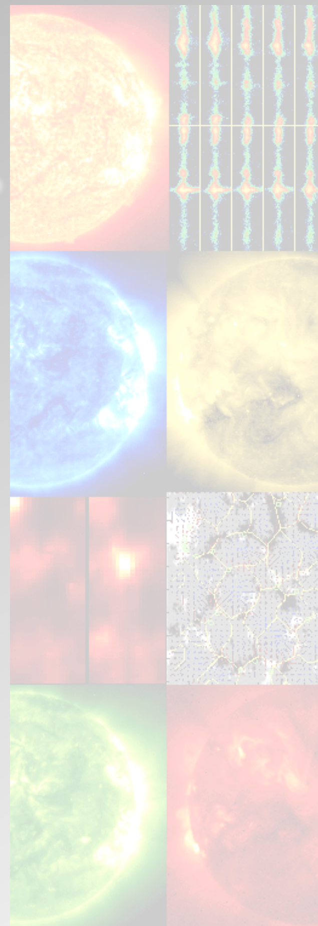
Solar Physics & Space Plasma Research Centre (SP²RC)

The Sun: A Hostile Neighbour



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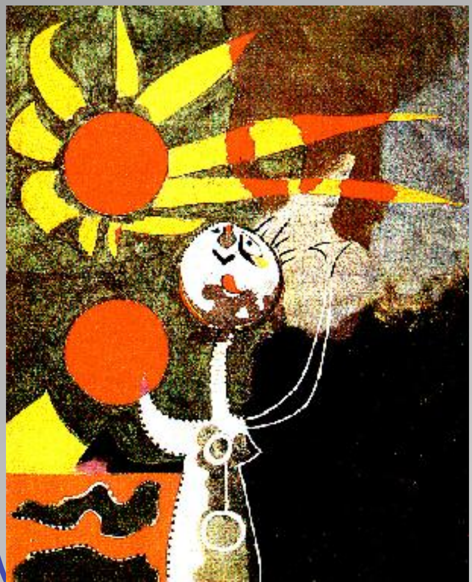
The structure of the Sun:
The solar atmosphere



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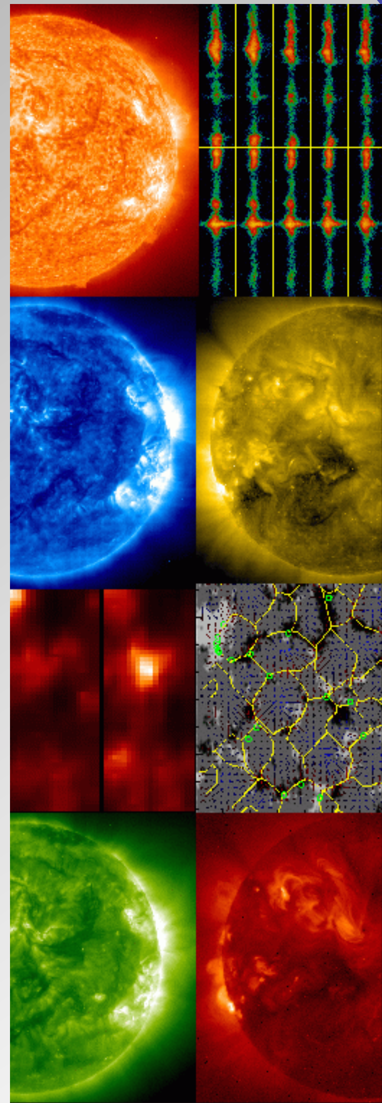
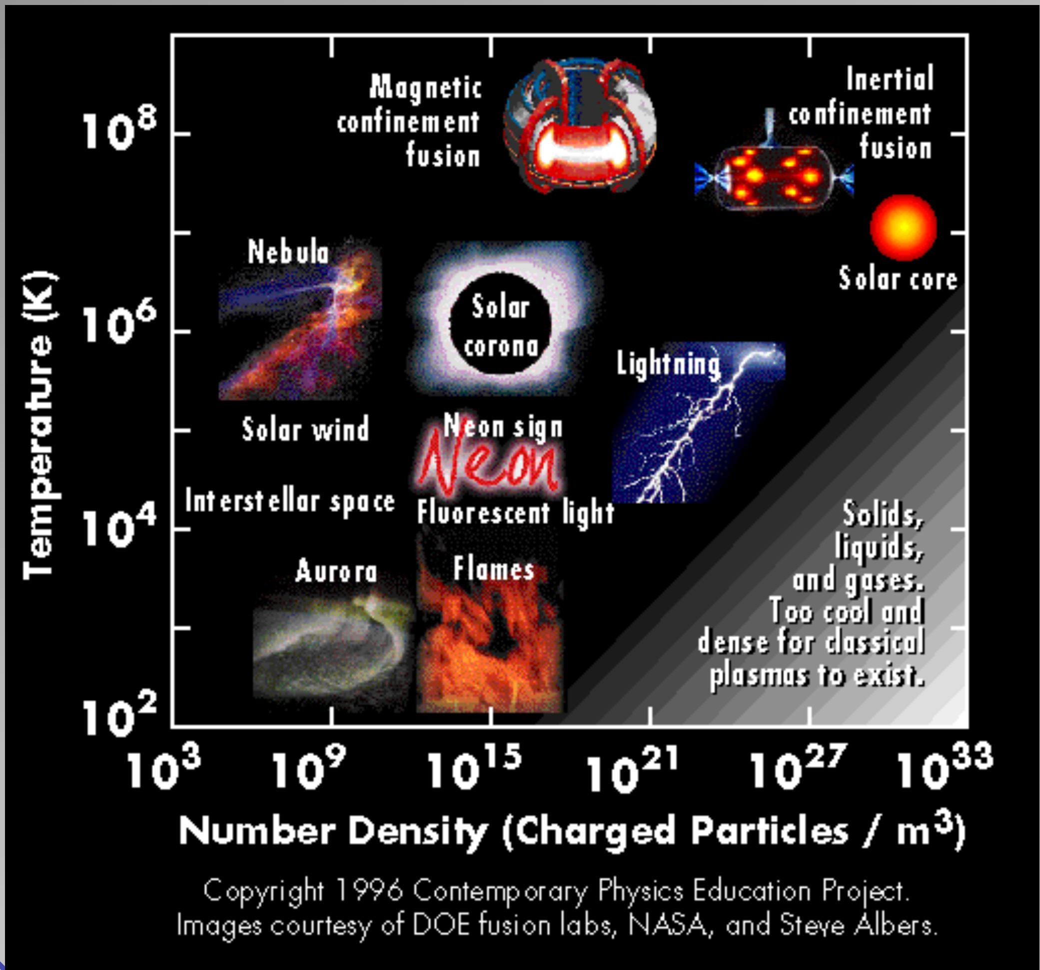


The Outline

- A little history of solar research
- Magnetic Sun
- MHD equations
- Potential and force-free fields
- Selected applications (dynamic Sun, SW, etc.)
- Conclusions

Why to Bother?



Modern Physics → Plasma Physics

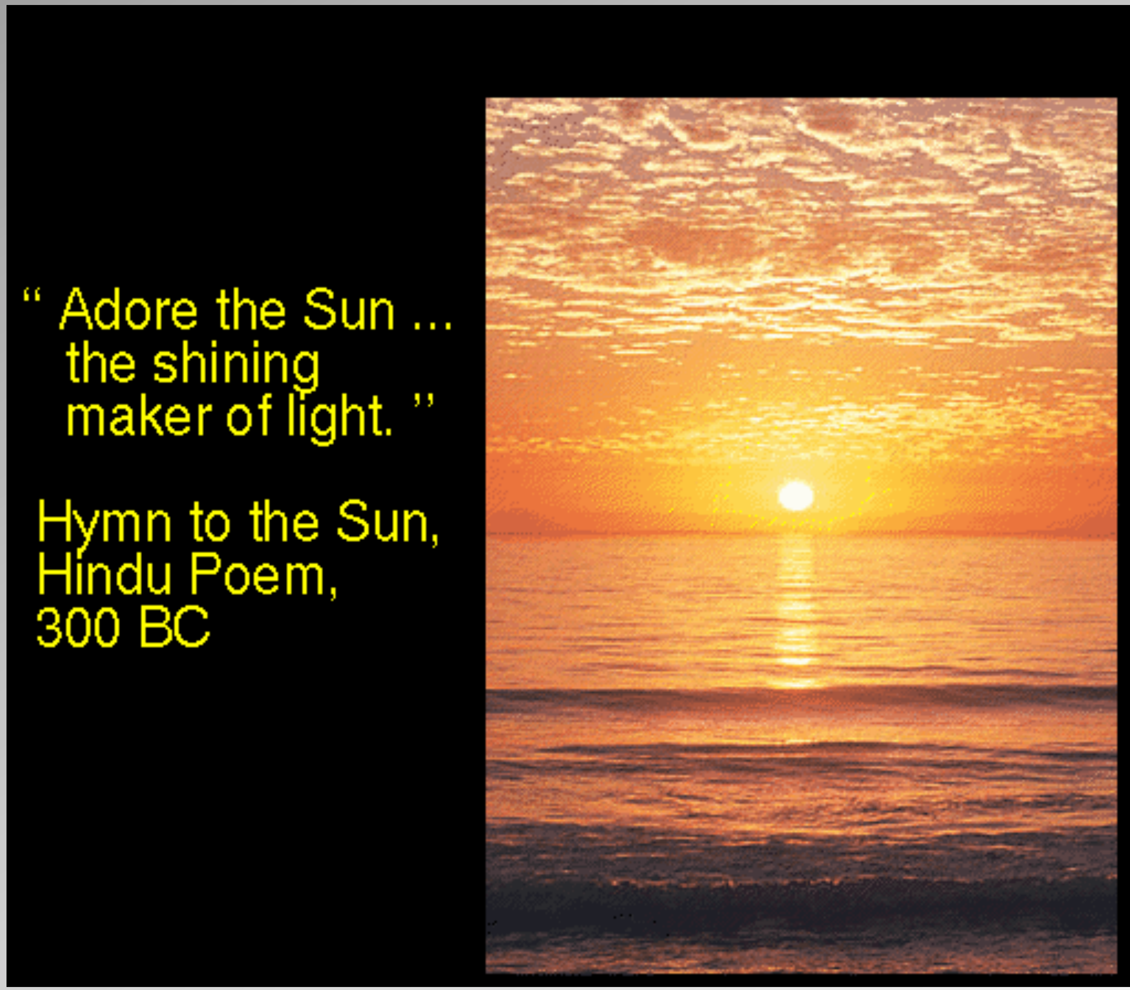
Solar and stellar interiors are composed of *ionised plasma* – and hence are excellent conductors of electricity

In fact, [illegible]% matter of Universe is in plasma state!

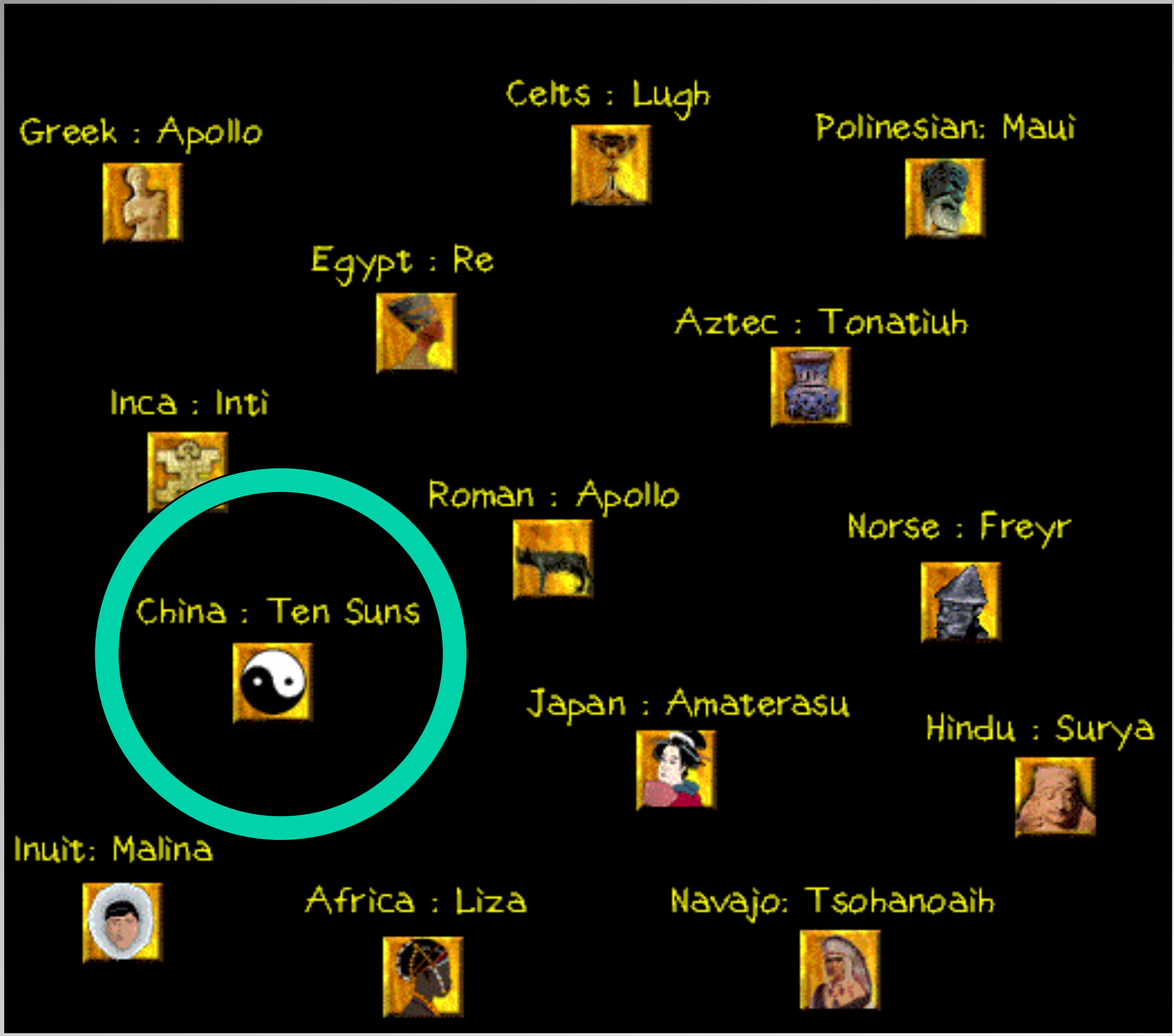
ST system is a natural plasma laboratory →geo-, astro- and tokamak physics,

To explore space plasmas waves, in general, are excellent diagnostic tools!!!

Solar History



Solar History



Solar History

And a modern worship of the Sun…

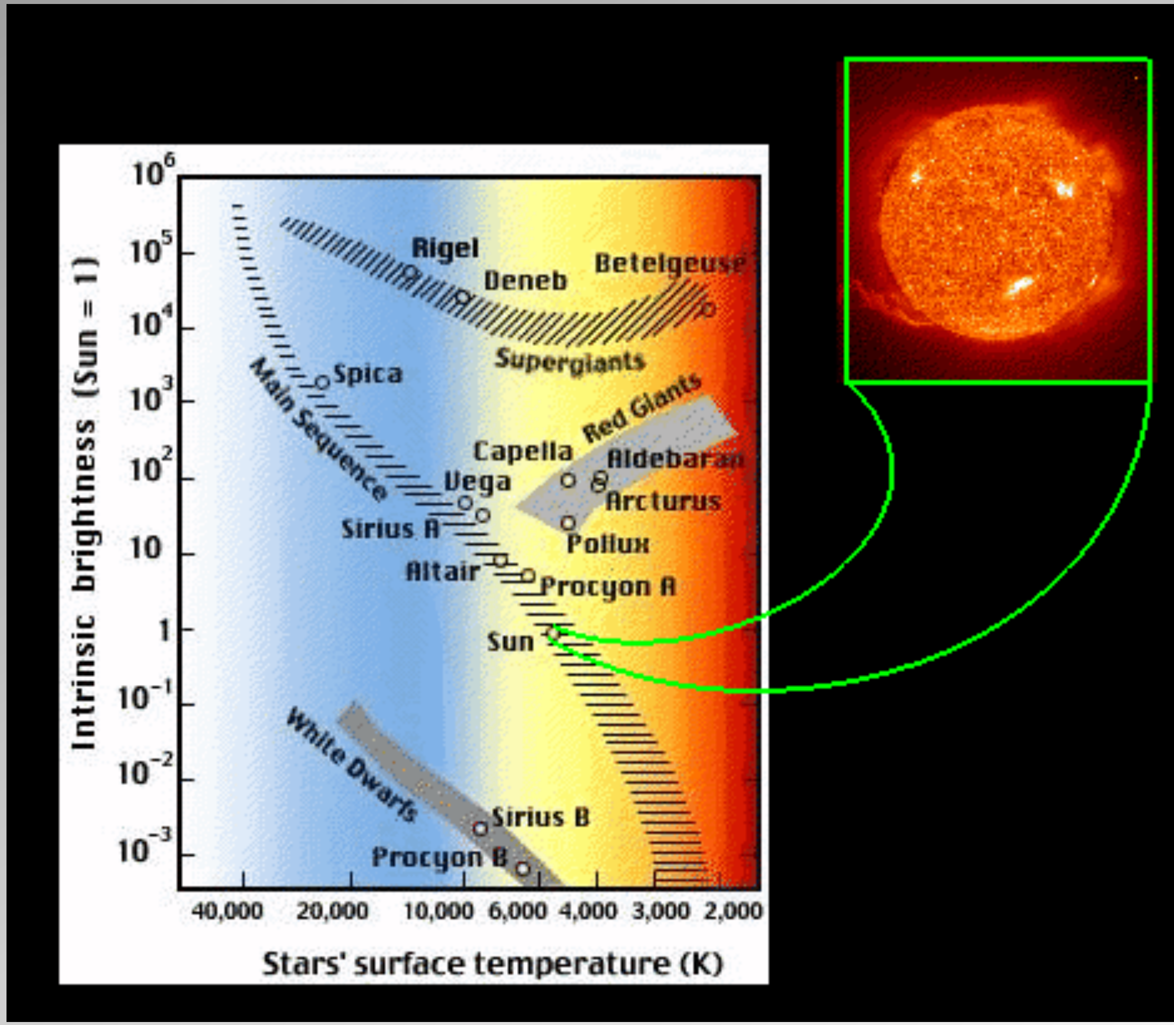
Solar History

And a modern worship of the Sun…

Solar History: Sky's worship continue?

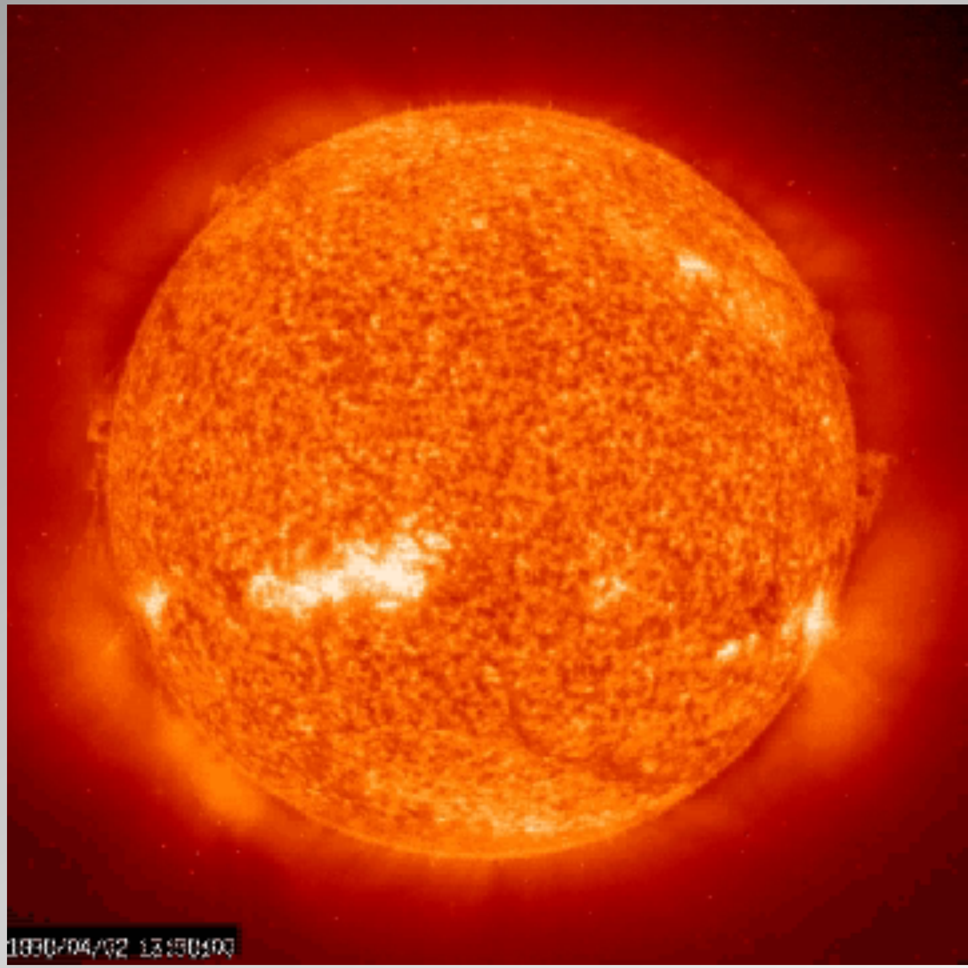
The Sun as a star

Hertzsprung-Russell Diagram (HRD)



Our own star: the Sun

Helium II image



Why to bother: "Big questions"

- What is the basis of stability and dynamics of solar atmospheric and ST structures?

- What mechanisms are responsible for heating in the solar atmosphere up to several million K?

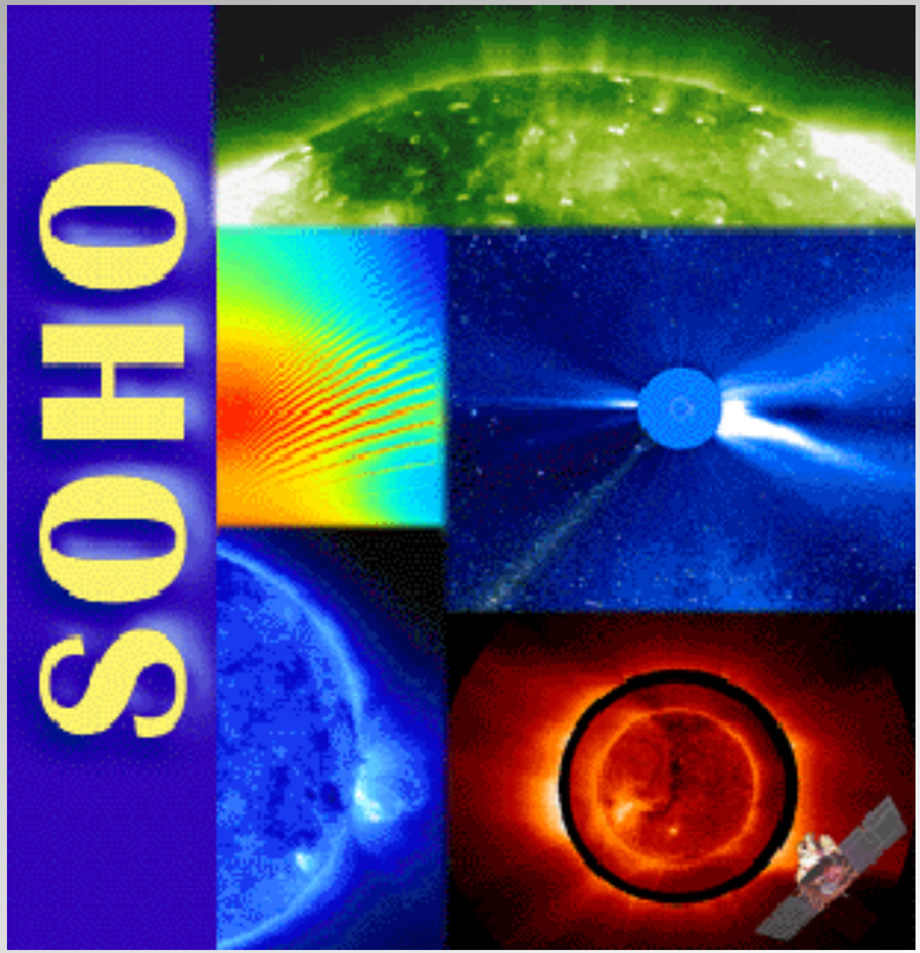
- What accelerates the solar wind up to measured speeds exceeding 700 km/s?

