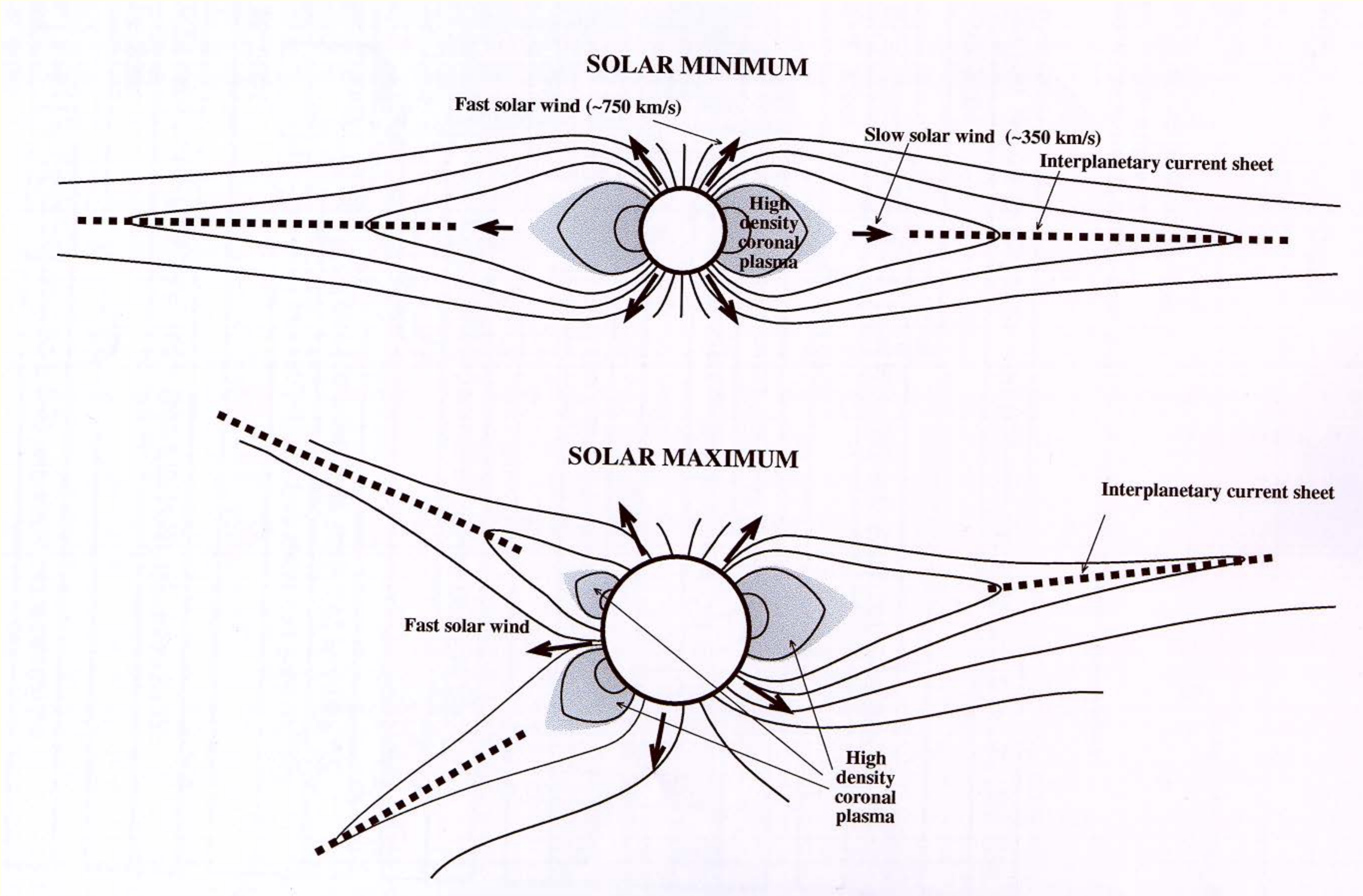
Solar and Heliospheric Observatory (SOHO)
LASCO C3 Coronagraph Movie

Solar wind

- **Fast solar wind in regions closer to poles**
- **Slow solar wind closer to equatorial plane**