- What are the physical processes behind the enormous energy releases (e.g. solar flares, megnetospheric substorms, energisation of ULF waves)?

Exploration: SOHO

The Solar and Heliospheric Observatory

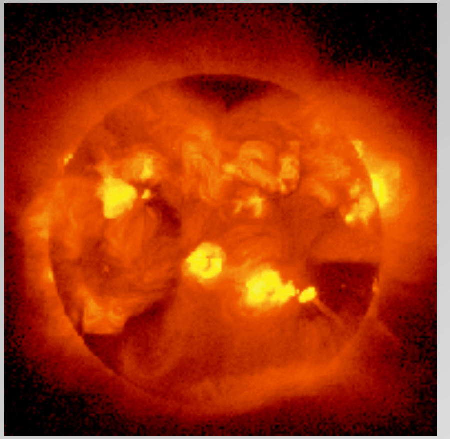
- Joint ESA and NASA project
- Suit of 12 instruments
- Launched in 1995
- 1.5 million km towards the Sun



Exploration: Yohkoh & TRACE

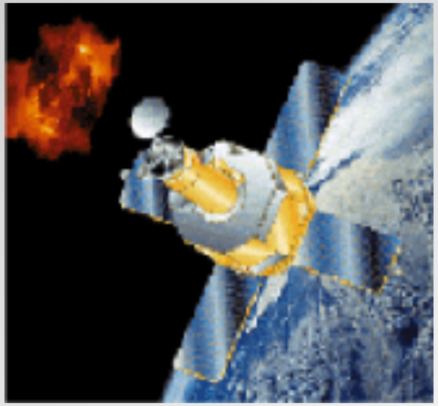
Yohkoh ("Sunbeam")

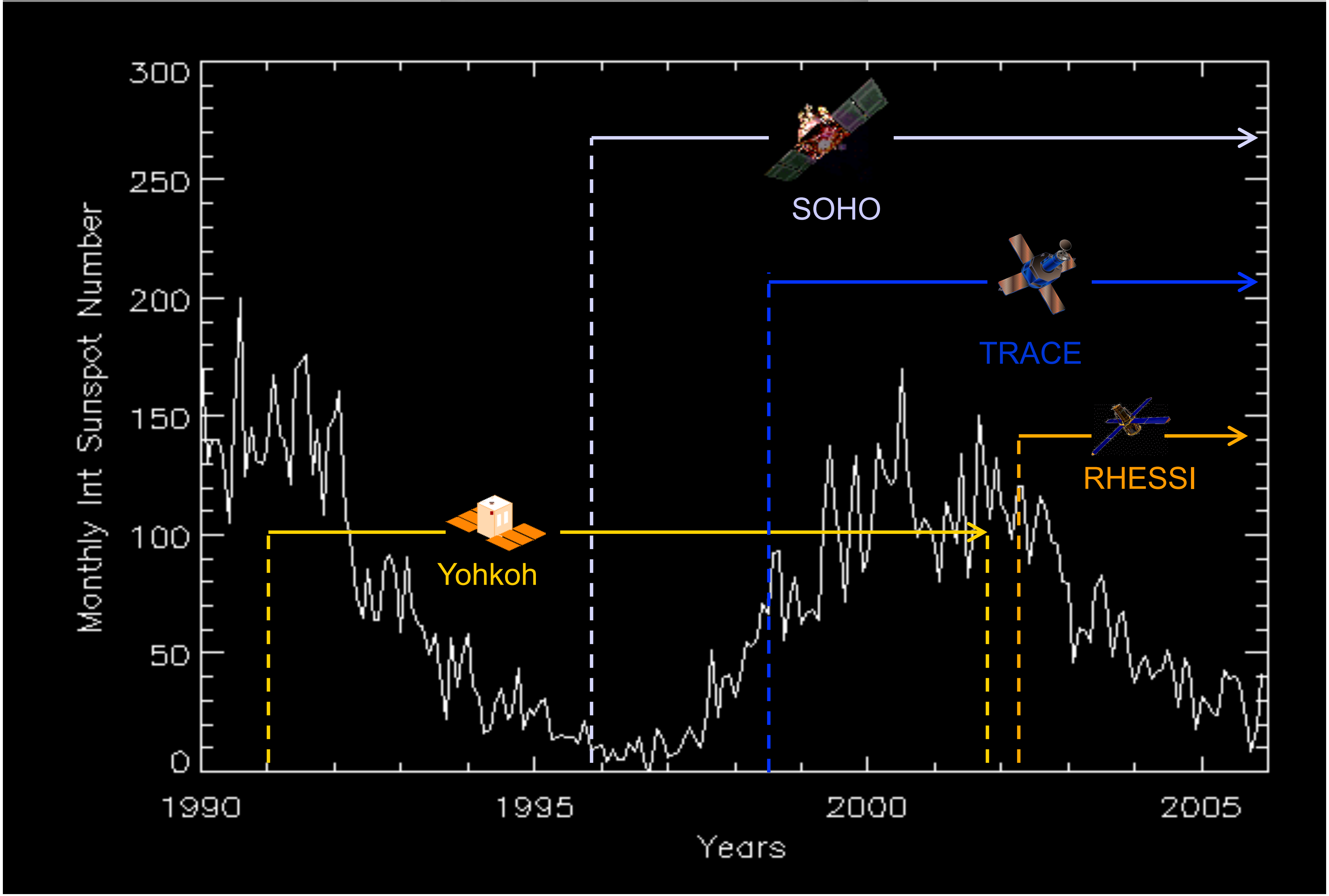
- Japan/UK/USA Mission
- Observed Sun in X-ray
- Launched in 1992



Transition **R**egion **a**nd **C**oronal **E**xplorer

- NASA Small Explorer
- EUV Mission
- Incredible resolution





SOHO
TRACE
RHESSI
Yohkoh
Monthly Int Sunspot Number
Years
300
250
200
150
100
50
0
1990
1995
2000
2005

Exploration: What is the MHD model?

- Single fluid (continuum) approximation, macroscopic description

- Locally charged, globally neutral "close to" LTE

- MHD: perturbations of magnetic field, plasma velocity and plasma mass density, described by the MHD ("single fluid" approximation) set of equations, which connects the magnetic field B, plasma velocity v , kinetic pressure p and density ρ.

- Simplified Maxwell's eqs + "classical" fluid dynamics

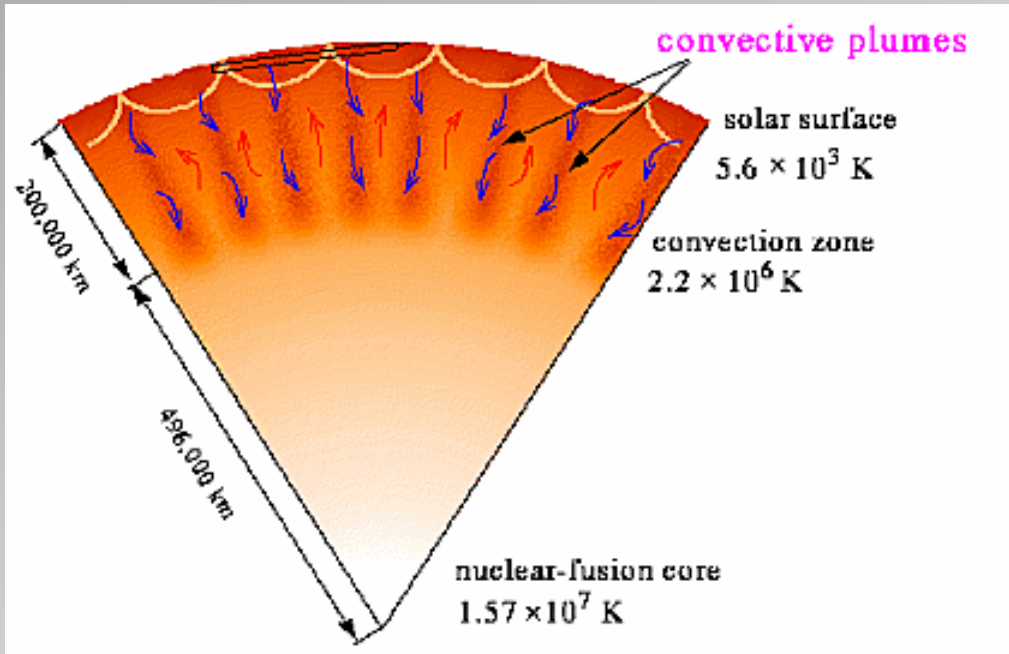
Exploration: Why to study MHD?

MHD plays a crucial approximation in the description of dynamics and structure of the solar interior, the entire solar atmosphere (sunspots, chromosphere, TR, corona, solar wind) and in Earth' magnetosphere. MHD approximation is adequately describes

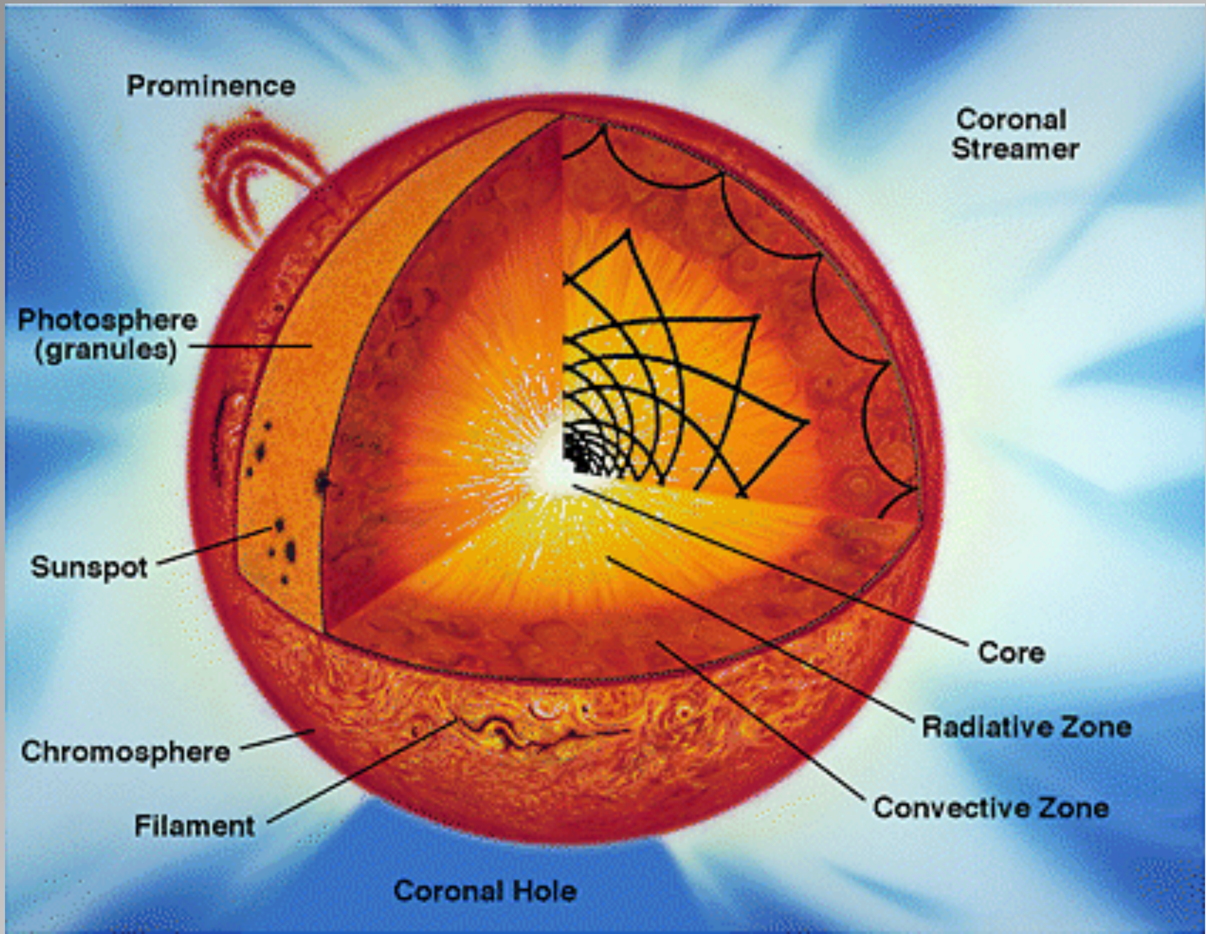
- **the evolution and development of plasma perturbations,**
- **the transfer of plasma energy and momentum,**
- **plasma heating / acceleration,**
- **helioseismology, solar atmospheric (magneto) seismology, magnetosphere seismology.**
- **Also, we use it because it is relatively simple when compared to other approaches (e.g., kinetic theory)!**

Convection zone

- Thickness ≈ 200,000 km
- Energy transfer by bulk motion



Helioseismology



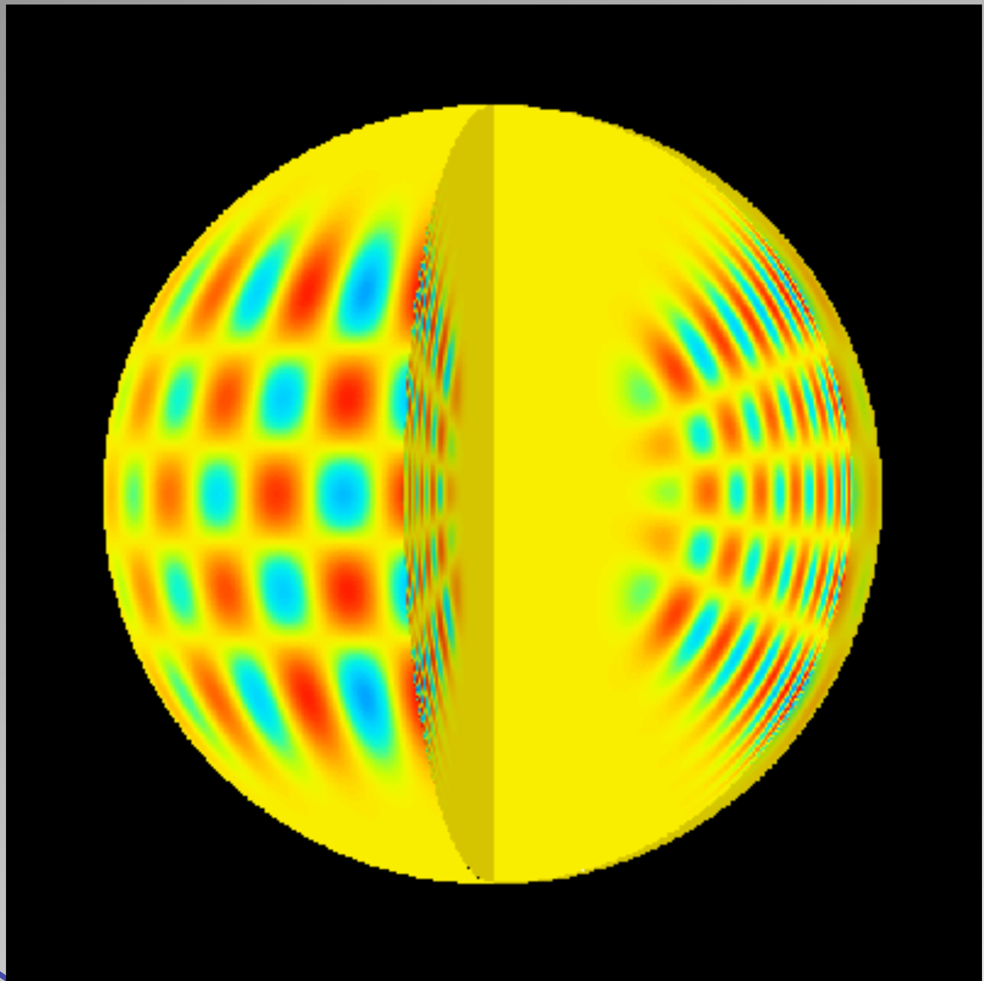
¤ more than 100,000 pulsation modes

¤ single mode

¤ three modes

¤ many modes

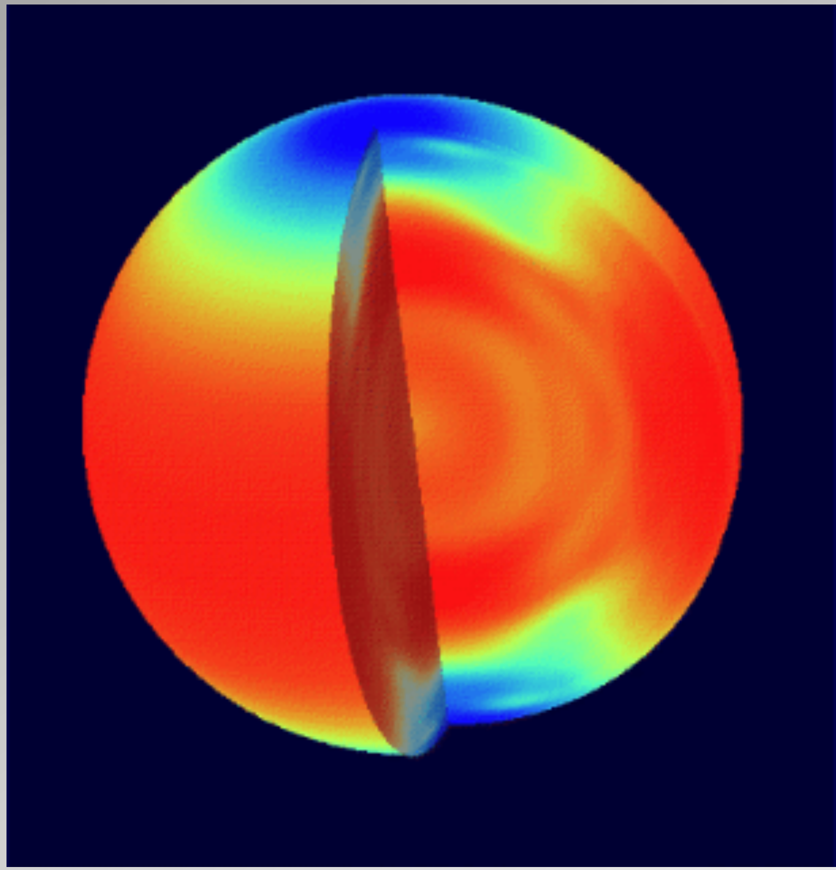
Helioseismology



- n=14 (radial nodes)
- m=16 (poloidal nodes)
- l=20 (spherical harmonic degree)
- The frequency of this mode determined from the MDI data is 2935.88 -> ~0.2 μHz.

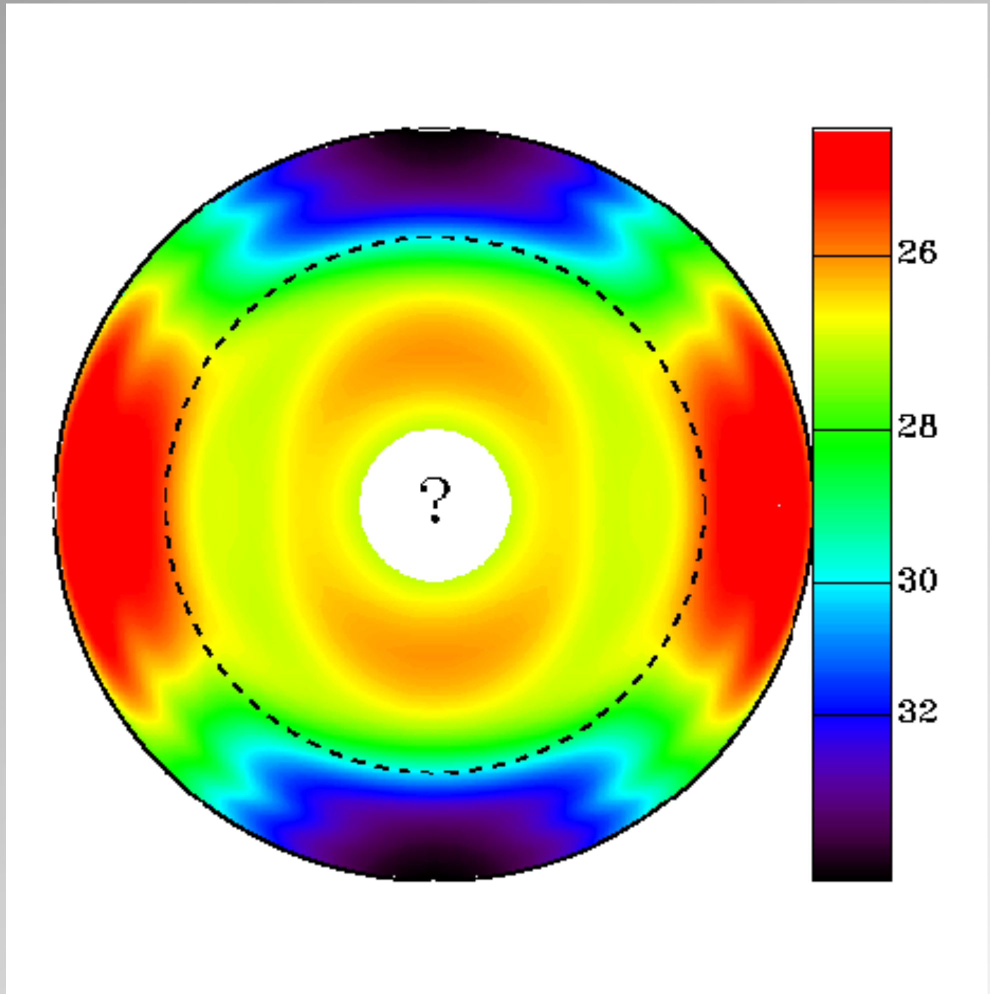
Differential rotation

- Equator ≈ 26 days
- Poles ≈ 35 days

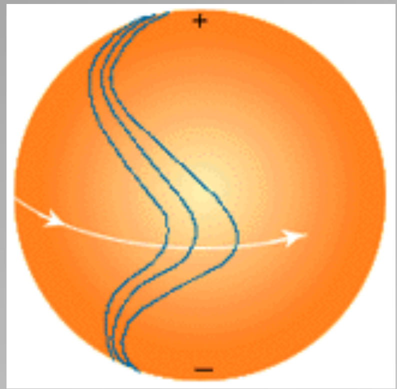


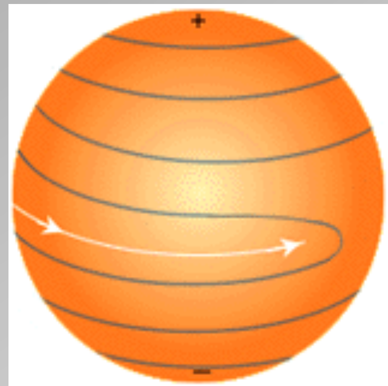
- Fast rotation
- Slower rotation

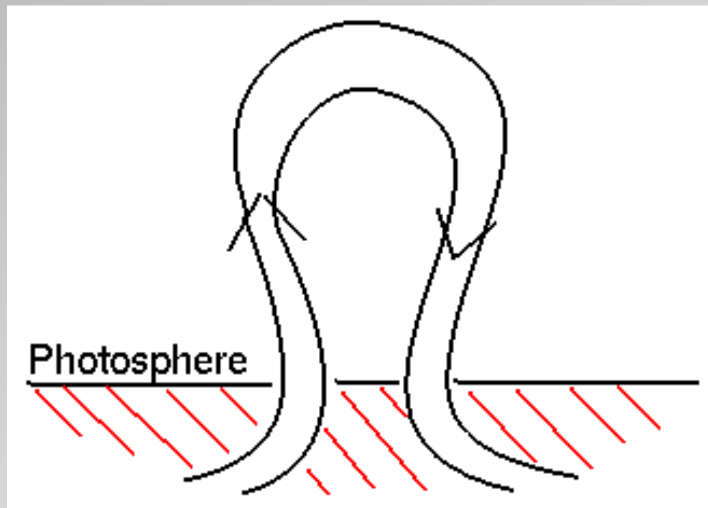
Differential rotation



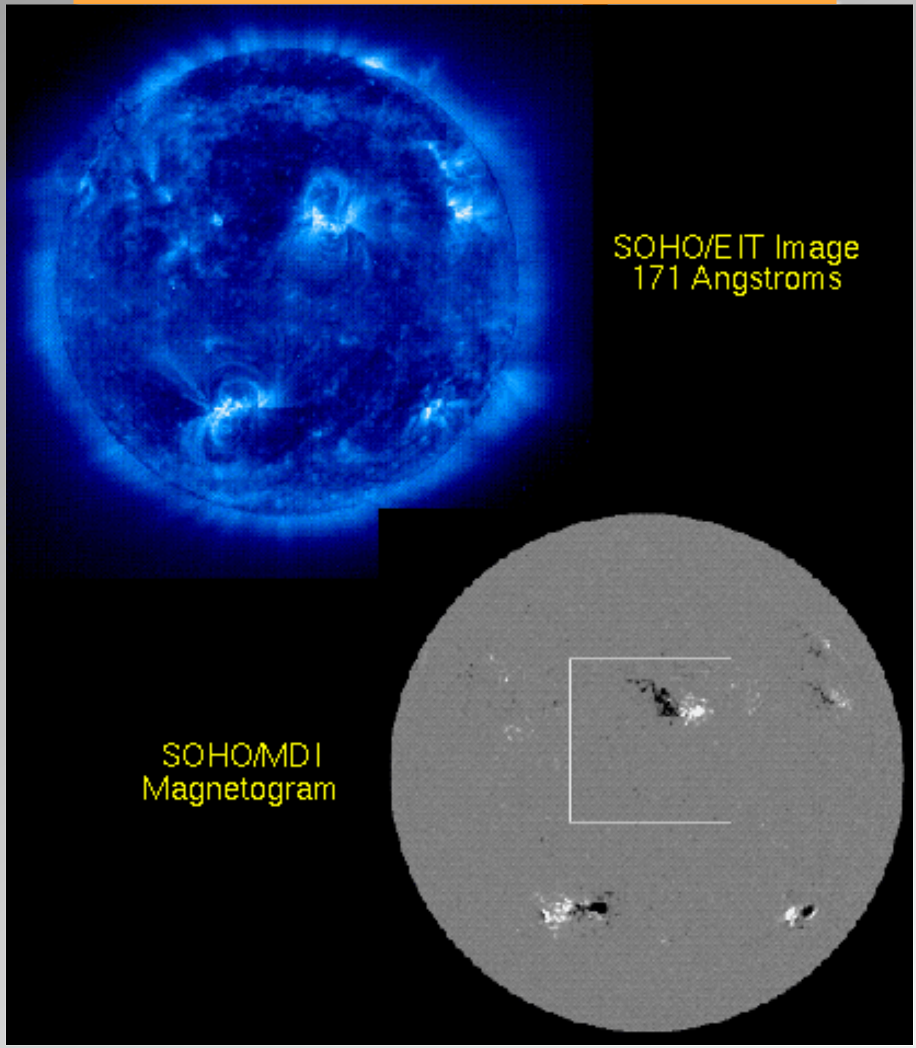
Differential rotation: twisting magnetic field!







Is the Sun magnetic?



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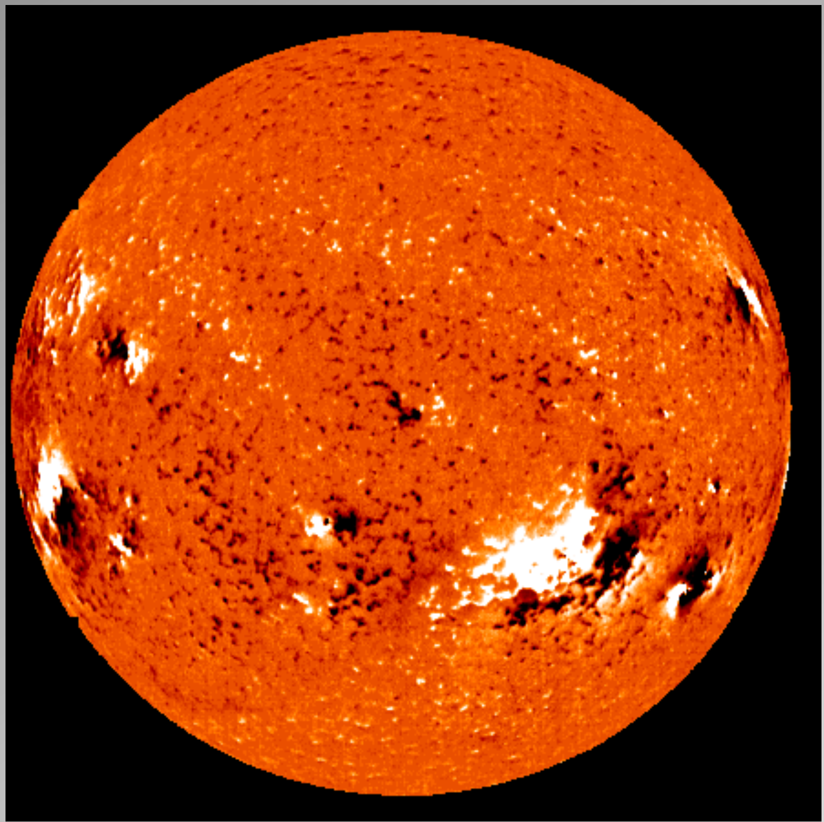
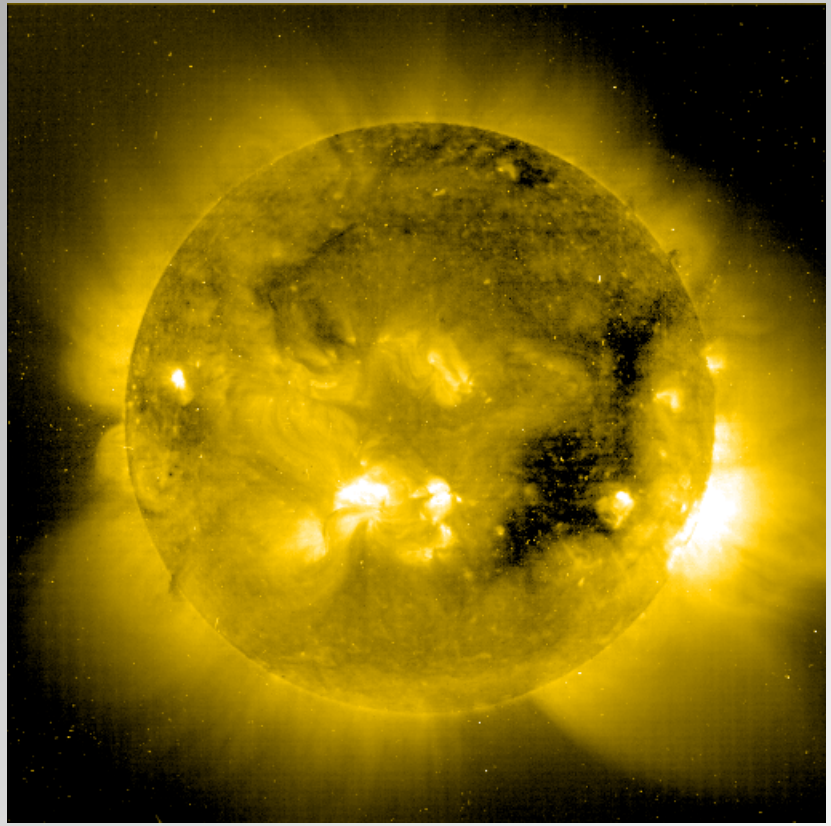
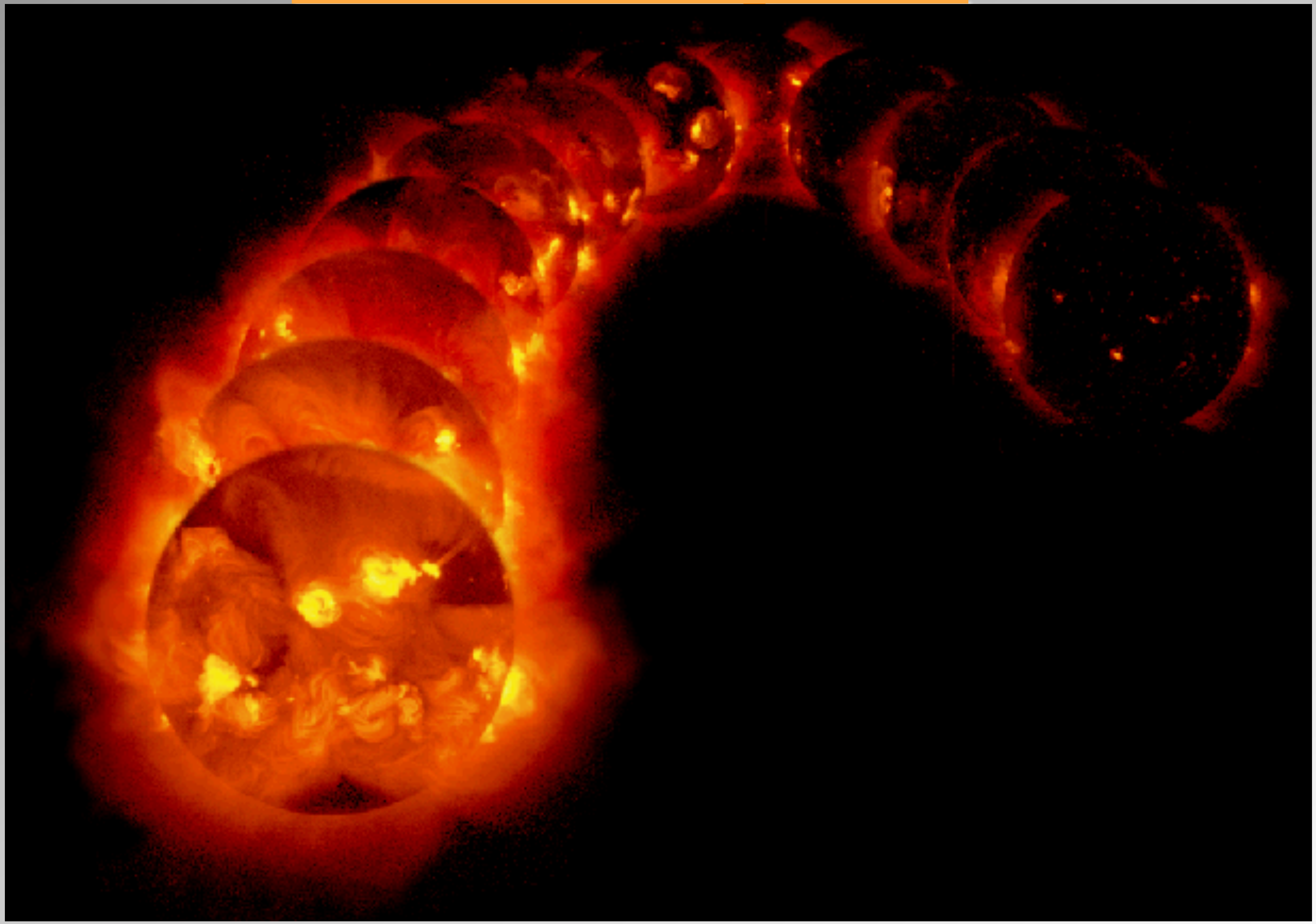


Ca II emission

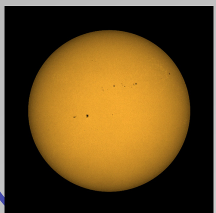


Extreme ultra-violet

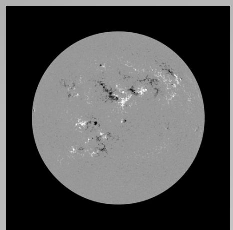
Is the Sun magnetic?



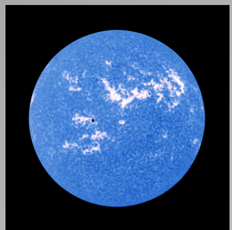
Magnetic coupling: the dynamic Sun



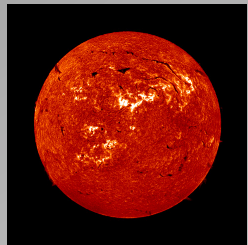
Visible
5000 K



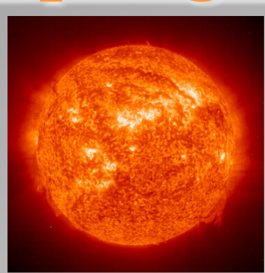
Magnetic field
5000 K



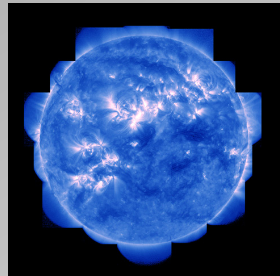
UV 1600 Å
8000 K



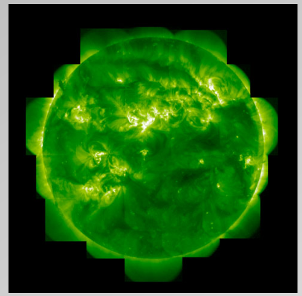
Hα
15,000 K



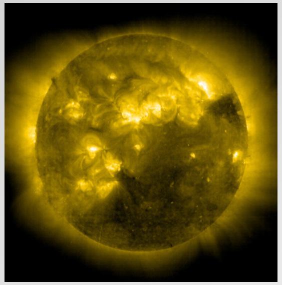
He EUV
50,000 K



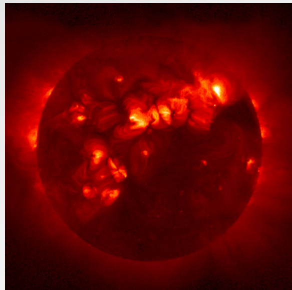
Fe VIII/IX EUV
1 MK



Fe XI
1.5 MK



Fe XIV
3 MK



X rays
4-6 MK

- Photosphere – chromosphere – TR – corona are **magnetically coupled**.
- Very highly **structured** and **dynamic**; challenge for magneto-seismology

Magnetic coupling: dynamic STS

- Photosphere – chromosphere – TR – corona (inluding solar wind) – magnetosphere – Earth's upper atmosphere are all **magnetically coupled**.
- Very highly **structured** and **dynamic**.

MHD seismology is a perfect tool to study this coupled, dynamic an structured system.

Two (biassed) particularly exciting aspects:

- **Influence on Earth – Space Weather**.
- **Influence of atmosphere** on global oscillations.
- **Role of *p* modes in the dynamics of the atmosphere!** (Not yet explored.)

Governing equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \qquad (1.1)$$

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} = -\frac{1}{\rho}\nabla p + \frac{1}{\rho}\mathbf{j} \times \mathbf{B} + \mathbf{F}_{\nu} \qquad (1.2)$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} \qquad (1.3)$$

$$\rho T\left(\frac{\partial s}{\partial t} + \mathbf{v} \cdot \nabla s\right) = -\mathcal{L} \qquad (1.4)$$

Governing equations

Notation: ρ is density, **v** velocity, p pressure, **B** magnetic induction, **E** electric field, **j** electric current, **T** temperature, s entropy per unit mass, $\mathbf{F}_\nu$ viscosity force, and L energy loss function

Ampere's law:

$$\mathbf{j} = \frac{1}{\mu} \nabla \times \mathbf{B} \qquad (1.5)$$

μ is magnetic permeability of empty space

Viscous force in isotropic plasmas $(\omega_i \tau_i << 1)$:

$$\mathbf{F}_\nu = \nu \left(\nabla^2 \mathbf{v} + \frac{1}{3} \nabla \nabla \cdot \mathbf{v} \right) \qquad (1.6)$$

ν is kinematic viscosity, $\rho\nu = \text{const}$ is dynamic viscosity

Governing equations

Ohm's law:

$$\sigma(\mathbf{E}+\mathbf{v}\times\mathbf{B})=\mathbf{j}+\frac{m_i\sigma}{\rho e}\mathbf{j}\times\mathbf{B} \qquad (1.7)$$

σ is conductivity, m_i ion mass, e proton electric charge. Last term is

Clapeiron law (R gas constant, $\tilde{\mu}$ mean atomic weight):

$$p=(R/\tilde{\mu})\rho T \qquad (1.8)$$

Entropy:

$$s=c_v\ln(p/\rho^{\gamma})+\text{const} \qquad (1.9)$$

c_v is specific heat at constant density, γ is adiabatic index (usually = 5/3)

Energy loss function:

$$\mathcal{L}=\nabla\cdot\mathbf{q}-\frac{1}{\sigma}j^2-\rho\nu\left\{\frac{1}{2}\sum_{j,k=1}^{3}\left(\frac{\partial v_j}{\partial x_k}+\frac{\partial v_k}{\partial x_j}\right)^2-\frac{2}{3}(\nabla\cdot\mathbf{v})^2\right\} \qquad (1.10)$$

Governing equations

Force-balance in magnetised plasmas

A magnetic field in a conducting fluid exerts a force per unit volume F_{mag}

$$\vec{F}_{mag} = \vec{j} \times \vec{B} = \frac{(\nabla \times \vec{B}) \times \vec{B}}{\mu_o}$$

where *j* is the current and B the magnetic induction (often referred to as magnetic field strength). This is the on the particles.

The equation of motion of an element of material inside a ‘flux tube’ in a conducting fluid is

$$-\nabla p + \rho \vec{g} + \nabla . \overline{S} + \frac{(\nabla \times \vec{B}) \times \vec{B}}{\mu_o} = \rho \dot{v}$$

where g is the local gravitational acceleration, p the gas pressure, ρ the density and S a tensor describing viscous stresses.

Setting $\dot{v} = 0$ we have the equation of magnetohydrostatic equilibrium.

Governing equations

Force-free and non-force-free fields

In the case of where all forces are negligible, except for the ***j*** x ***B*** force, the MHS equation reduces to

$$\vec{j} \times \vec{B} = 0$$

This is known as the 'force-free' condition. The gas pressure has virtually no influence (low-β plasma).

The photosphere is not force free. Moving outwards in the atmosphere the gas pressure and viscosity decrease, and the force-free condition becomes a good approximation (from ~500km above τ_{500nm} =1)

Above a few tenths of a solar radius, the field is again not force-free.

Frozen-in fields

The magnetic field is for the most part 'frozen-in' to the coronal plasma. This is the same as saying that the plasma is highly conducting.

We can demonstrate this by looking at field advection and diffusion. Start with Ohm's law:

$$\vec{E} + \vec{v} \times \vec{B} = \frac{\vec{j}}{\sigma}$$

σ = conductivity = $1/\eta\mu_o$

Take the curl of this equation, and use $\nabla \times \vec{E} = -(\partial\vec{B}/\partial t)$ to eliminate E.

$$\frac{\partial\vec{B}}{\partial t} = \nabla \times (\vec{v} \times \vec{B}) - \eta\nabla \times (\nabla \times \vec{B})$$

where we have also used $\nabla \times \vec{B} = \mu_0 \vec{j}$

Expanding the last term, and using $\nabla . \vec{B} = 0$ we arrive at the induction equation

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

Frozen-in fields

The two terms on the left hand side represent the advection of field by the flow, and the dissipation of field due to resistivity

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

1 2

Normally in the solar atmosphere (e.g. corona), conductivity σ is very high, so $\eta = 1/\mu_o \sigma$ is very small.
In this case, term 2 is negligible in comparison with term 1. So the equation becomes

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{v} \times \vec{B})$$

v x ***B*** is the component of flow perpendicular to the magnetic field. So perpendicular flows distort B, and vice versa. **The field is locked to the plasma.**

(In fact one must prove that the total magnetic flux through a surface remains constant as the field is deformed).

Limits of applicability

• Speeds are much less than the speed of light.
(In the solar corona: $v <$ a few thousand km/s).

• Characteristic times are much longer than the Larmour rotation period and the plasma period.

In the solar corona: f_{MHD} Hz. E.g., for B=10 G, $n_e = 5\text{x}10^{14}$ m^{-3}

f_{gyro}= Hz

f_{plasma}= Hz

Limits of applicability

- The Hall effect is insignificant. The ratio of the dispersive and "wave" terms in the dispersion relation (the dispersive correction to the phase speed):

$$H = \frac{2\pi v_A}{\omega_{\rm gyro} L} \approx \frac{5\times 10^2}{L[\rm m]}$$

For $\lambda = 5\mathrm{x}10^5$ m H=0.001

- Characteristic times are much longer than the collision times.