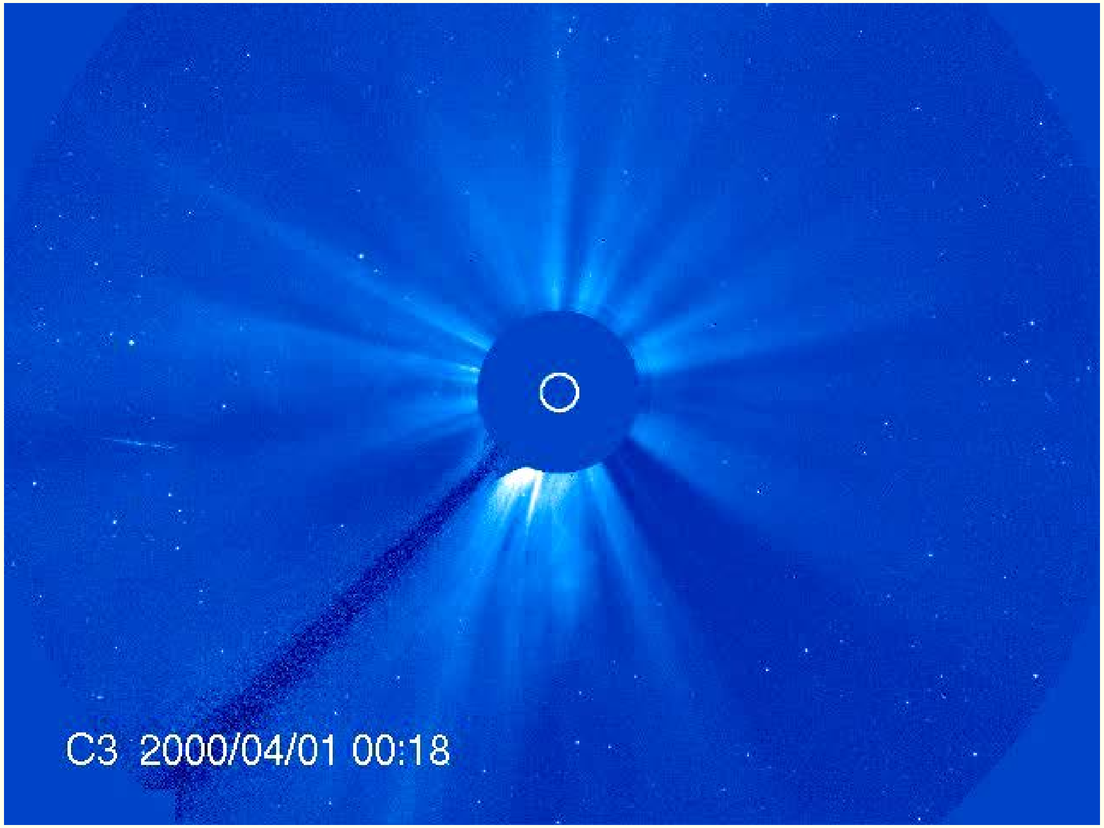


Solar wind



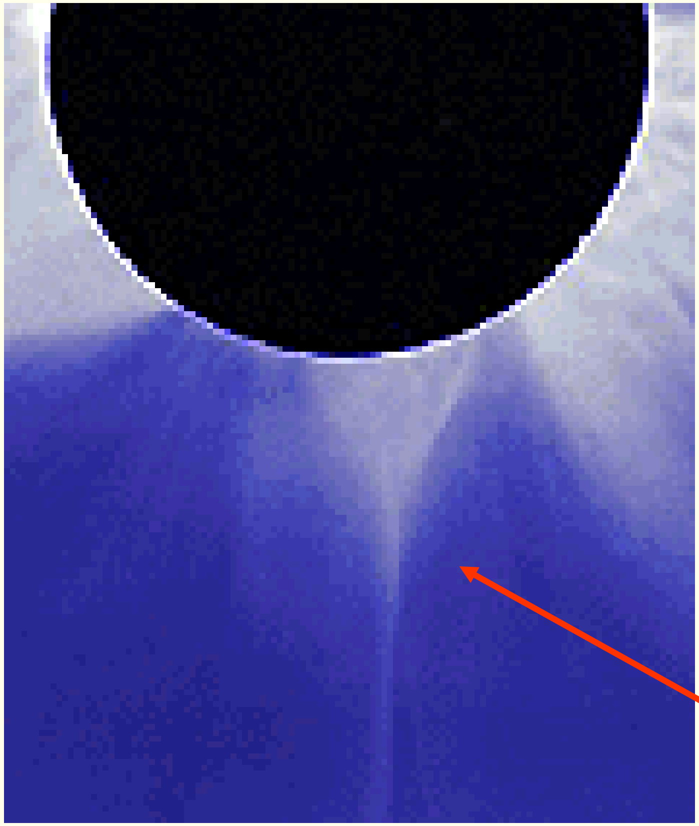
SOLAR MINIMUM
Fast solar wind (~750 km/s)
Slow solar wind (~350 km/s)
Interplanetary current sheet
High density coronal plasma
SOLAR MAXIMUM
Interplanetary current sheet
Fast solar wind
High density coronal plasma