- Characteristic spatial scales are larger than the mean free path length

$$L >> l_{ii}[\rm m] \approx \frac{7.2\times 10^7 T^2[\rm K]}{n[\rm m^{-3}]} \qquad l_{ii} \approx 10^5 - 10^6 \text{ m}$$

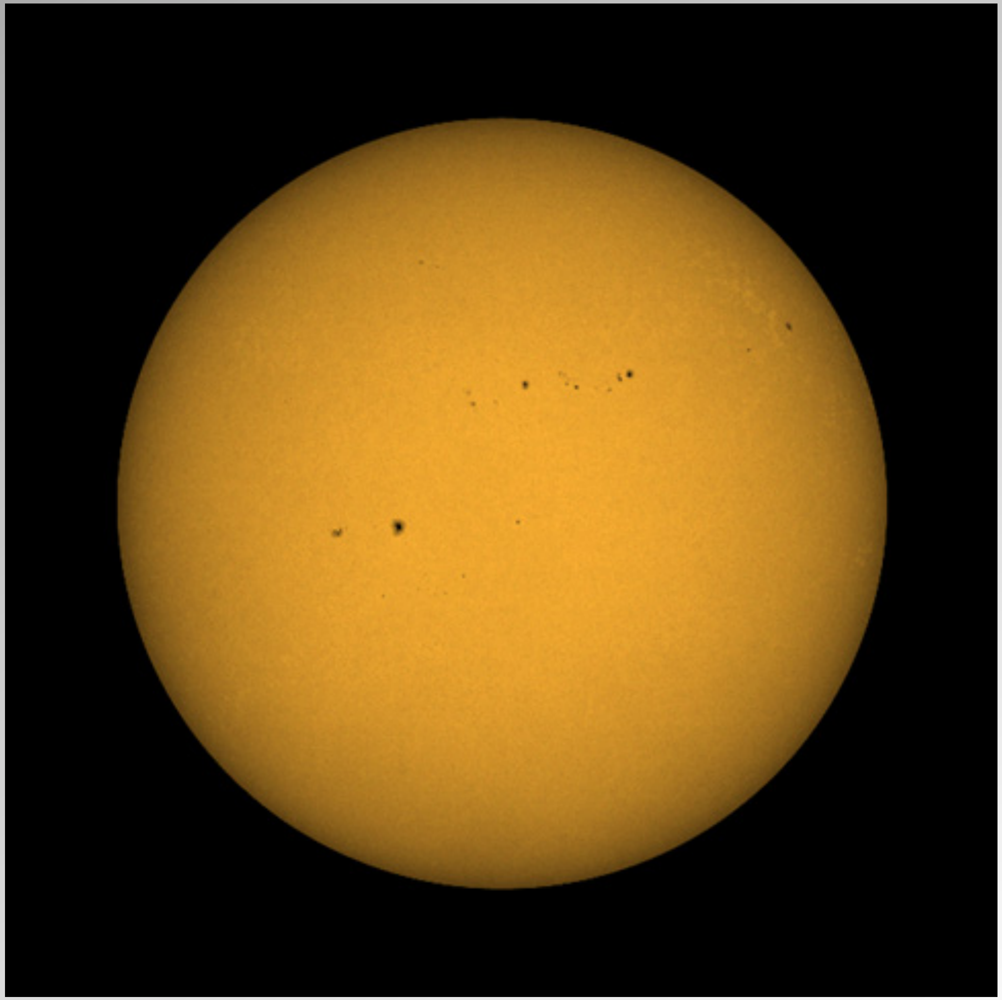
Important limits

- Cold plasma

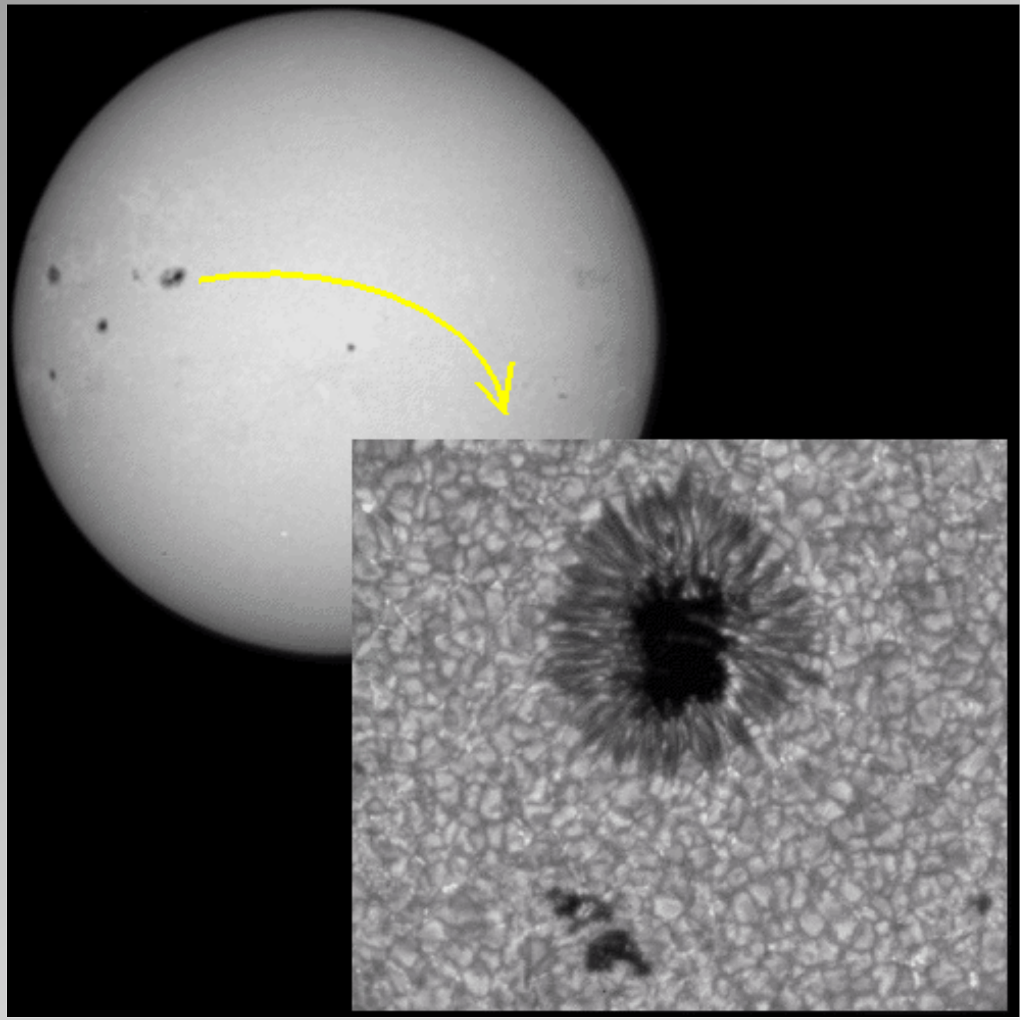
- Incompressible plasma

Photosphere

- Visible surface of the Sun
- Only ≈ 100 km thick
- Temperature ≈ 6000 K

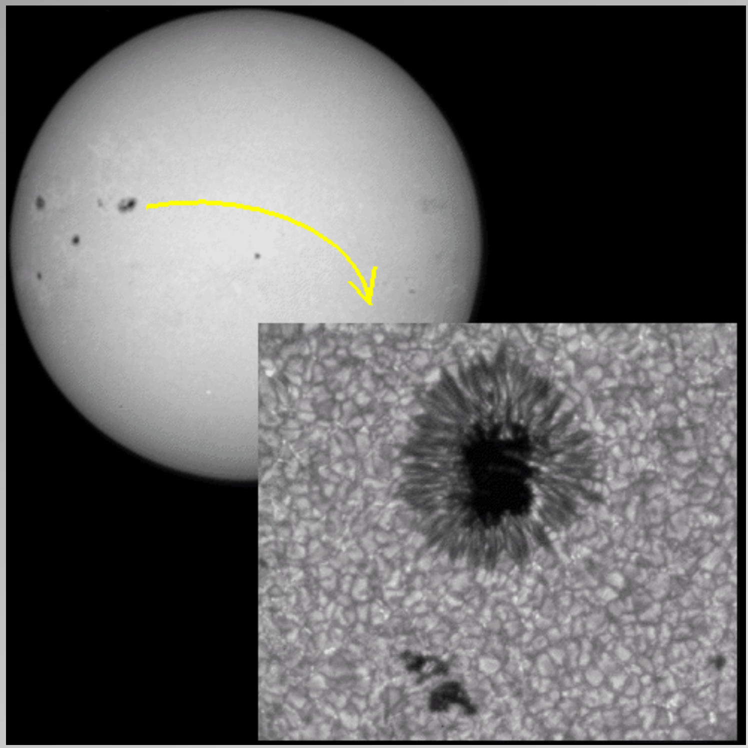


Photosphere: sunspots I



Photosphere: structure of sunspots

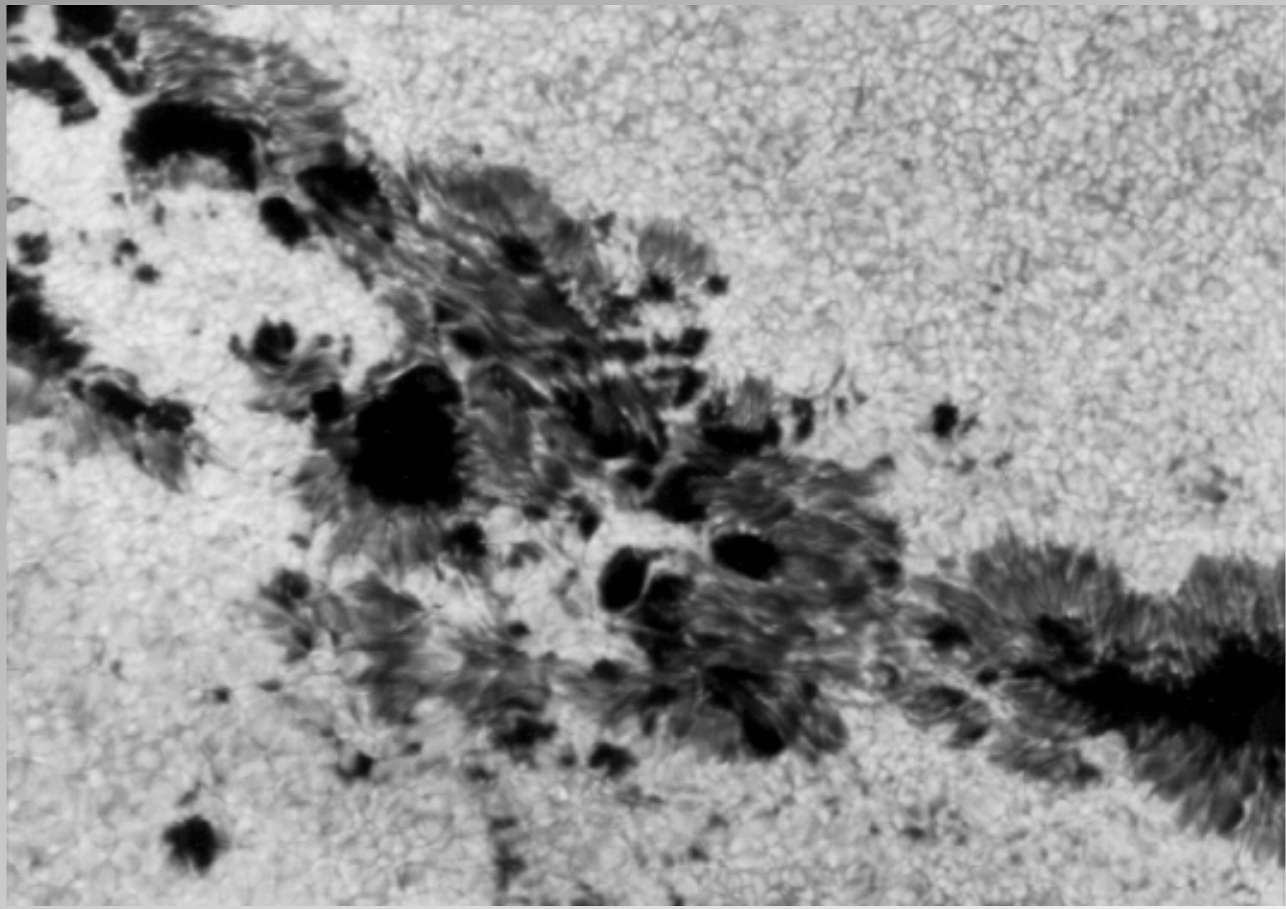
Sunspots are cooler than their surroundings because their strong magnetic field inhibits convection below the level of the photosphere. Hence, internal heat flux F_i, is reduced compared to external heat flux F_e



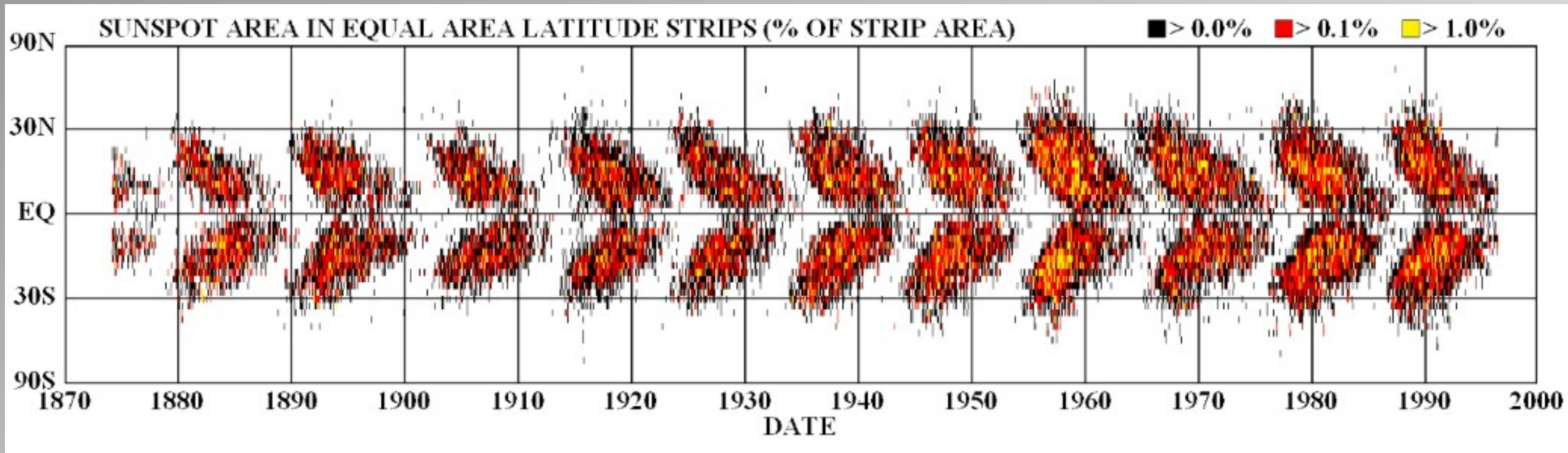
Sunspot field structure determined by lateral pressure balance

$$P_i + \frac{B_i^2}{2\mu_o} = P_e + \frac{B_e^2}{2\mu_o}$$

Photosphere: sunspots II

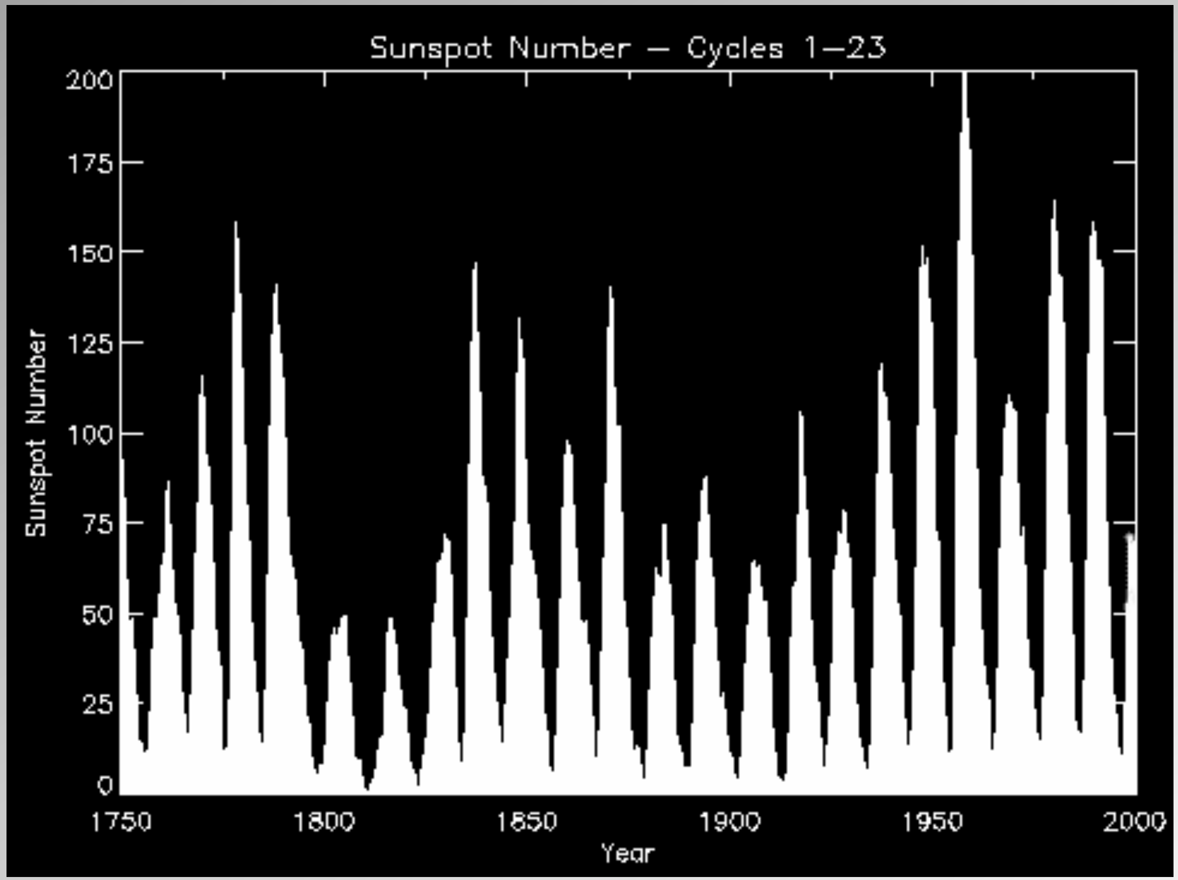


Solar cycle

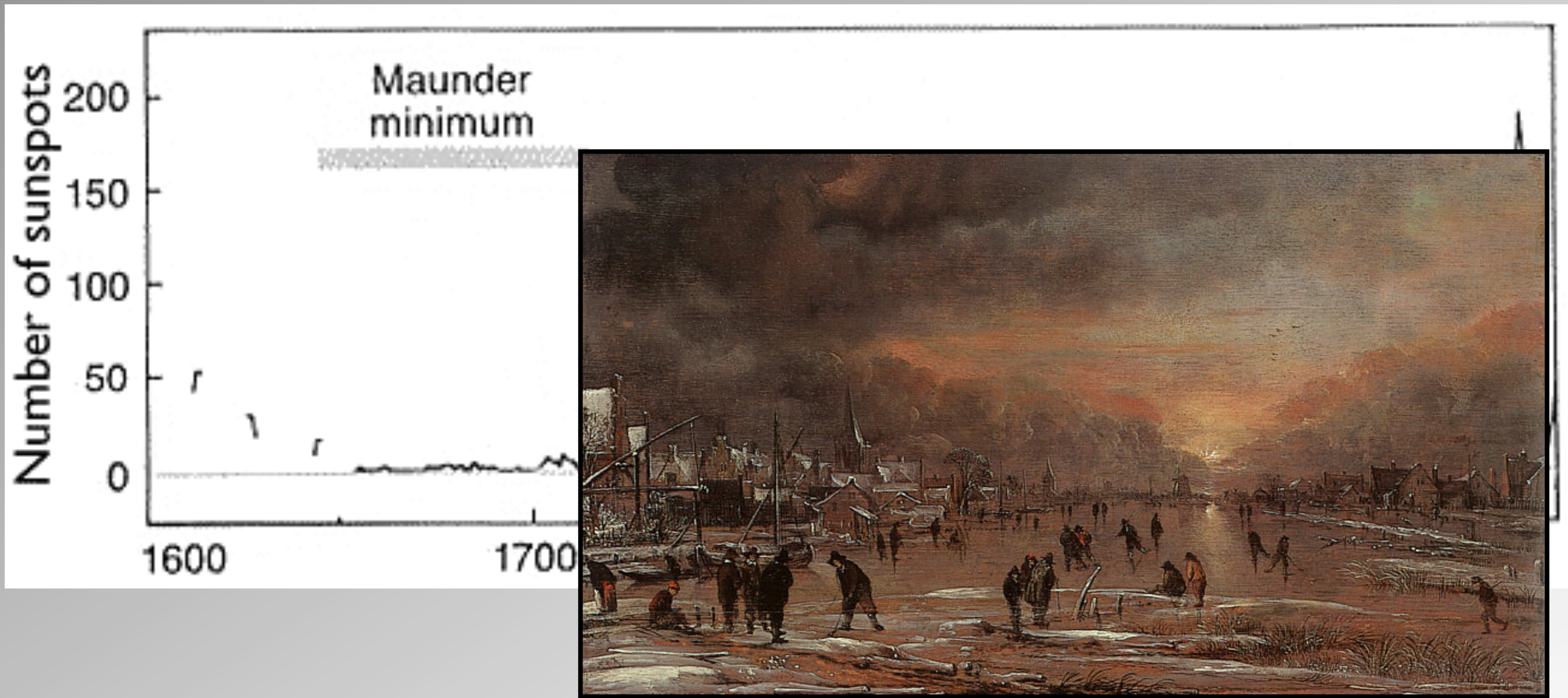

SUNSPOT AREA IN EQUAL AREA LATITUDE STRIPS (% OF STRIP AREA)
> 0.0%
> 0.1%
> 1.0%
90N
30N
EQ
30S
90S
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
DATE

Solar cycle

- Approximate 11 year cycle
- Whole magnetic field reverses

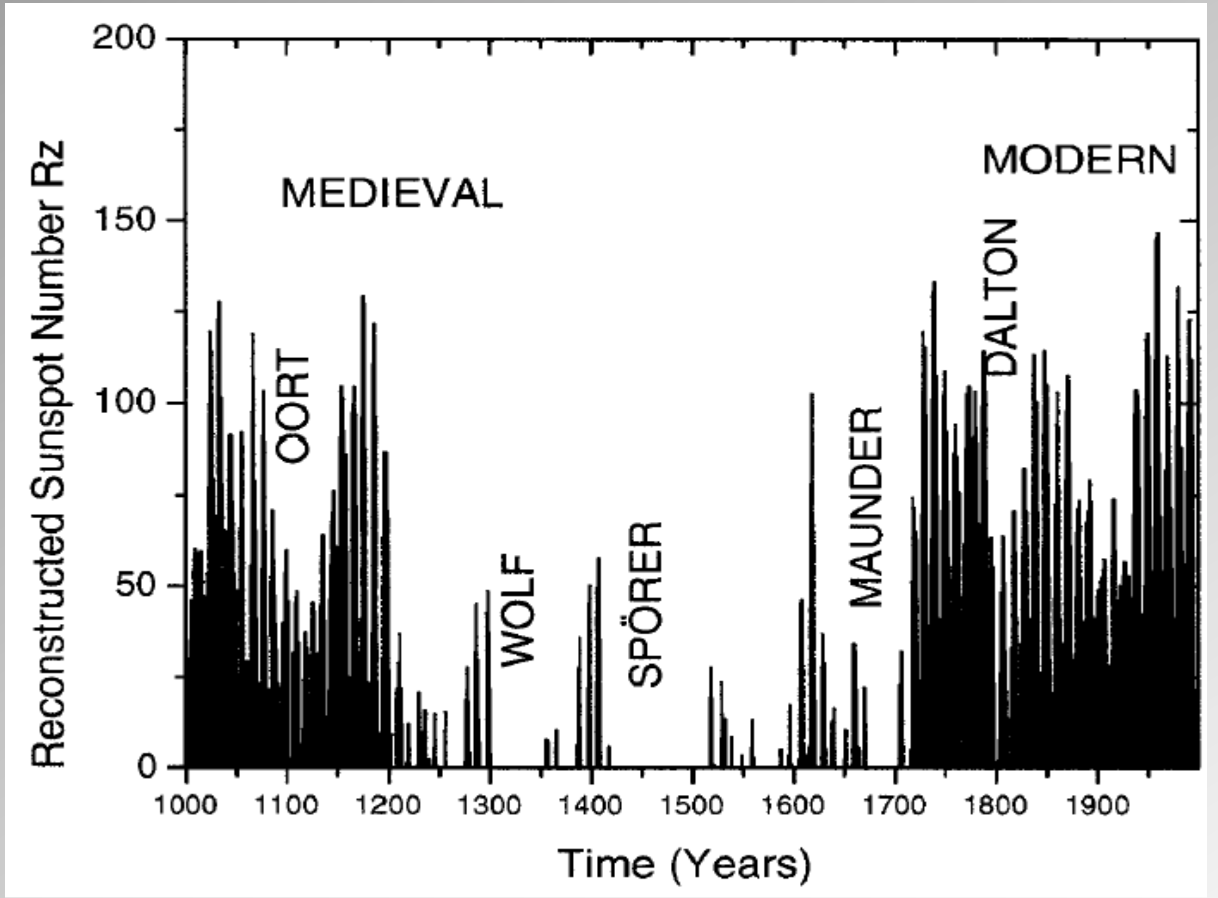


Solar cycle



Aert van der Neer [1603/4 - 1677] ‘Sports on a Frozen River’, ca. 1660

Solar cycle: Grand Minima/Maxima

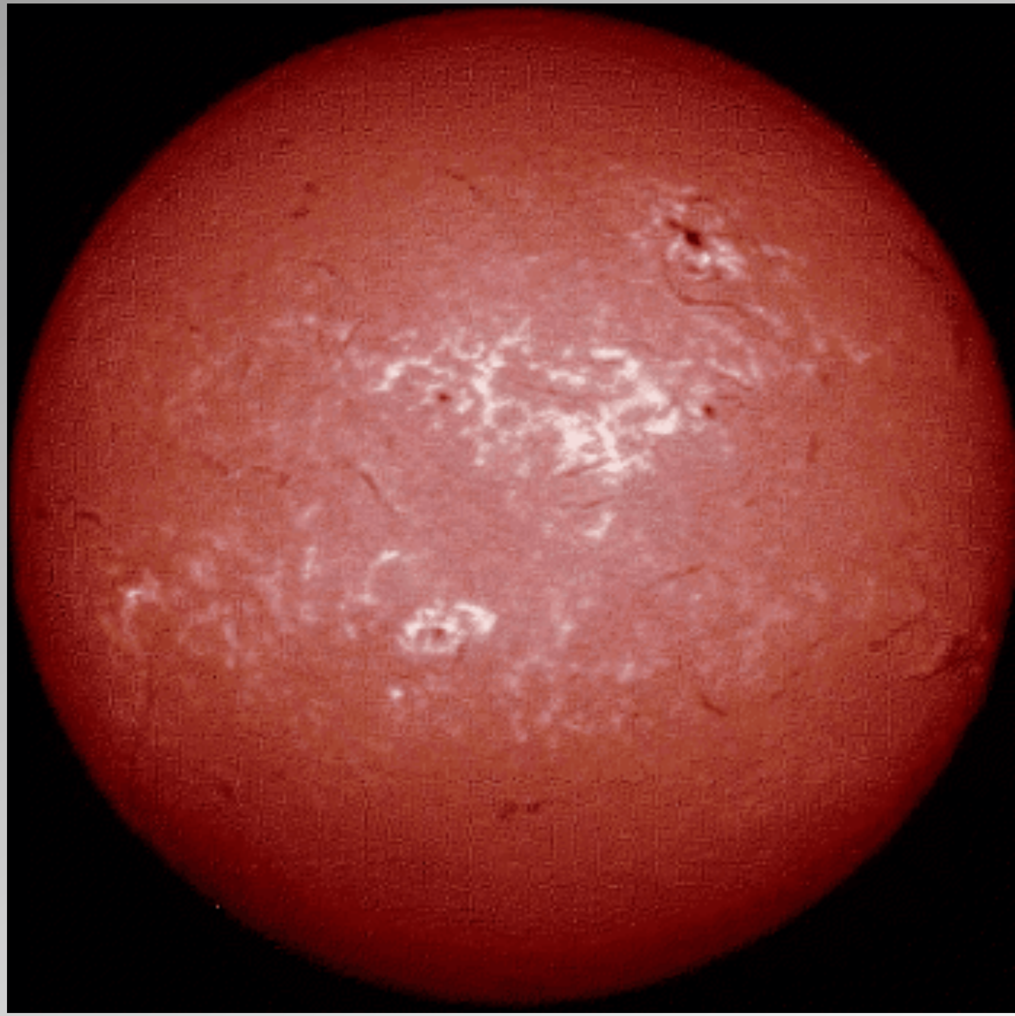


Rigozo et al., 2001, Solar Physics

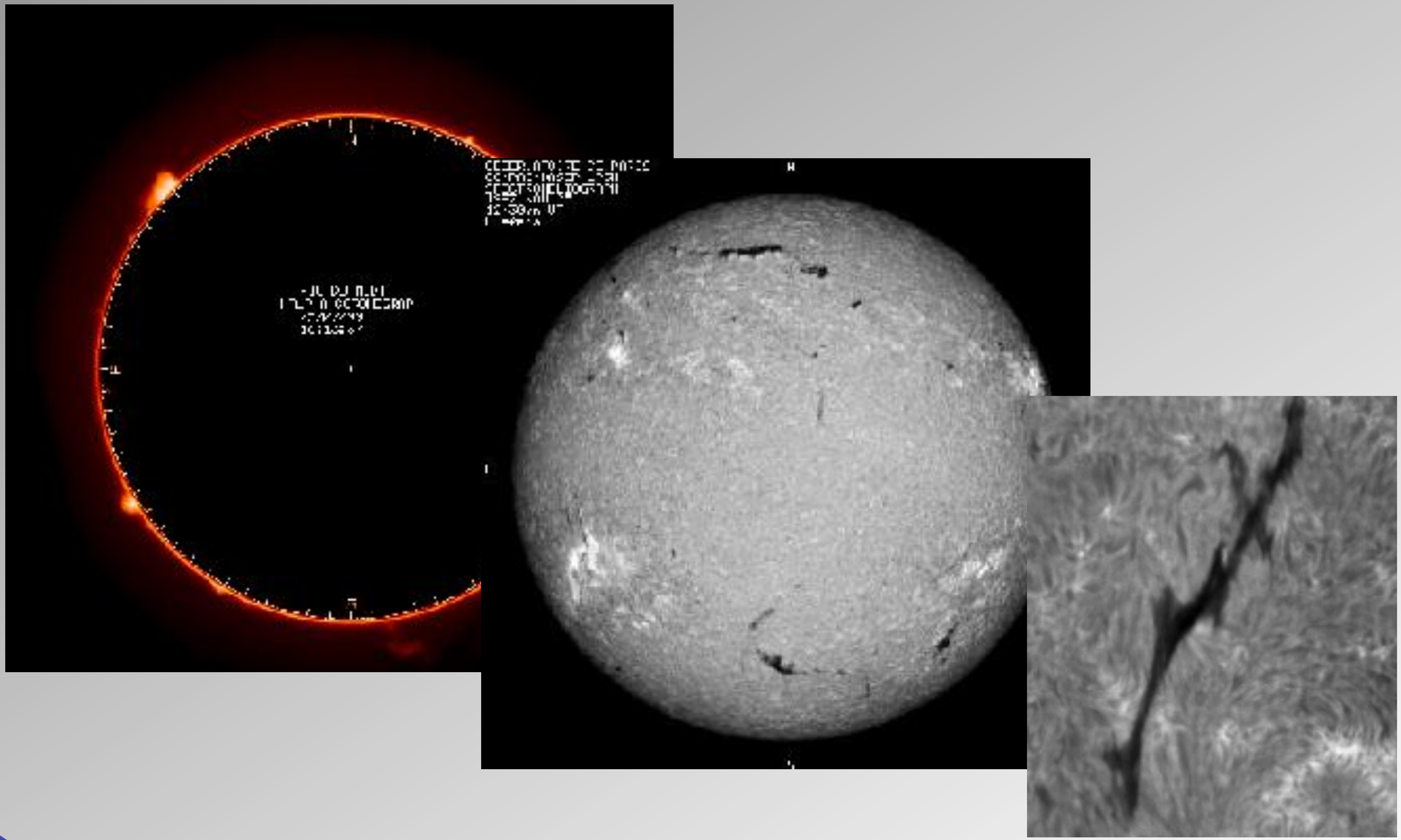
Solar Physics & Space Plasma Research Centre (SP^{2}RC)

Chromosphere

- Hydrogen alpha filter image
- Thickness ≈ 2500 km



Prominences/filaments

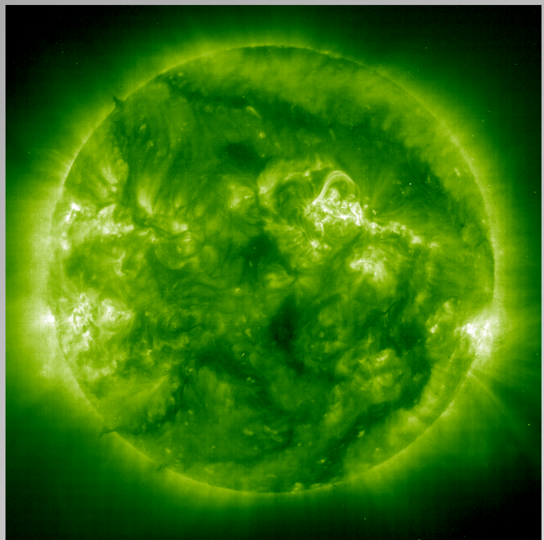


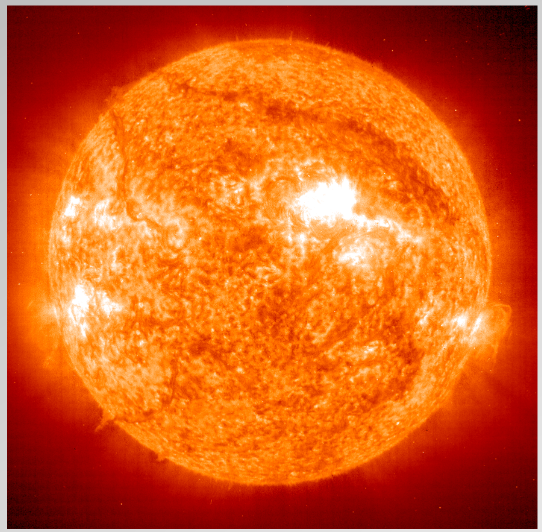
Prominences/filaments

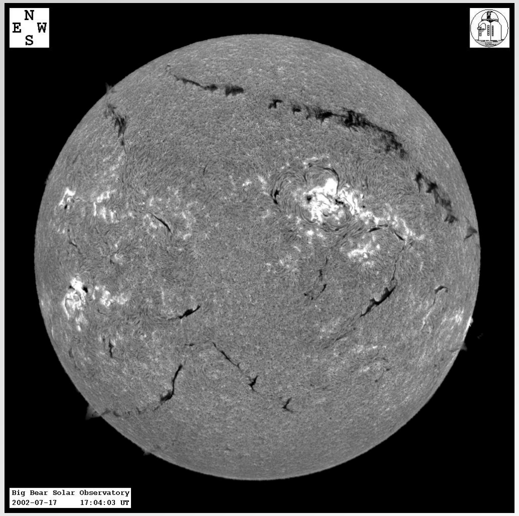
Filaments - called prominences when they appear in emission at the limb - are cool (20,000K) dense ($10^{21}m^{-3}$) gas which is thermally isolated from the surrounding corona.

They appear in active regions and in the quiet sun, and overlay magnetic neutral lines.

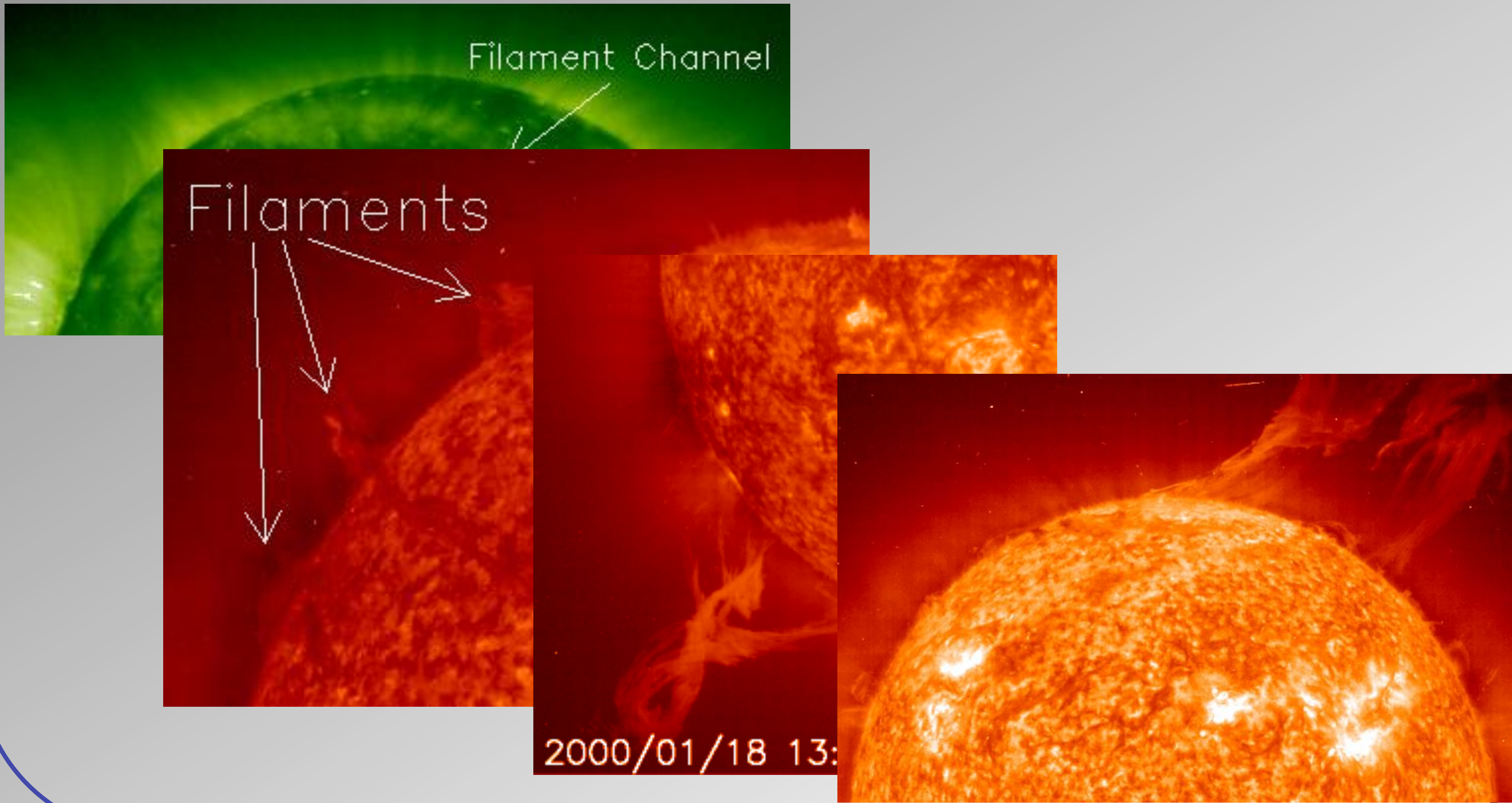
AR filaments tend to erupt within a few days, QS filaments can last and grow for weeks.



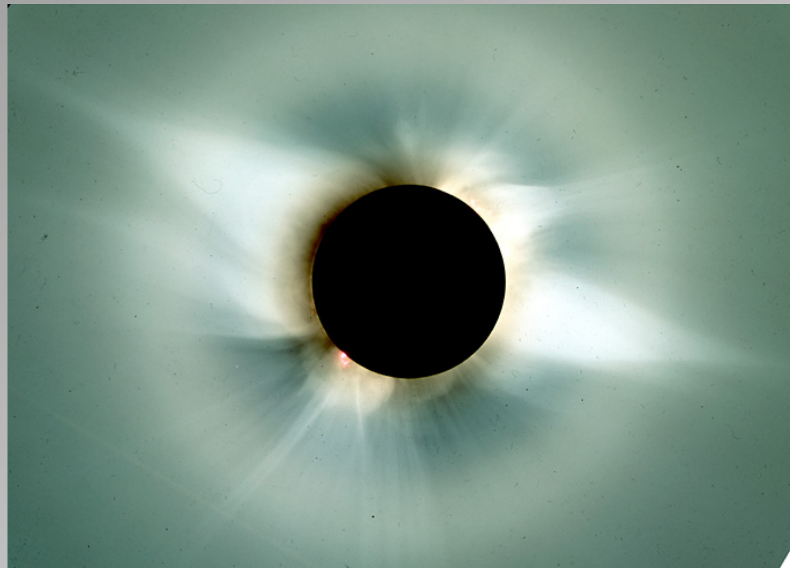




Prominences/filaments (ctd)

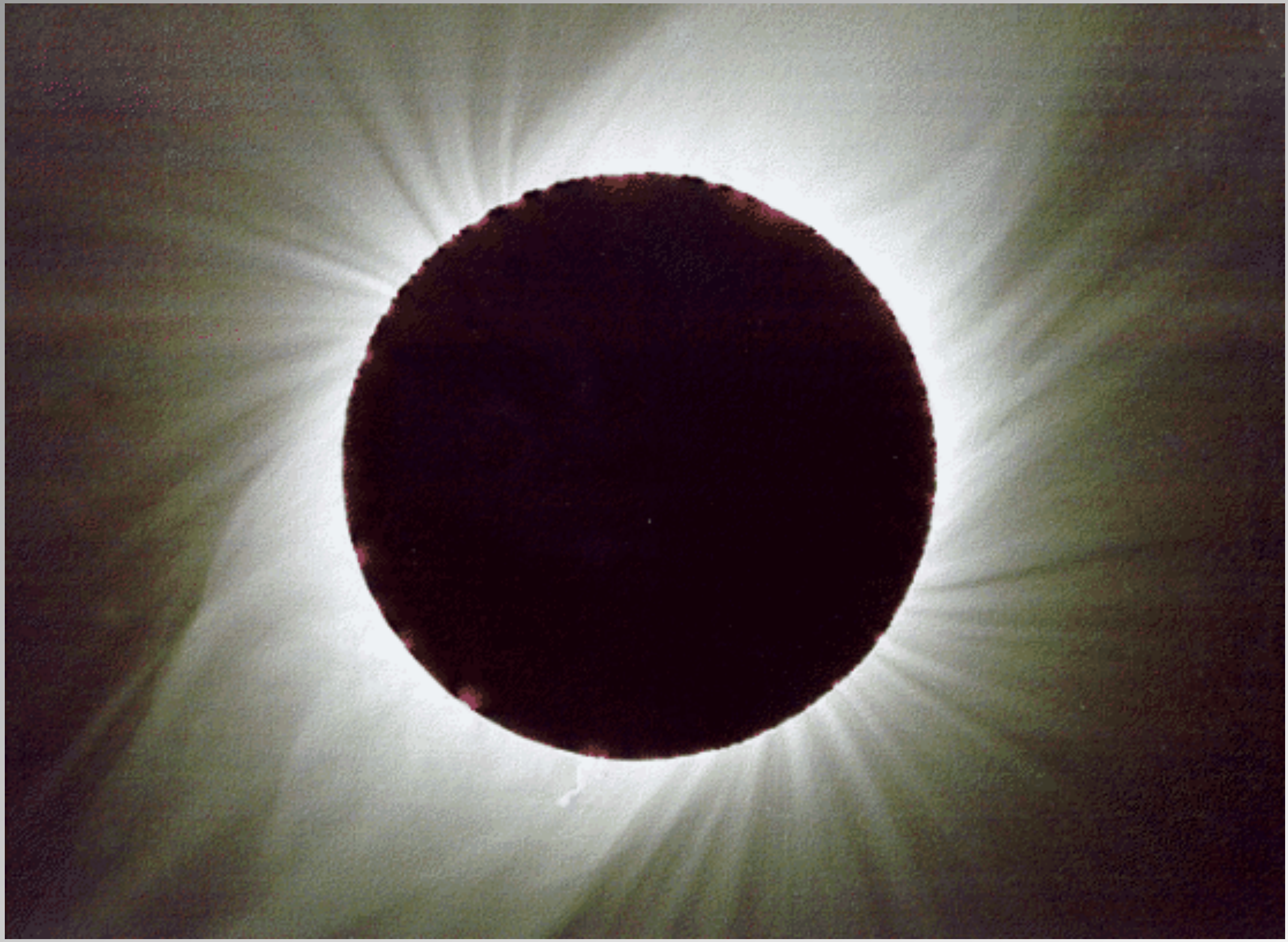


The corona at eclipse



- 1860s – "coronium" discovered
- 1902 – "coronium" has lesser atomic weight than hydrogen (Mendeleev)
- 1930s – spectral lines due to known elements at very high stages of ionisation (Grotrian, Edlén)

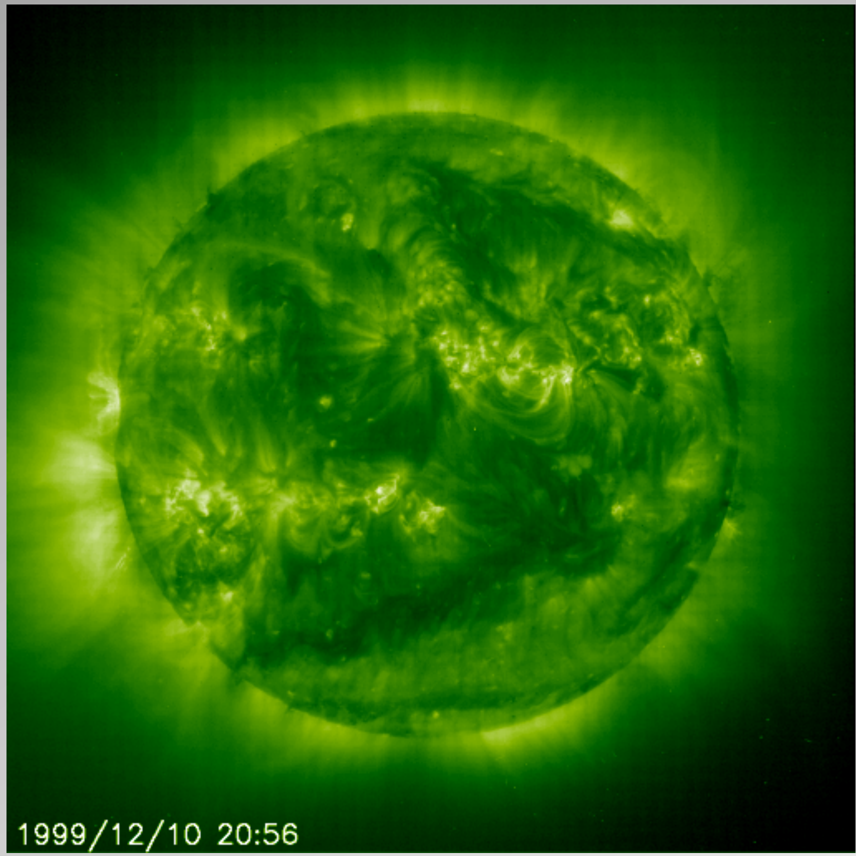
The corona at eclipse



What is the corona?