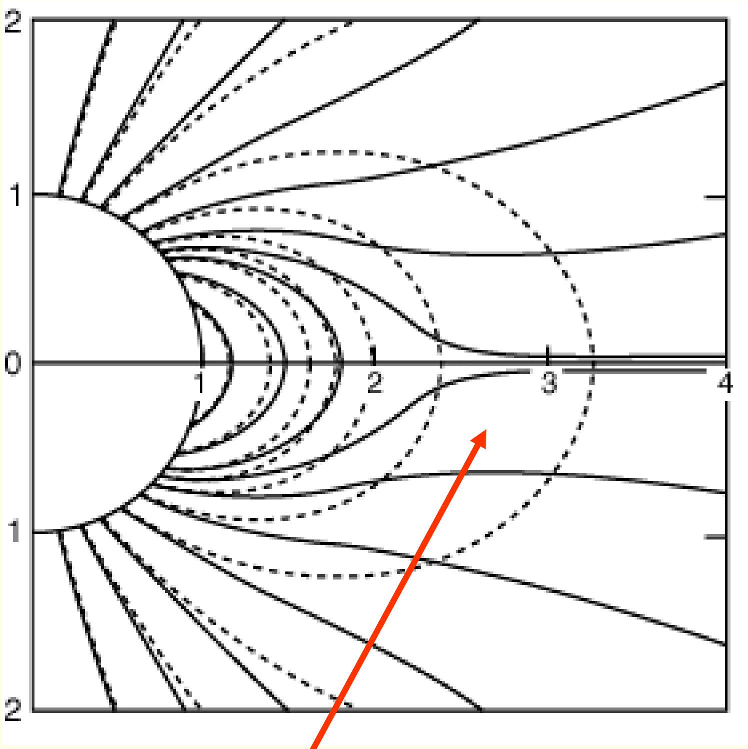
More active solar wind



Solar and Heliospheric Observatory (SOHO)
LASCO C3 Coronagraph Movie

Helmet streamers

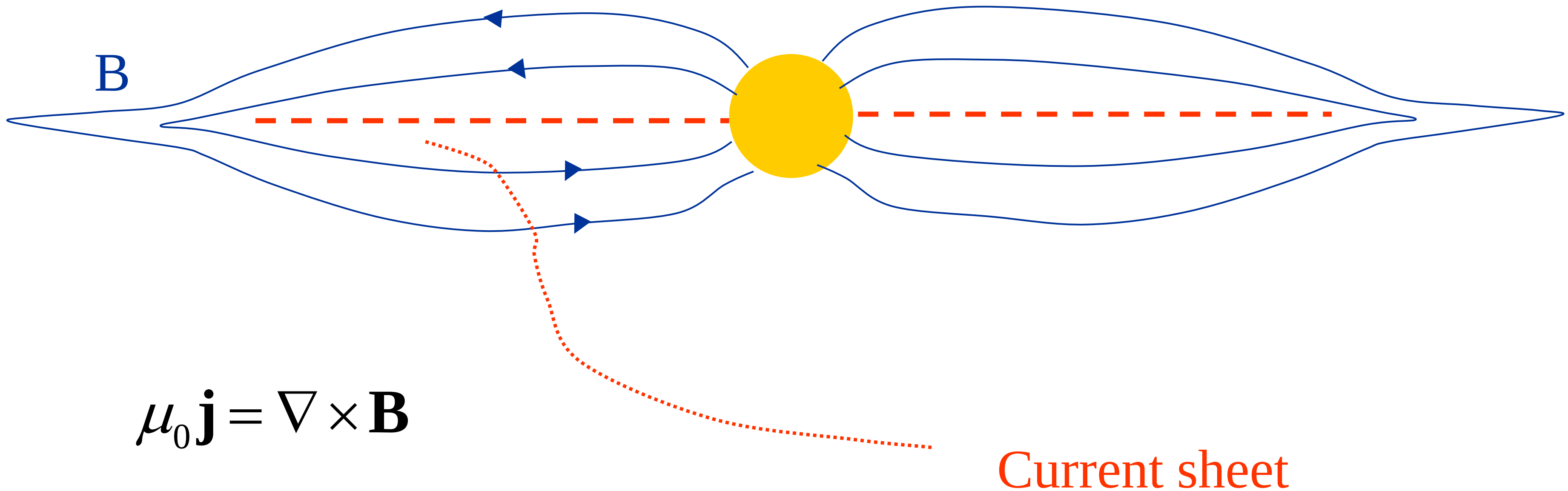




Magnetic field drawn out by solar wind.
This also brakes the solar wind.