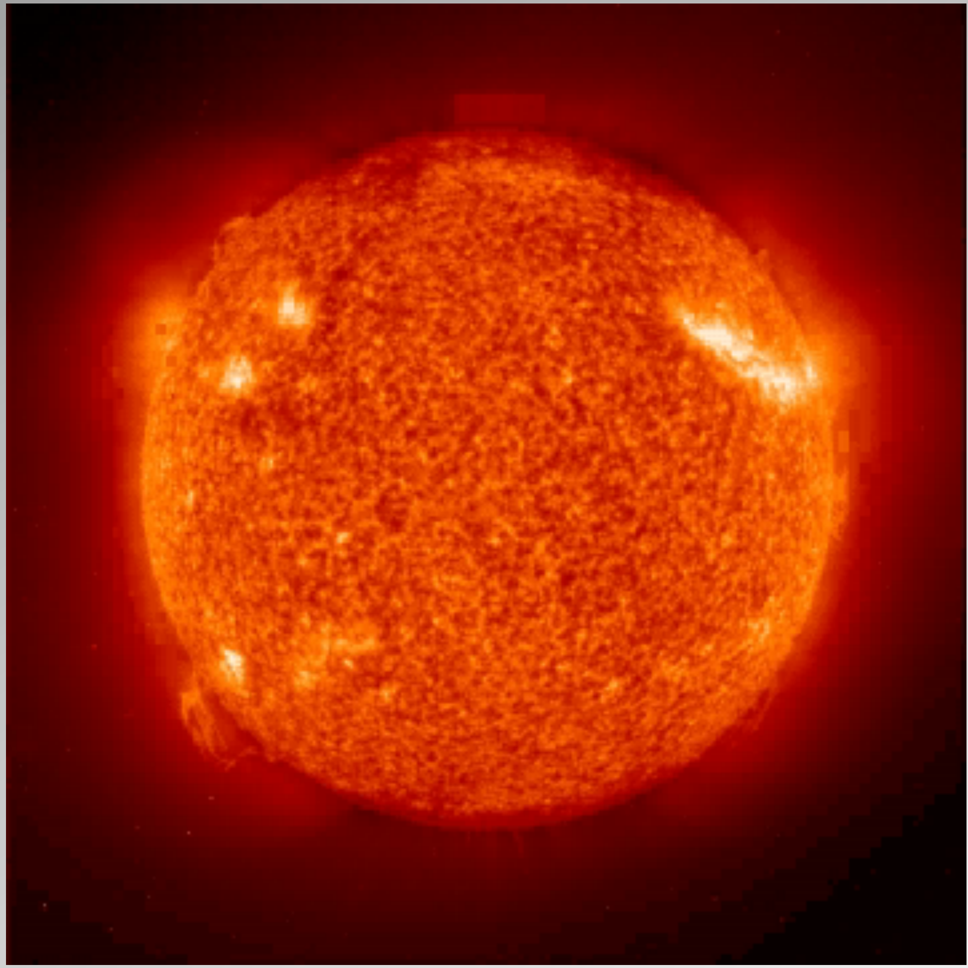
- The corona of the Sun is the upper, **hottest** and **magnetically dominated** part of the solar atmosphere.
- Physical processes in the corona affect the whole solar system and play a crucial role in **solar-terrestrial connections**, and consequently in geophysics.
- The solar corona is a natural **plasma laboratory**, where one can find and investigate the plasma in various conditions and configurations.
- Investigation of the corona is important not only for solar physics, geophysics and astrophysics but also for physics of laboratory plasmas.

Corona from space

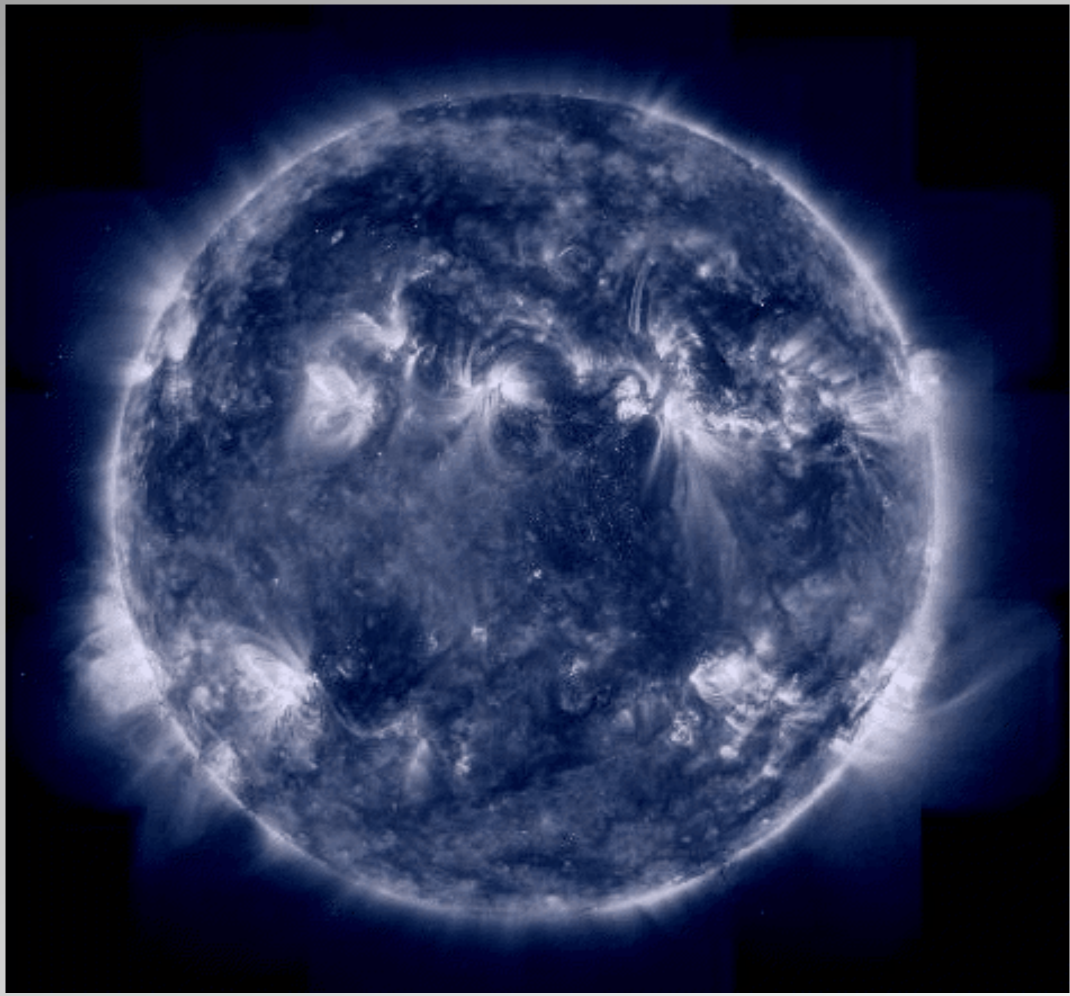


- **Early warning: very rich in structures!**

Corona from space

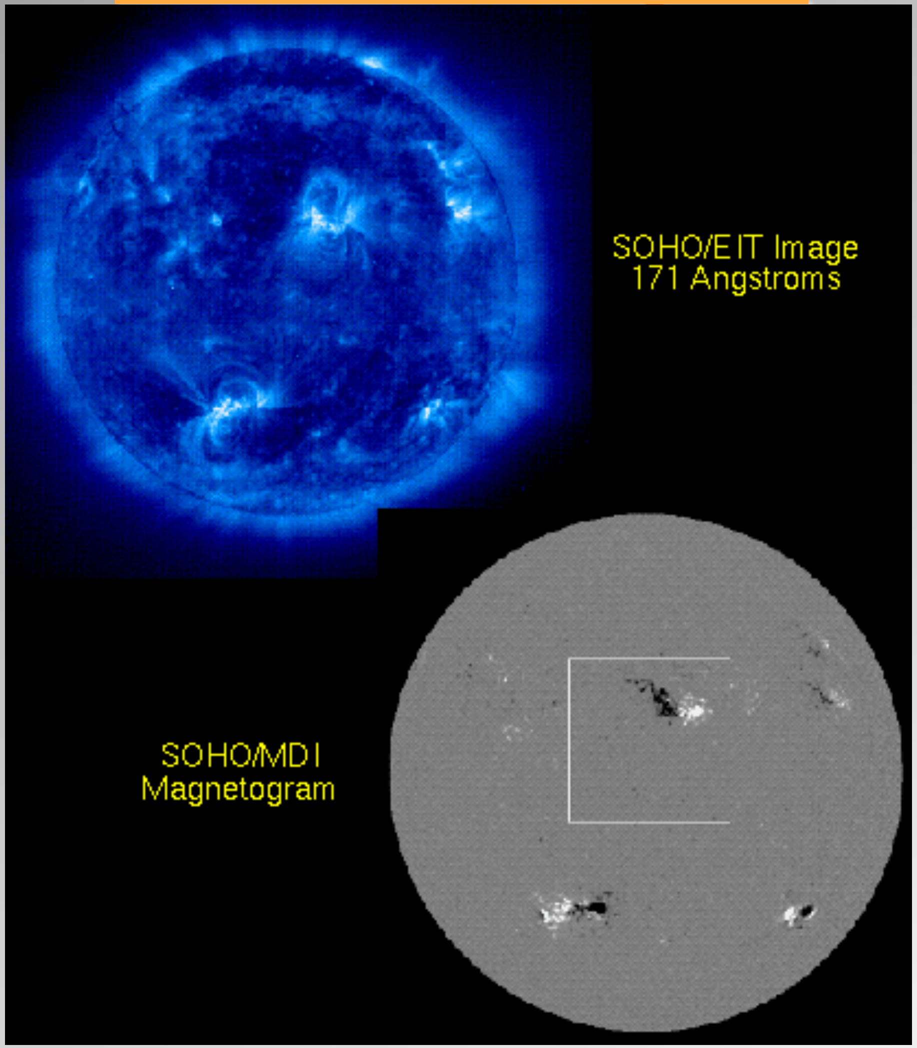


Corona from space



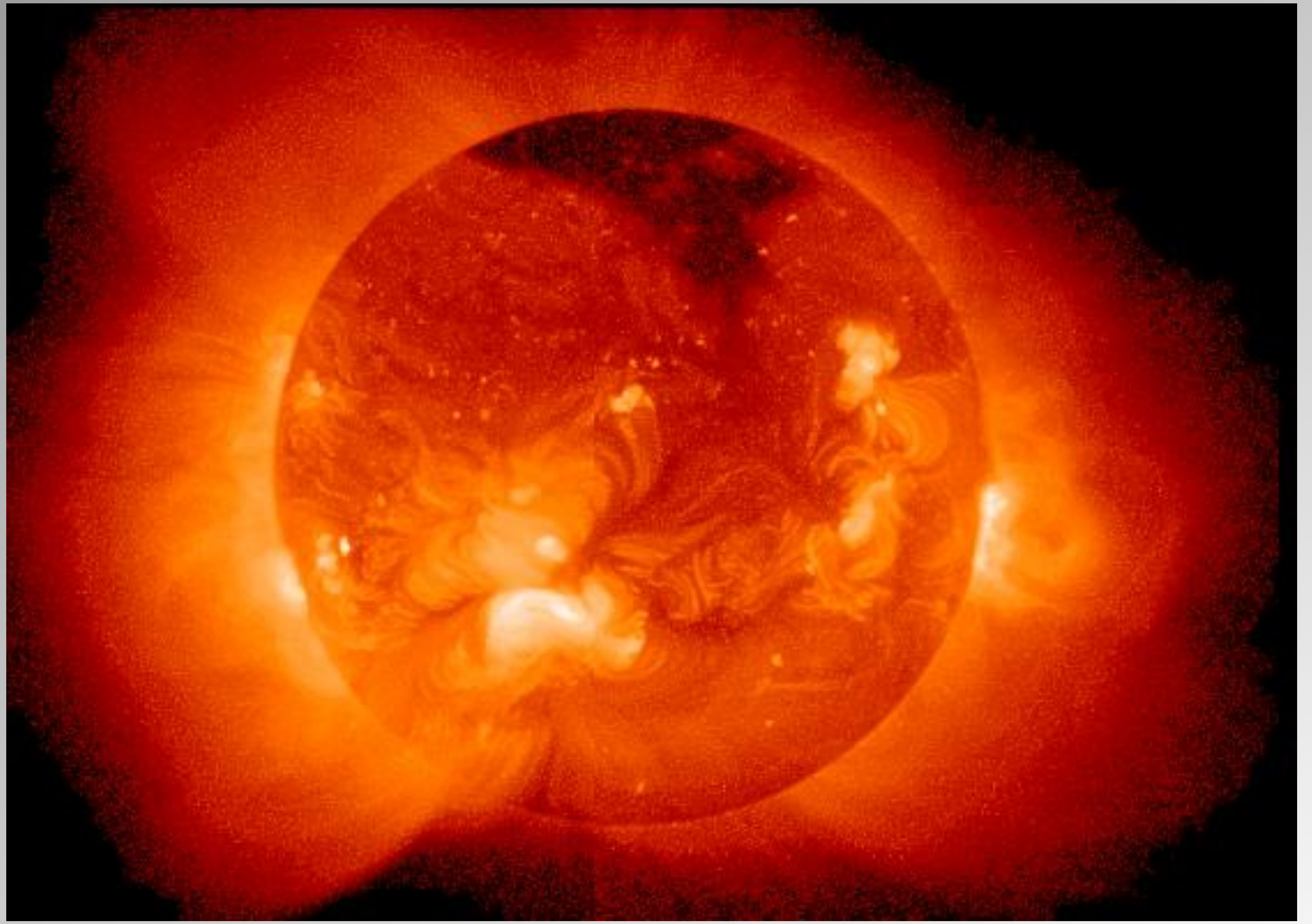
- TRACE Fe IX/X 171 Angstrom line

Corona from space



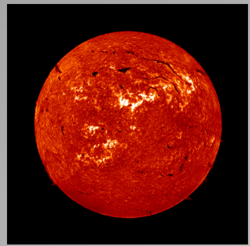
The X-ray corona

- An atmosphere of hot ionised gases
- Average temperature ≈ 2 million K!