Solar wind

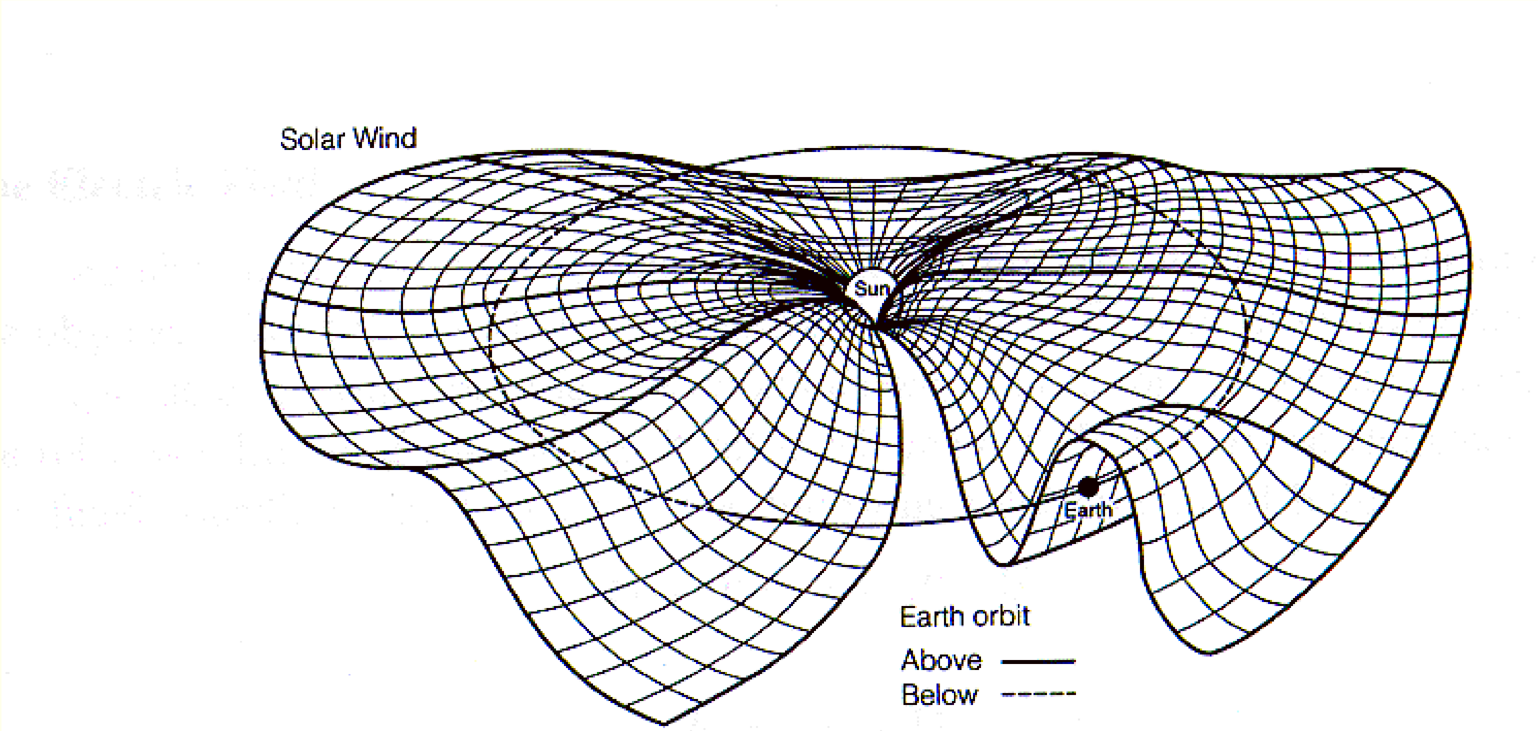
Interplanetary current sheet



$$\mu_0 \mathbf{j} = \nabla \times \mathbf{B}$$

Solar wind

Interplanetary current sheet

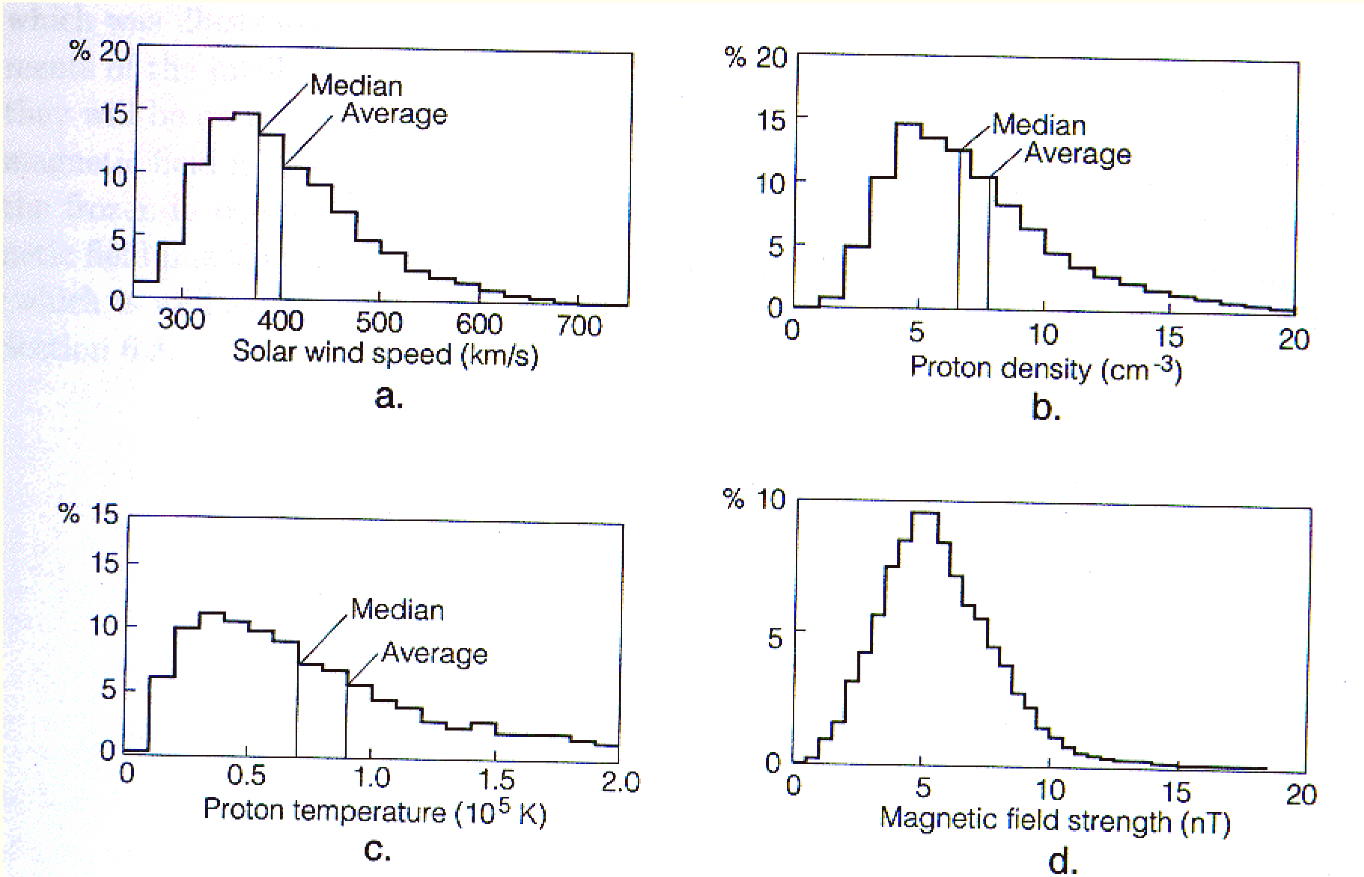


Later we will see that the N-S component of the interplanetary magnetic field (IMF is important for the coupling between solar wind and magnetosphere)