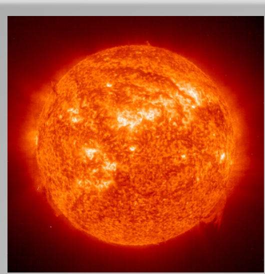


Solar interior - atmosphere

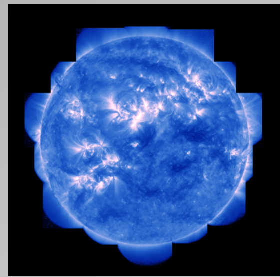
Hα
15,000 K



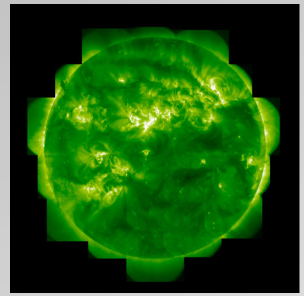
He EUV
50,000 K



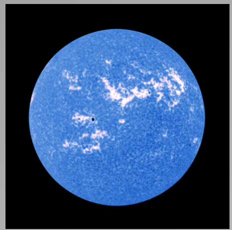
Fe VIII/IX EUV
1 MK



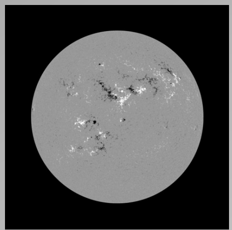
Fe XI
1.5 MK



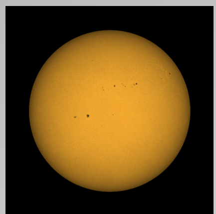
UV 1600 Å
8000 K

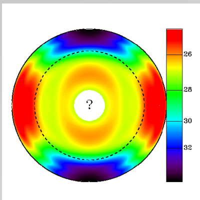


Magnetic field
5000 K

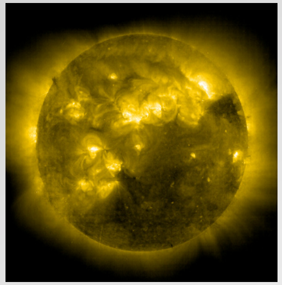


Visible
5000 K

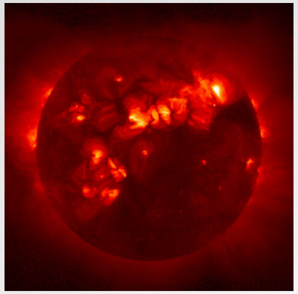




Fe XIV
3 MK

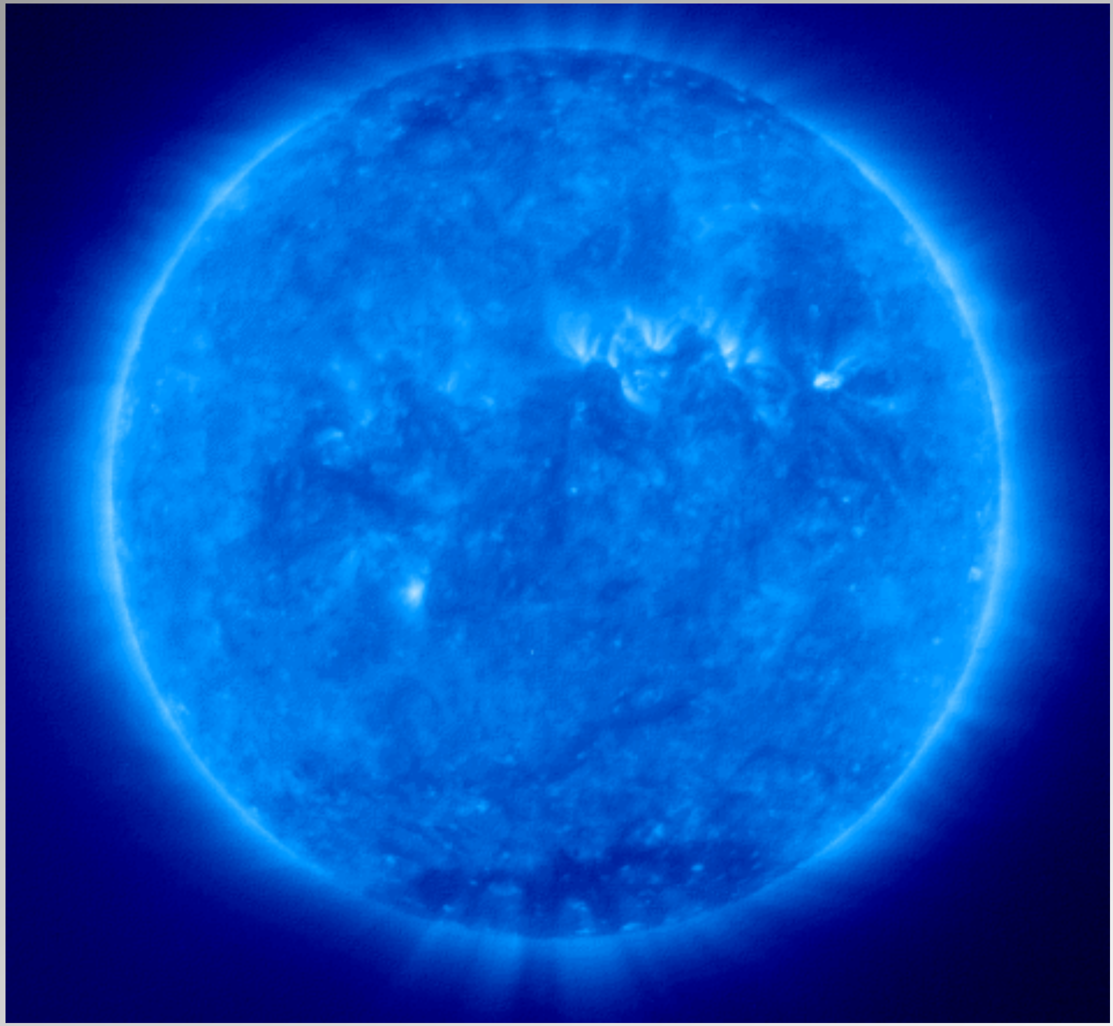


X rays
4-6 MK

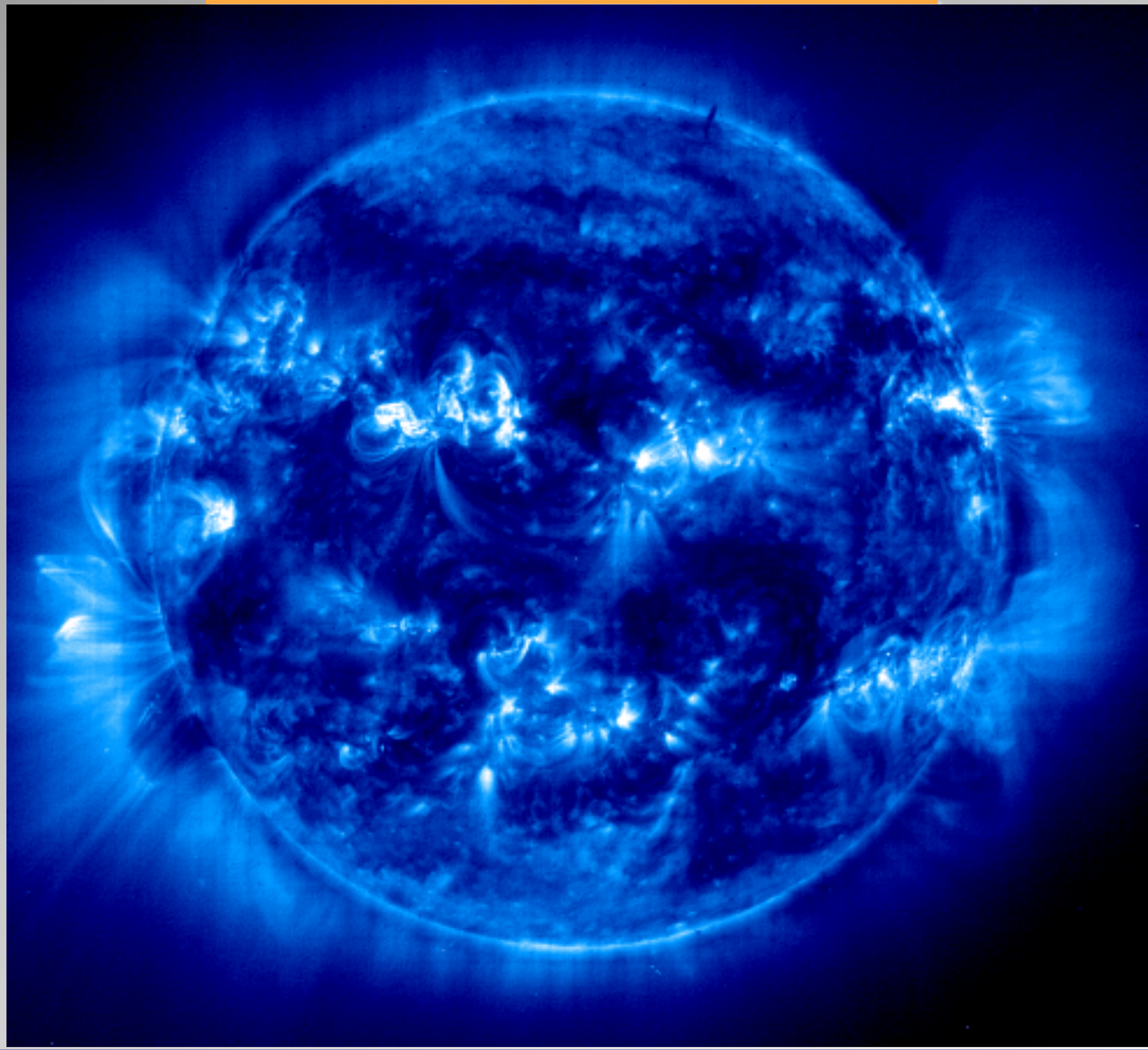


- Highly inhomogeneous
- Ubiquitous magnetic field

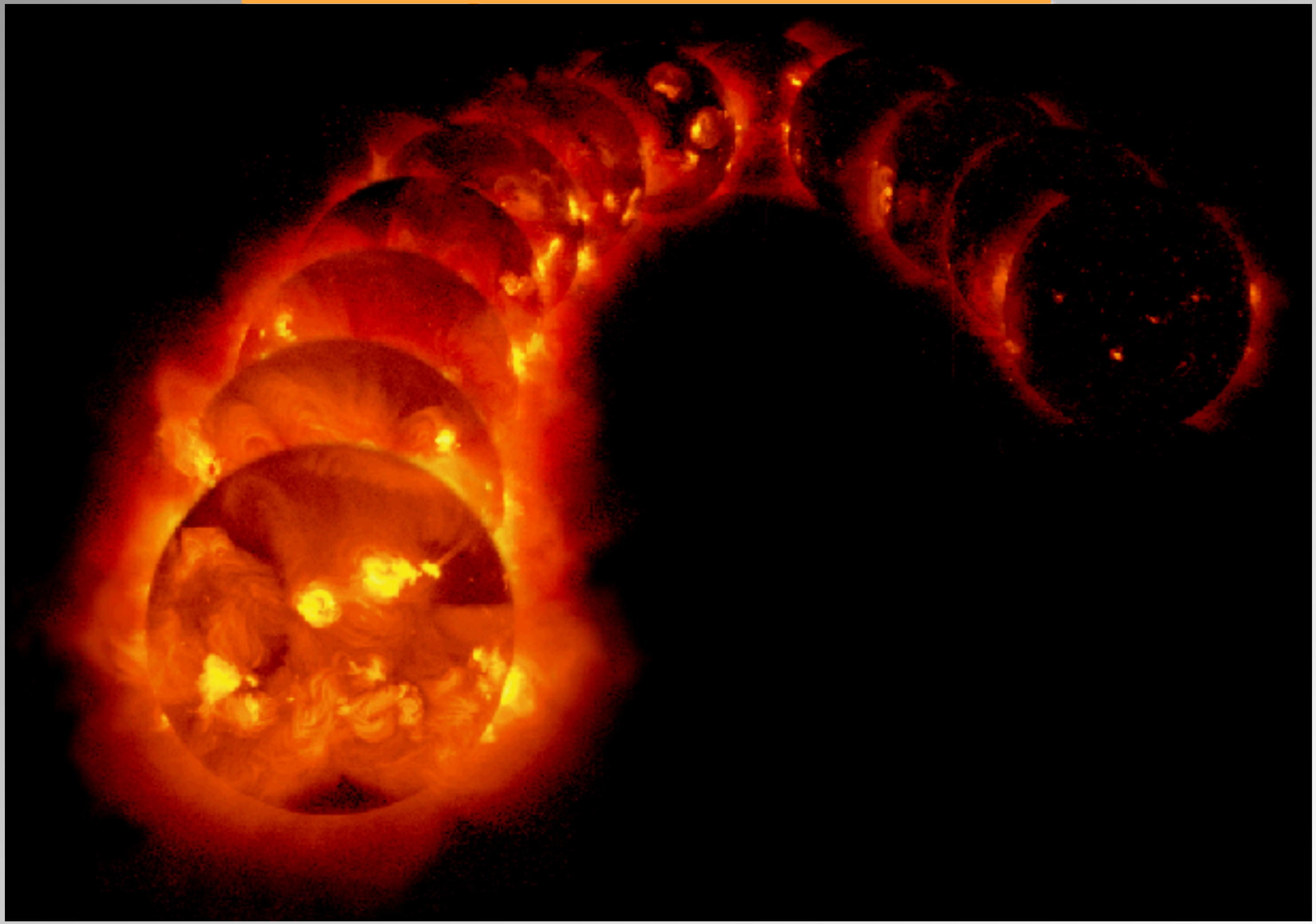
EUV corona in 1995



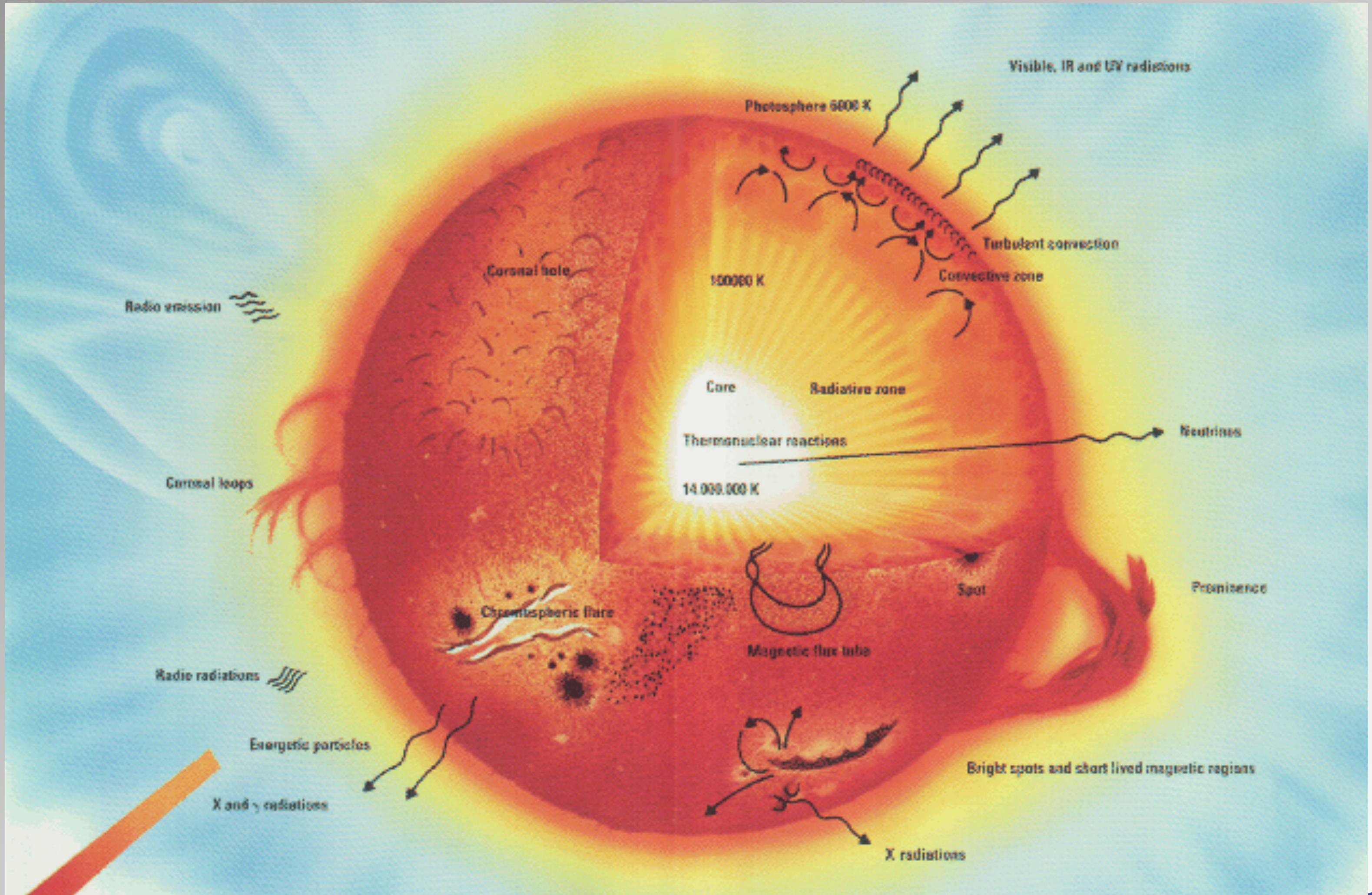
EUV corona in 2000



Solar cycle in the corona



Corona at my desk



Coronal structures

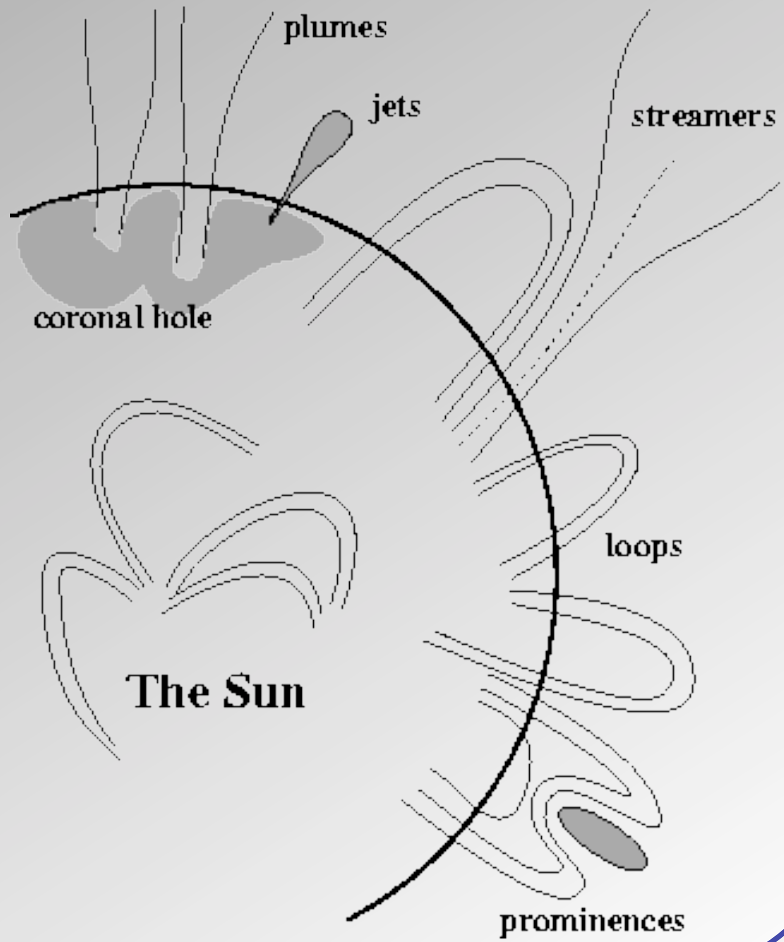
The corona is highly structured in magnetic field, in plasma density and in temperature.

There are two main classes of coronal structures:

• **Closed structures**: loops (R~100-200 Mm) which are hot (~ 2-3x10^6 K) and dense (up to 7x10^{15} m^{-3}). Life time: hours-days. However, loop ensembles called active regions (ARs) can live much longer.

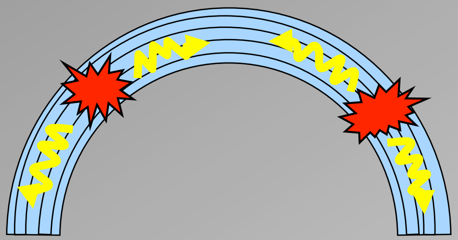
• **Open structures**: coronal holes, streamers, plumes inside the holes. Life time: days-weeks.

In addition, there are very dynamic plasma jets of various scales and speeds (erupting prominences, EEs, TRBs, etc.).

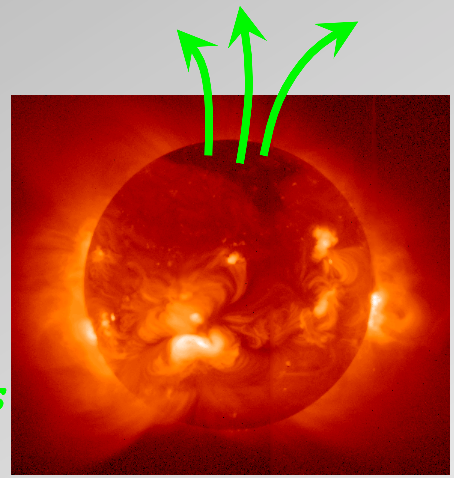


Coronal structures (ctd)

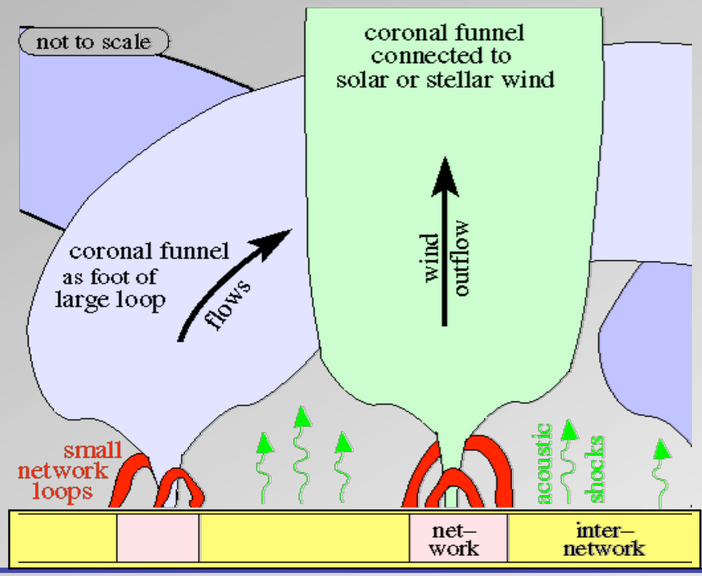
Magnetically closed regions:
network & active regions



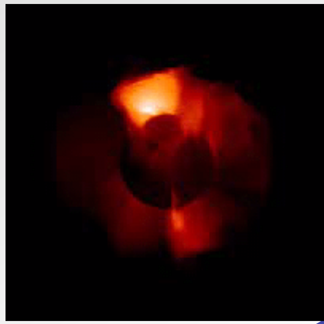
open regions:
coronal holes



"coexisting" open and closed regions



stellar coronae



Characteristics of corona

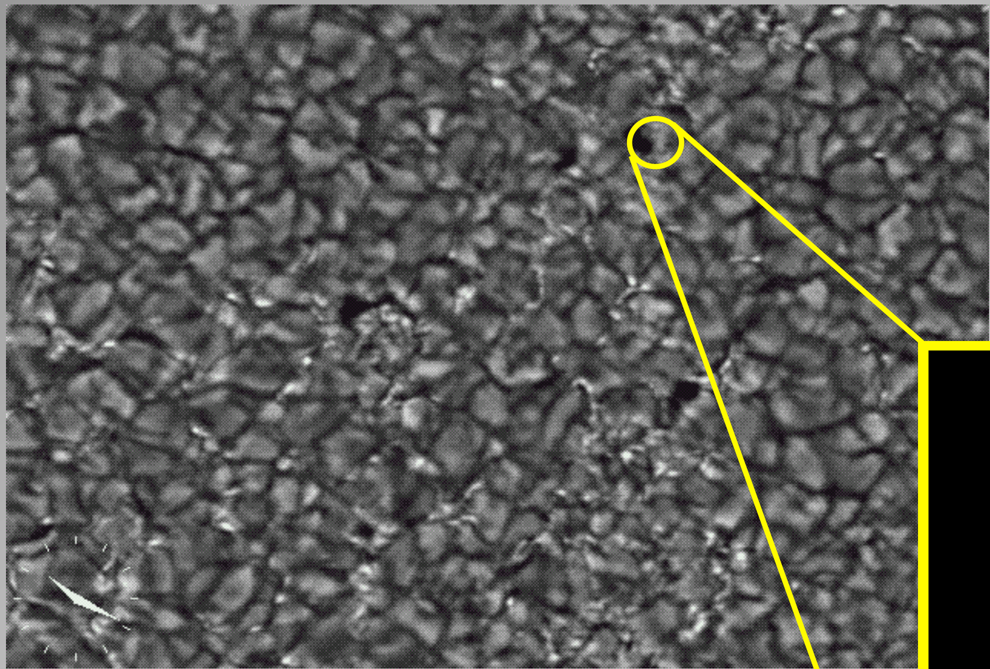
Fundamental puzzles of the corona:

- What mechanisms are responsible for heating of the corona up to several million K?

- What accelerates the solar wind up to measured speeds exceeding 700 km/s?

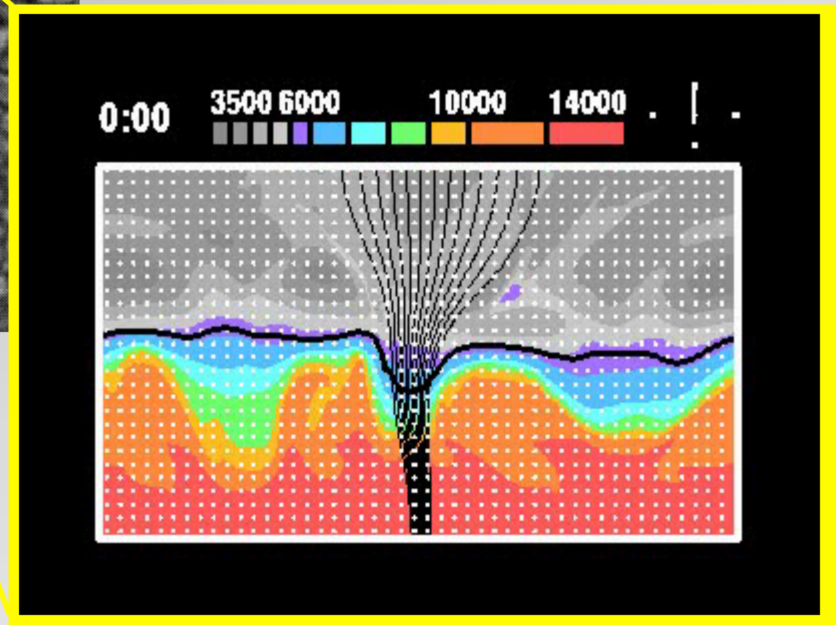
- What are the physical processes behind solar flares and coronal mass ejections (CME), magnificent phenomena accompanied by an enormous energy release? (The energy release can be up to 10^{33} erg).

Coronal structures: the underlying driver (ph)



Dutch Open Telescope, La Palma
12. Sept. 1999 [Sütterlin & Rutten]

2D-simulation of a flux tube embedded in photospheric granulation (radiation-MHD)
[Steiner et al. (1997) ApJ 495, 468]



≈ 25 000 km x 38 000 km

observation in G-Band ≈ 430 nm
granulation (Ø ≈1000 km)
G-band bright points:
small magnetic flux tubes, which are brighter than their surrounding

≈ 2400 km x 1400 km, ≈ 18 min

Potential and force-free fields

If magnetic field $\mathbf{B}=(B_x, B_y, B_z)$ is known as a fnc of position, then the field lines are defined by

$$\frac{dx}{B_x}=\frac{dy}{B_y}=\frac{dz}{B_z}=\frac{ds}{B}$$

In parametric form in terms of the parameter s, the field lines satisfy

$$\frac{dx}{ds}=\frac{B_x}{B}, \qquad \frac{dy}{ds}=\frac{B_y}{B}, \qquad \frac{dz}{ds}=\frac{B_z}{B},$$

where the parameter s is the distance along the field line.

Potential and force-free fields

Plasma-β

If characteristic length (L) << scale height (Λ) ➔ neglect gravity

$$0 = -\nabla p + \mathbf{j} \times \mathbf{B} \qquad \mathbf{j} = \frac{1}{\mu} \nabla \times \mathbf{B}$$

$$\nabla p \approx \frac{p}{L} \qquad \frac{1}{\mu} \nabla \times \mathbf{B} \times \mathbf{B} \approx \frac{B^2}{\mu L}$$

Ratio of pressure gradient and Lorenz force:

$$\beta := \frac{\text{gas pressure}}{\text{magnetic pressure}} = \frac{p}{B^2 / 2\mu}$$

Potential and force-free fields

Plasma-β

Can be evaluated by the formula

$$\beta = 3.5x10^{-21} nTB^{2}, \text{ where } n \text{ [m}^{3}\text{], } T \text{ [K], and } B \text{ [G].}$$

Solar corona:

Solar photospheric magnetic flux tubes:

Solar wind near Earth:

Potential and force-free fields

Force-free fields

If β<<1, gas pressure neglected w.r.t. magnetic pressure

$$0 \approx \mathbf{j} \times \mathbf{B}$$ Magnetic field called **force-free**

Potential force-free fields

Suppose **j**:=0

$$\mathbf{j} = \nabla \times \mathbf{B} = 0$$ Magnetic field called **potential**

Most general solution:

$$\mathbf{B} = \nabla\varphi, \text{ where } \varphi \text{ is the scalar magnetic potential}$$

Solenoidal condition ($\nabla \cdot \mathbf{B}=0$) has to be satisfied, i.e.

$$\nabla^2\varphi = \frac{\partial^2\varphi}{\partial x^2} + \frac{\partial^2\varphi}{\partial y^2} + \frac{\partial^2\varphi}{\partial z^2} = 0$$ Laplace equation

Potential and force-free fields

Potential fields

Solution: 2-dimensional plane [*xz*], method of separataion of variables φ:=*X(x)Y(y)*

$$X''Y + XY'' = 0$$

$$\frac{X''}{X} = -\frac{Y''}{Y} = -k^2 = \text{const}$$

$$X'' = -k^2 X \Rightarrow X(x) =$$

$$Y'' = k^2 Y \Rightarrow Y(y) =$$

Boundary conditions: $\varphi(x,0)=F(x)$, $\varphi(0,y)= \varphi(l,y)=0$, $\varphi \to 0$ as $y \to \infty$, giving

$b=d=0$ and $\sin kl = 0 \Rightarrow k = \frac{n\pi}{l}$

Potential and force-free fields

Potential fields

Full solution obtained by summing over all possible solutions. Let A_k=ac,

$$\varphi(x,y) = \sum_k A_k \sin kx \exp(-ky) \quad \text{where} \quad F(x) = \sum_k A_k \sin kx$$

Example

$$F(x) := \sin\frac{\pi x}{l} \Rightarrow A_1 = 1, A_n = 0, n \geq 2$$

$$\varphi(x,y) = \sin\frac{\pi x}{l} \exp(-\pi y / l)$$

$$\mathbf{B} = \nabla\varphi \qquad B_x = \frac{\partial\varphi}{\partial x} = B_0 \cos\frac{\pi x}{l} \exp(-\pi y / l),$$

$$B_y = \frac{\partial\varphi}{\partial y} = -B_0 \sin\frac{\pi x}{l} \exp(-\pi y / l)$$

Prominences/filaments

Filament support comes from the magnetic tension force in dipped magnetic fields or flux ropes. This opposes the downwards force of gravity.

In static equilibrium (neglecting pressure gradients and viscous terms), the force-balance equation is:

$$\rho\vec{g} + \frac{(\nabla\times\vec{B})\times\vec{B}}{\mu_o} = \rho\vec{g} - \nabla\left(\frac{B^2}{2\mu_o}\right) + \frac{(\vec{B}.\nabla)\vec{B}}{\mu_o} = 0$$

Magnetic pressure

Magnetic tension

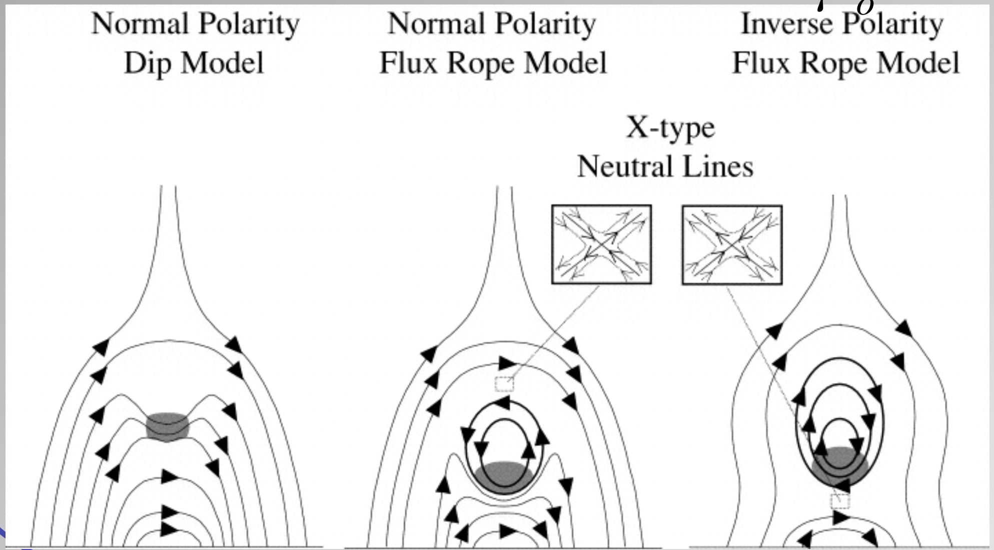


Image from Gilbert et al. 2001

These upward-curving field lines can be envisaged in a number of geometries.