Solar wind

Some basic facts

Average values



$n_p = 8$ cm^{-3}

$v = 320$ km/s

$T_p = 4 \cdot 10^4$ K

$T_e = 10^5$ K

$B = 5$ nT

$\Phi_K = \rho v^3/2 = 0.22$ mW/m^2

The solar wind today

Average values

$n_p = 8\ cm^{-3}$

$v = 320\ km/s$

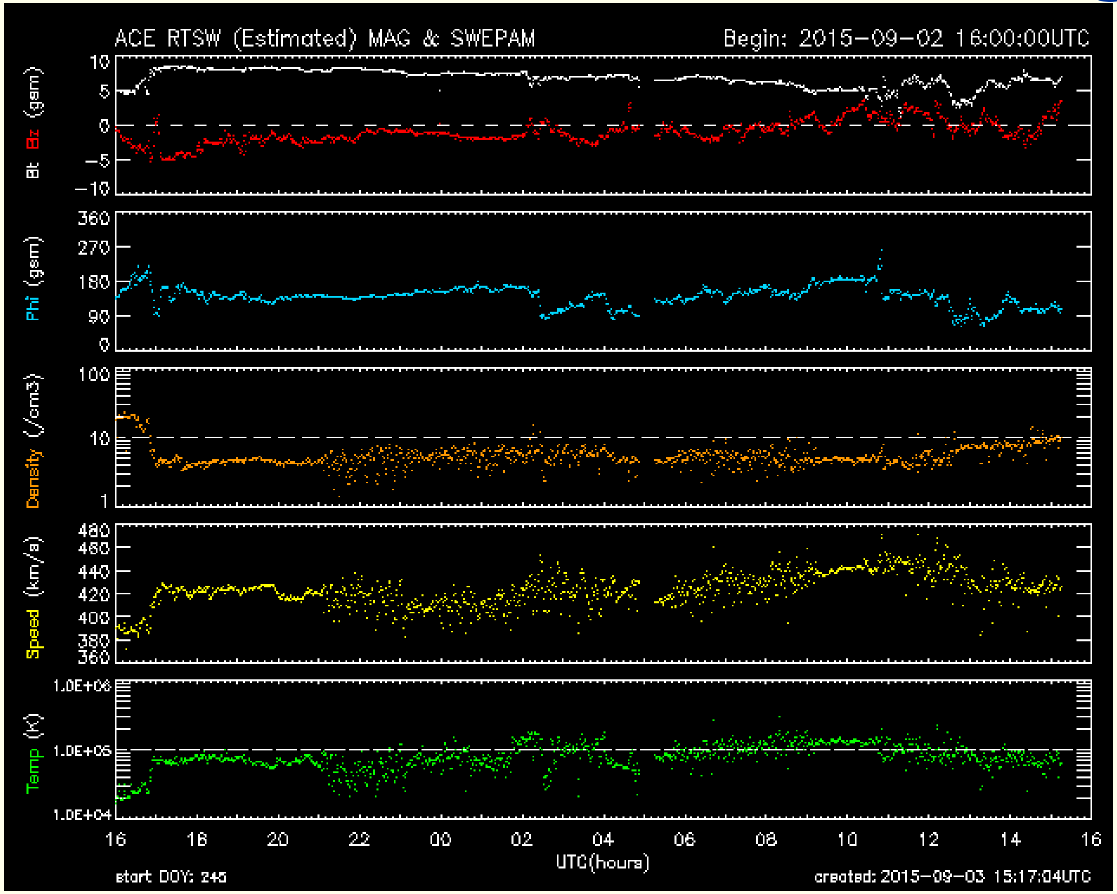
$T_p = 4 \cdot 10^4\ K$

$T_e = 10^5\ K$

$B = 5\ nT$

$p_D = \rho v^2/2 = 0.7\ nPa$

$\Phi_K = \rho v^3/2 = 0.22\ mW/m^2$



Measurements from ACE spacecraft

http://www.swpc.noaa.gov/communities/space-weather-enthusiasts

Space Weather Prediction Centre

Guess how long does it take the solar wind to flow from the Sun to the Earth?

Blue	8 min	Yellow	1.5 days
Green	5 hours	Red	5 days

$$t = \frac{s}{v} = \frac{1.496 \cdot 10^{11}}{320 \cdot 10^{3}} = 467\,500\ s = 129.9\ h = 5.4\ days$$

Red

But maybe

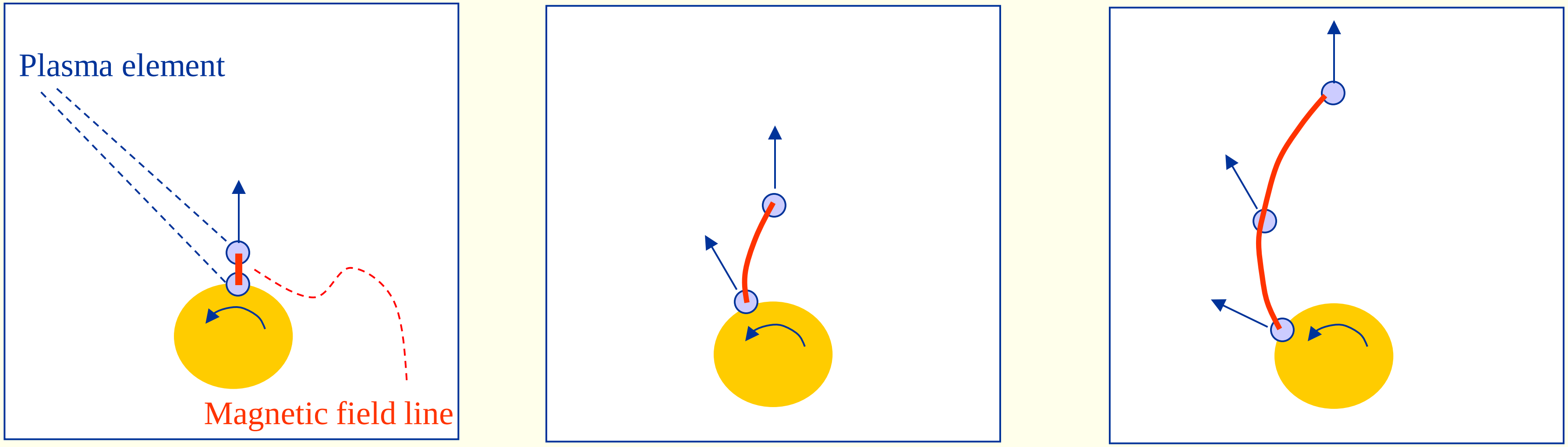
Yellow

if the solar wind is much faster

Does anyone happen to know the mathematical formula for the spiral caused by a rotating garden sprinkler?

Solar wind

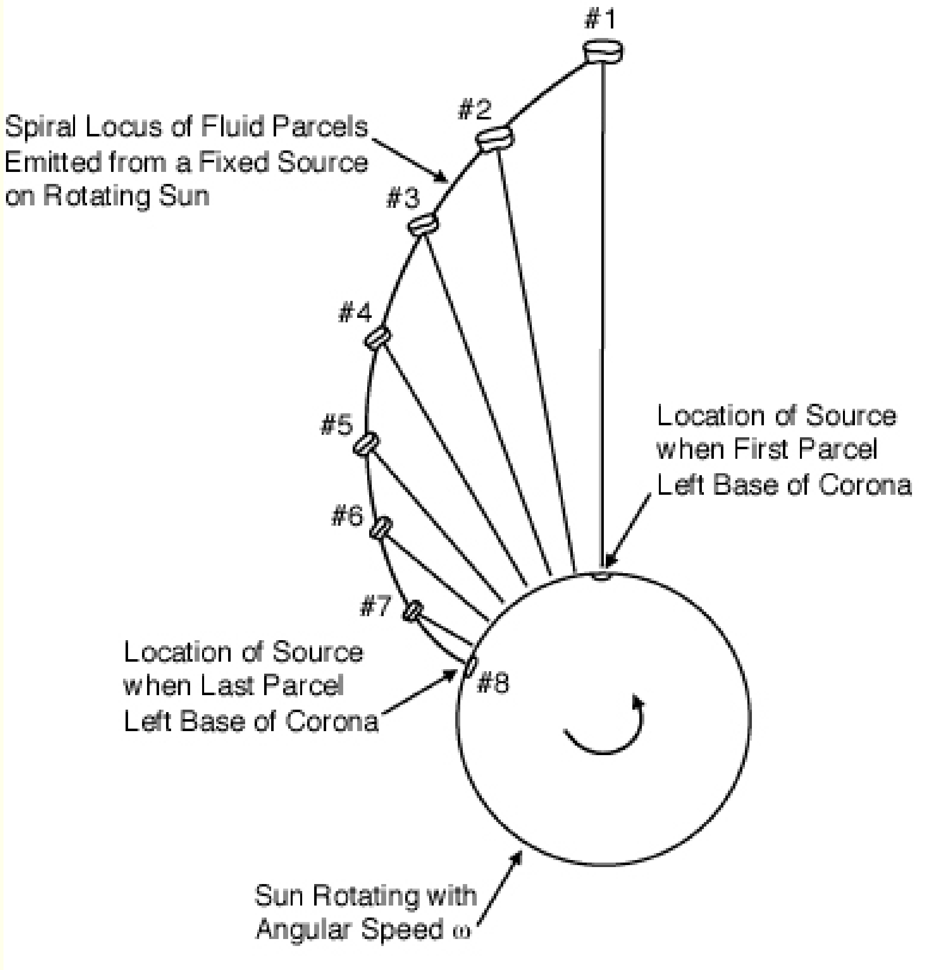
Magnetic field frozen into solar wind



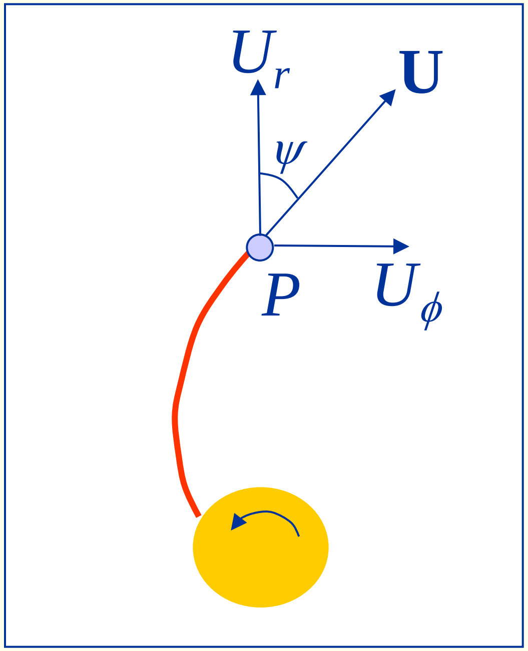
This is now seen from ”above”! (Looking down on the ecliptic plane from the pole.)

Solar wind

Parker spiral



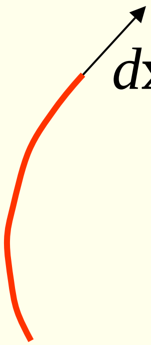
Parker spiral



Derivation of Ψ (Parker angle)

Consider a coordinate system rotating with the sun. The plasma element P in this coordinate system has two velocity components: U_r and U_ϕ .

Since the magnetic field is frozen into the solar wind, and follows the orbit of the plasma element P, at any time B has to be parallel to U. Then we have:

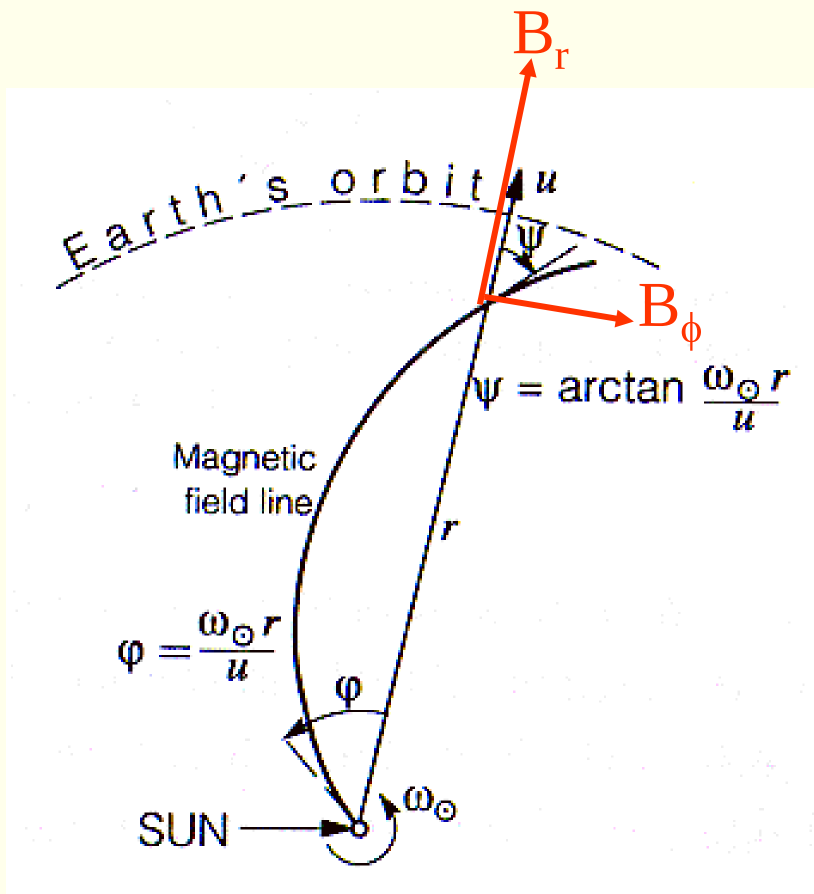


$$d\mathbf{x} = \mathbf{U}_{\mathbf{sw}} dt$$

$$\tan\psi = \frac{B_\phi}{B_r} = \frac{U_\phi}{U_r} = \left(\frac{\omega r}{u_{SW}} \right)$$

Solar wind

Parker spiral

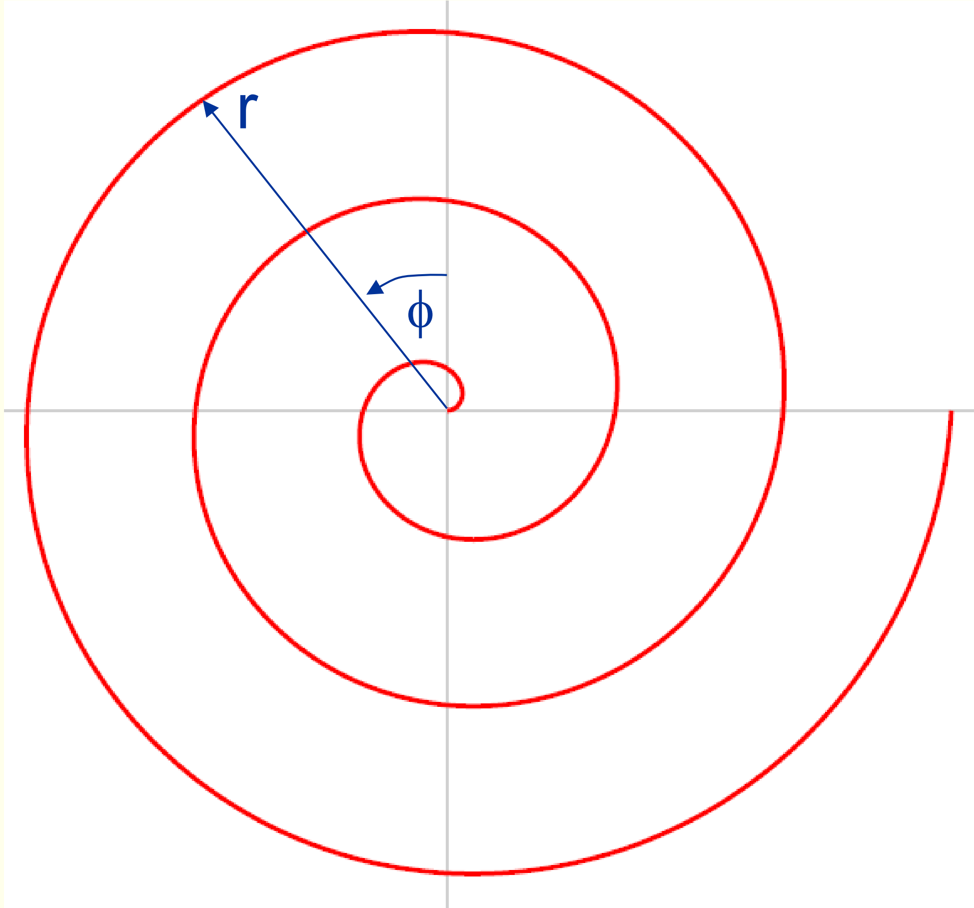


Archimedean spiral:

$$\frac{B_\phi}{B_r} = \tan\psi = \left(\frac{\omega r}{u_{SW}}\right)$$

Archimedean spiral

An Archimedean spiral (also arithmetic spiral), is a spiral named after the 3rd-century-BC Greek mathematician Archimedes; it is the locus of points corresponding to the locations over time of a point moving away from a fixed point with a constant speed along a line which rotates with constant angular velocity. Equivalently, in polar coordinates (r,ϕ) it can be described by the equation (*Wikipedia*)



$$r = a + b\phi$$

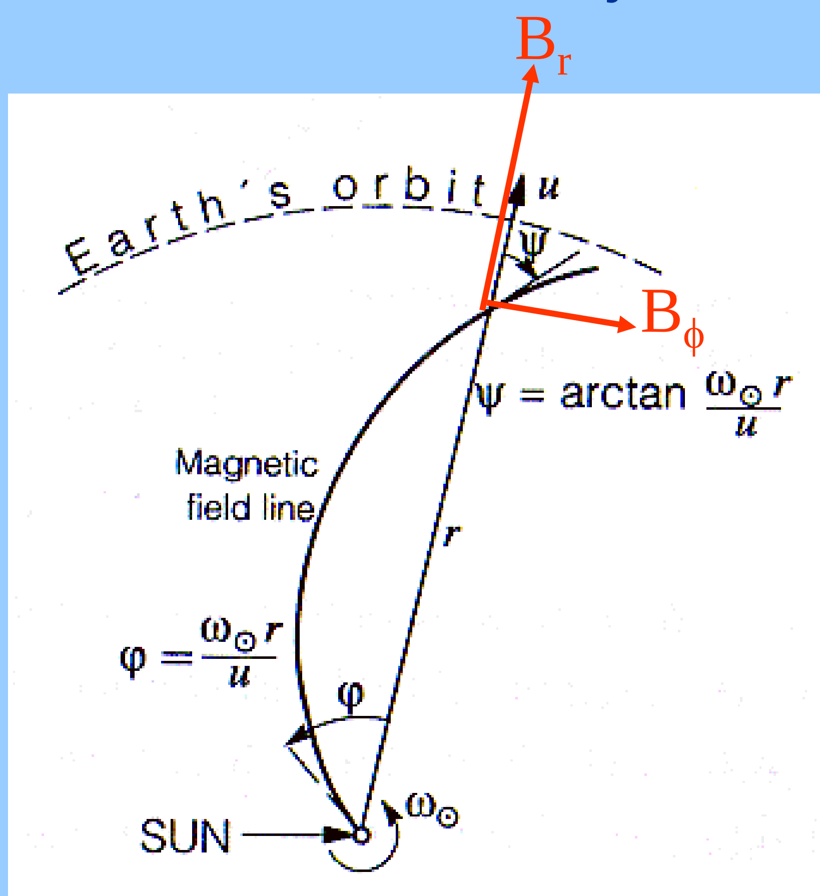
$$r = a + b\omega t$$

$$\frac{dr}{dt} = b\omega = u_{SW}$$

$$b = \frac{u_{SW}}{\omega}$$

$$r = R_{sun} + \frac{u_{SW}}{\omega}\phi$$

Use rotation period T of sun: $T = 27$ days



$r = 1$ A.U.

What is the angle Ψ at Earth's orbit for a typical solar wind speed?

Yellow	$\approx 50°$
Red	$\approx 80°$
Blue	$\approx 1°$
Green	$\approx 10°$

$$\Psi = \arctan(\frac{\omega r}{u})$$

What is ω?

$$\omega = 2\pi f = \frac{2\pi}{T} = \frac{2\pi}{27 \cdot 24 \cdot 60 \cdot 60} = 2.7 \cdot 10^{-6} s^{-1}$$

$$\Psi = \arctan(\frac{\omega r}{u}) = \arctan(\frac{2.7 \cdot 10^{-6} \cdot 1.5 \cdot 10^{11}}{320 \cdot 10^{3}}) = \arctan(1.27) = 52^{\circ}$$

Yellow

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