Potential and force-free fields

Non-potential force-free fields

Suppose β<<1 and $L << \Lambda$ but $\boldsymbol{j}\neq 0$ from

$$0 \approx \mathbf{j} \times \mathbf{B} \Rightarrow \mu \mathbf{j} = \alpha \mathbf{B}$$ (current parallel to magnetic field)

$$\nabla \times \mathbf{B} = \alpha \mathbf{B}, \alpha = \alpha(\mathbf{r}, t)$$

Constrains on α

$$\underbrace{\nabla\cdot(\nabla\times\mathbf{B})}_{\text{identically}=0} = \nabla \cdot (\alpha \mathbf{B})$$

$$0 = \nabla \cdot (\alpha \mathbf{B}) = \alpha \underbrace{\nabla\cdot\mathbf{B}}_{0} + \mathbf{B} \cdot \nabla \alpha$$

$$\mathbf{B} \cdot \nabla \alpha = 0$$ (α=const along magnetic field lines!)

Potential and force-free fields

Non-potential force-free fields

- α:=0, force-free potential fields
- α:=const

$$\nabla \times (\nabla \times \mathbf{B}) = \nabla \times (\alpha \mathbf{B}) = \alpha \nabla \times \mathbf{B} = \alpha^2 \mathbf{B}$$

$$\nabla \times (\nabla \times \mathbf{B}) = \underbrace{\nabla(\nabla \cdot \mathbf{B})}_{=0} - \nabla^2 \mathbf{B} = -\nabla^2 \mathbf{B}$$

$$-\nabla^2 \mathbf{B} = \alpha^2 \mathbf{B}$$

Helmholtz equation

- α:=$\alpha(\mathbf{r})$

$$\nabla \times (\nabla \times \mathbf{B}) = \nabla \times (\alpha \mathbf{B}) = \alpha \nabla \times \mathbf{B} + \nabla \alpha \times \mathbf{B} = \alpha^2 \mathbf{B} + \nabla \alpha \times \mathbf{B}$$

$$\nabla \times (\nabla \times \mathbf{B}) = -\nabla^2 \mathbf{B}$$

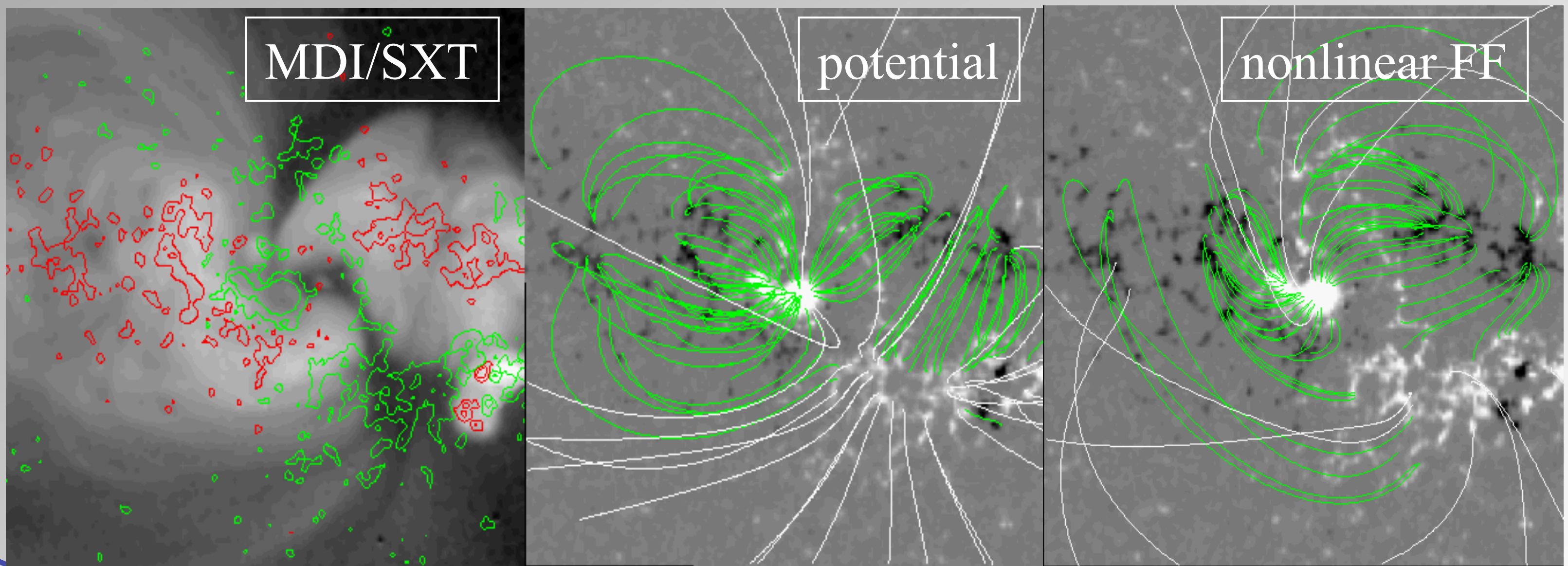
$$\alpha^2 \mathbf{B} + \nabla^2 \mathbf{B} = \mathbf{B} \times \nabla \alpha \qquad [\mathbf{B} \cdot \nabla \alpha = 0]$$

Photospheric magnetic fields

Force-free and non-force-free fields

From the same photospheric field distributions, one can extrapolate the coronal magnetic field (by solving $\nabla.B=0$ and $\nabla\times B=\alpha B$, with appropriate upper boundary conditions)

The extra energy stored in non-potential fields is exhibited as 'twist'. It is this excess of energy which can be released in the form of a solar flare or coronal mass ejection.



Equilibrium of coronal loops

The magnetic field has a lowest energy or 'potential' state, which is completely untwisted.

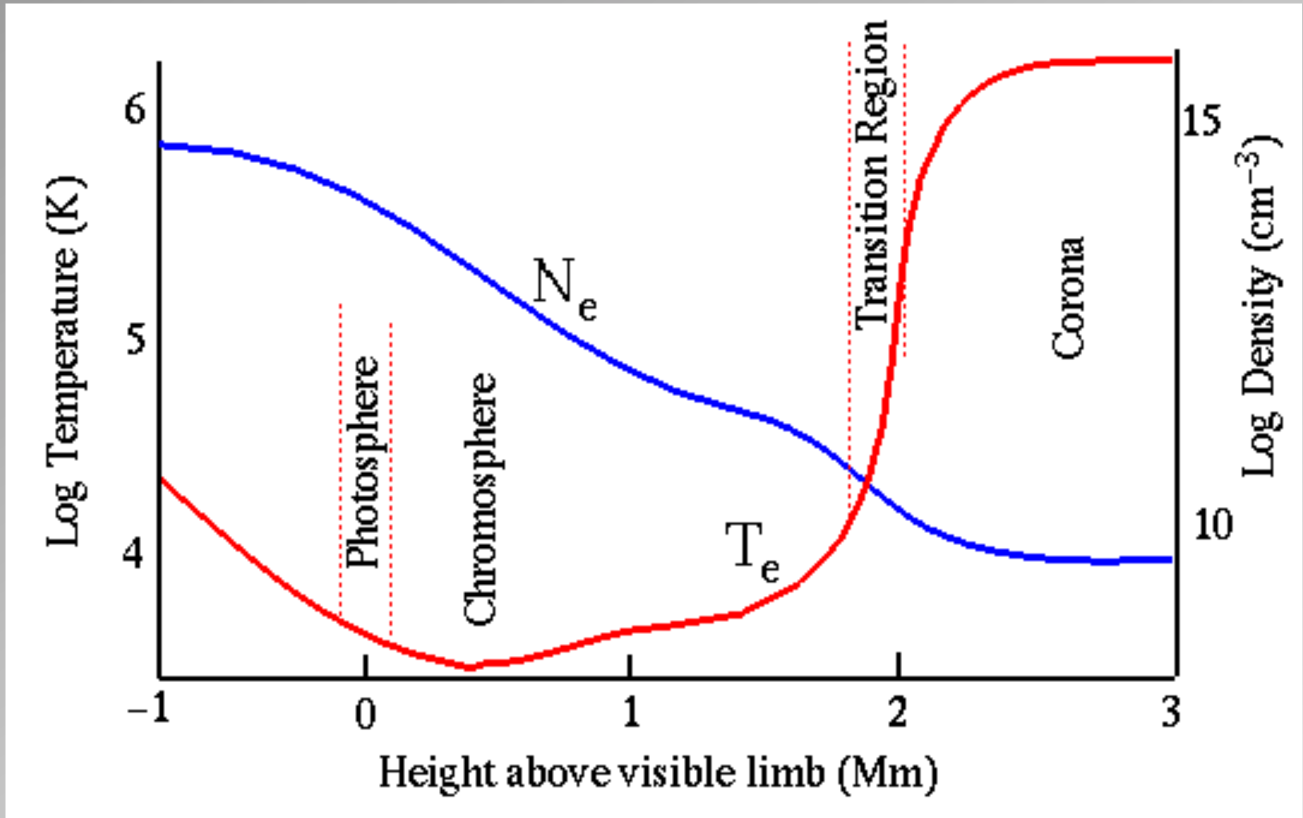
$$\nabla \times B = \mu_o j = 0$$

In general, a force-free magnetic field can carry field-aligned currents, which correspond to twisting up (putting energy into) the field. Generally we have

$$\nabla \times \vec{B} = \alpha(x, y)\vec{B}$$

$\alpha = 0$:	potential field. There are no currents
$\alpha =$ const:	linear force-free field. $j = \alpha B$
$\alpha \neq$ const:	non-linear FFF

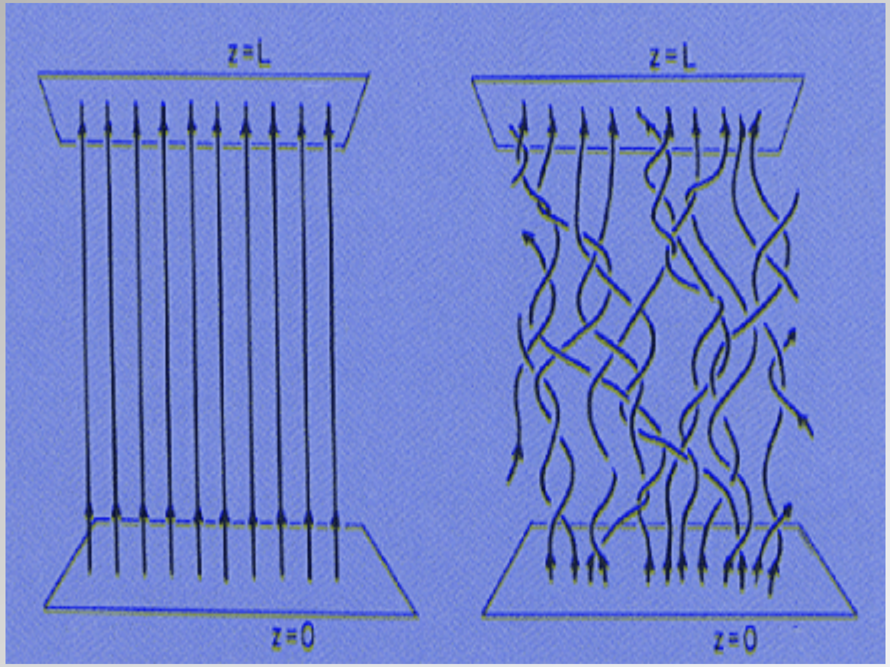
Coronal temperatures



- Extra energy reservoir required in the corona
- Magnetic field with turbulent photosphere likely source

Thermodynamics of coronal loops

Parker, 1988



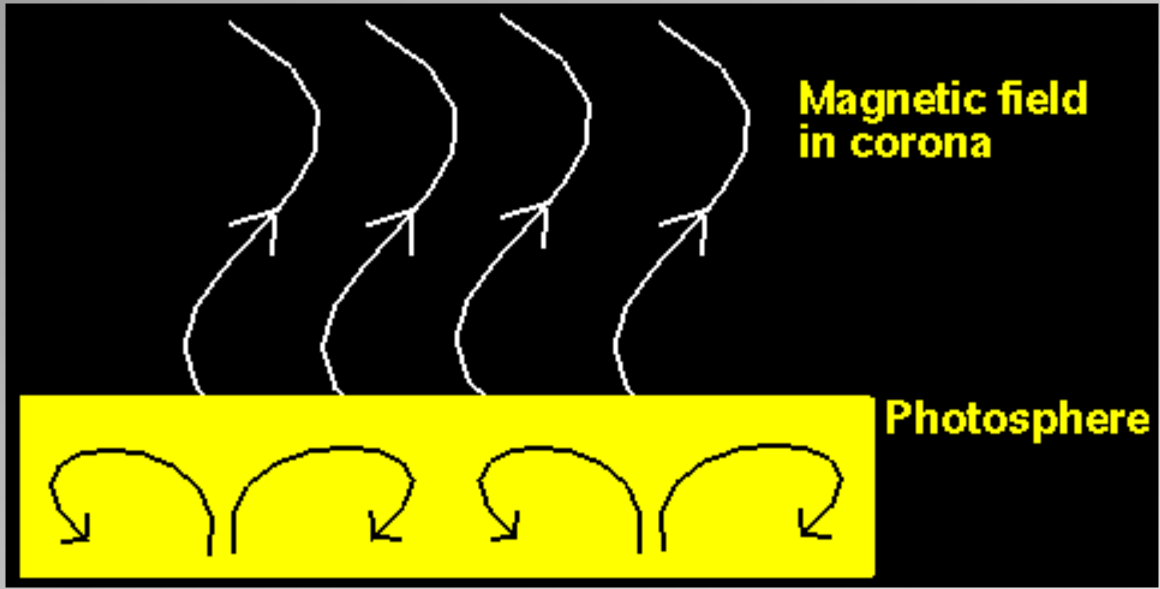
Suggested that the corona is heated by numerous small localised events called Nanoflares = 10^{24} erg

(10^{33} erg solar flare)

Footpoints of the coronal field experience random and continuous shuffling.

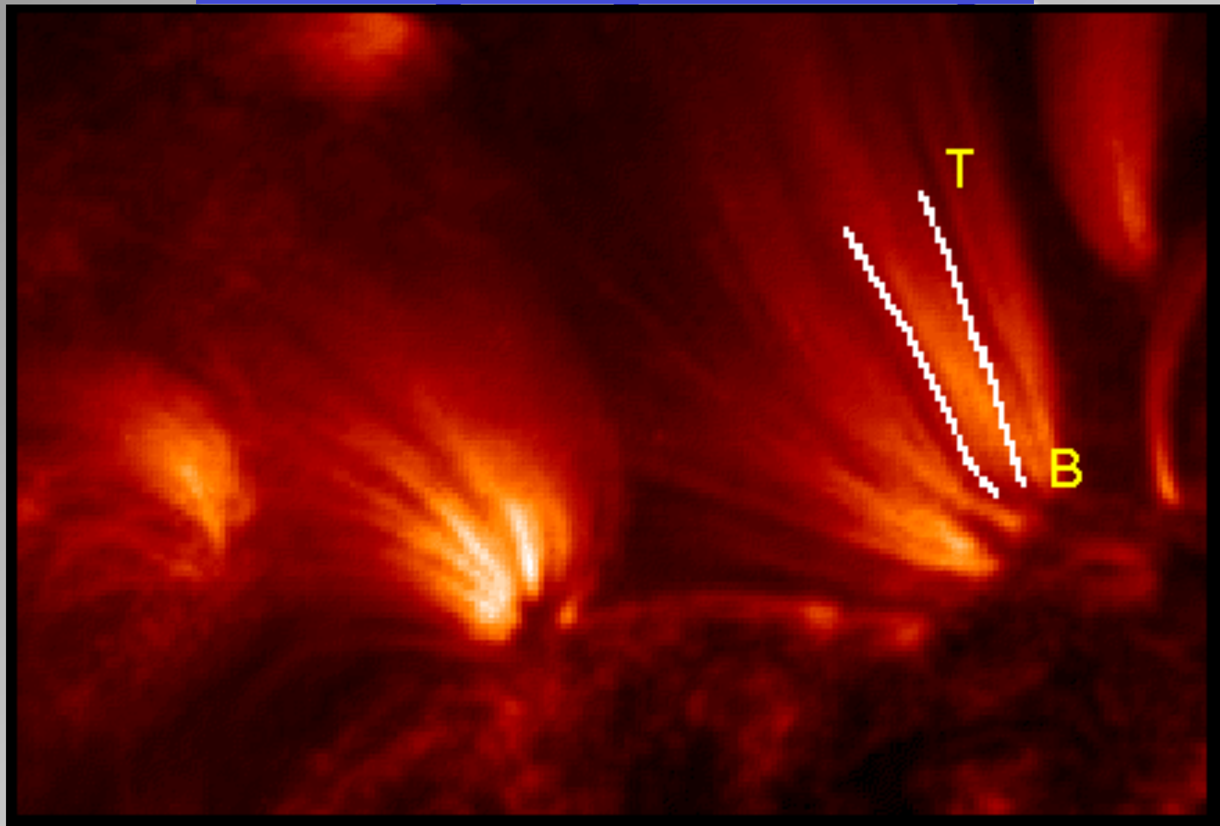
Magnetic Reconnection

Solar waves



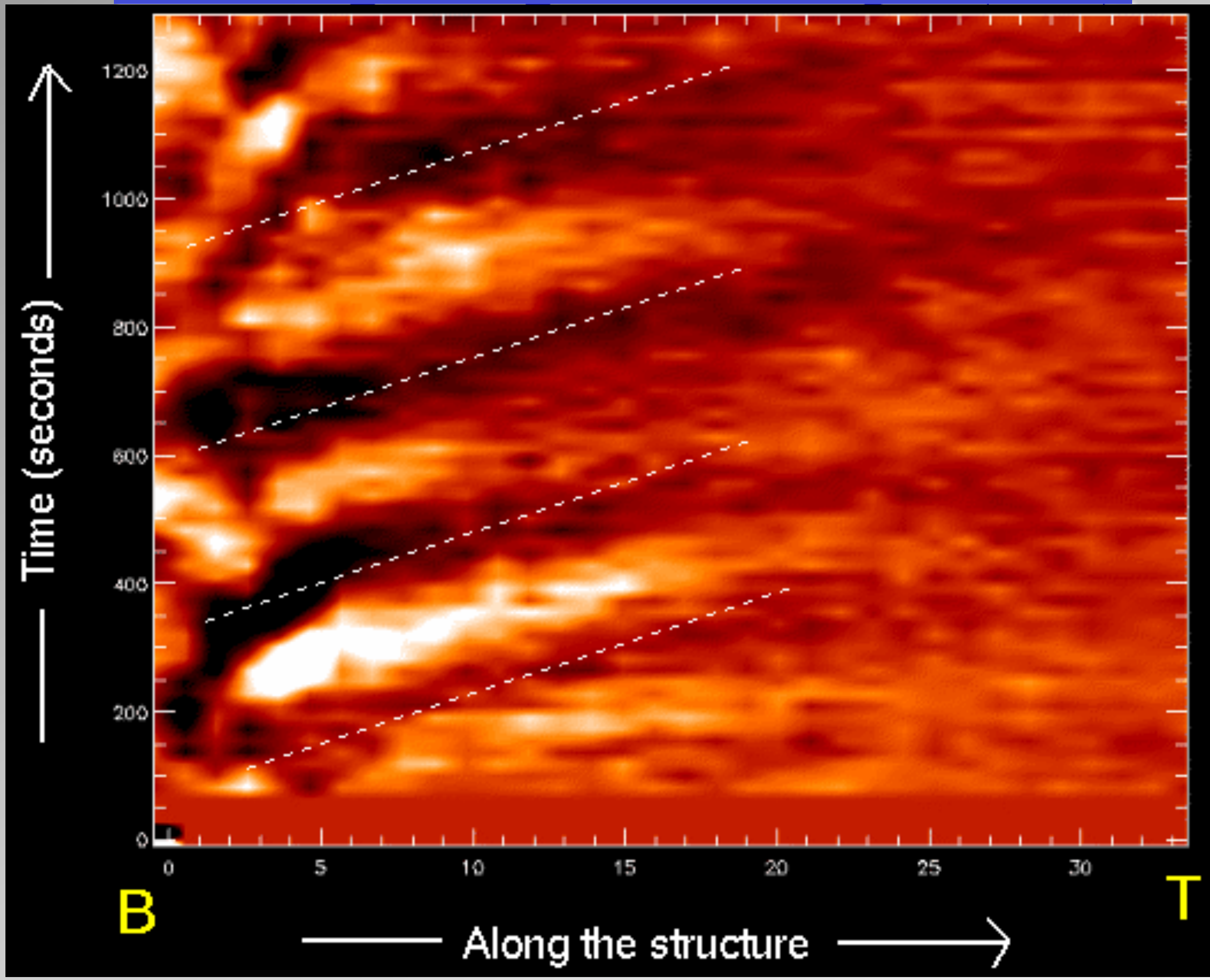
- Corona has *frozen in field condition*
- Magnetic field rooted into turbulent photosphere
- Generates "waves" that dump energy in corona
- (Slow) Magneto-acoustic waves

Surfing magnetic loops



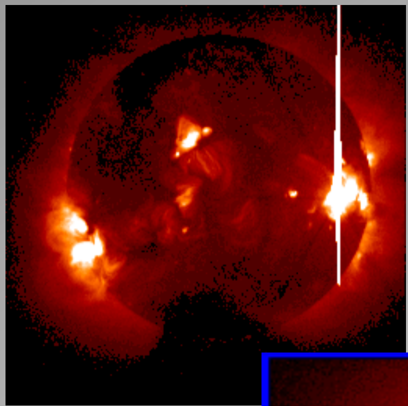
- Rapid (every 15 s) TRACE 171 Angstrom image
- Track changes in brightness
- Wave travels outwards from B to T

Surfing magnetic loops (ctd)

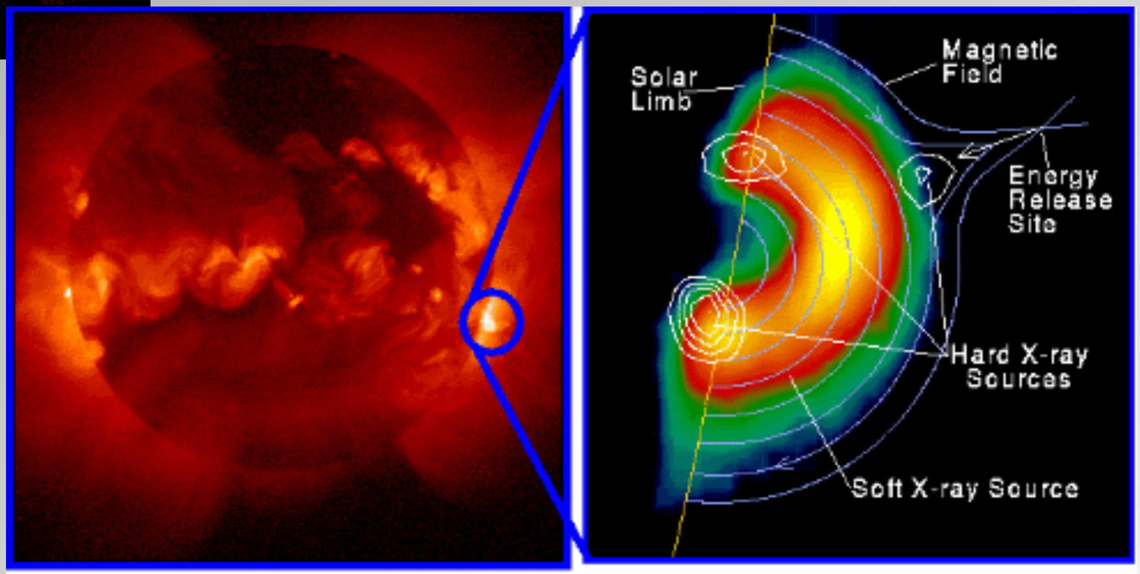


• Difference image in brightness out from the loop base

Solar flares

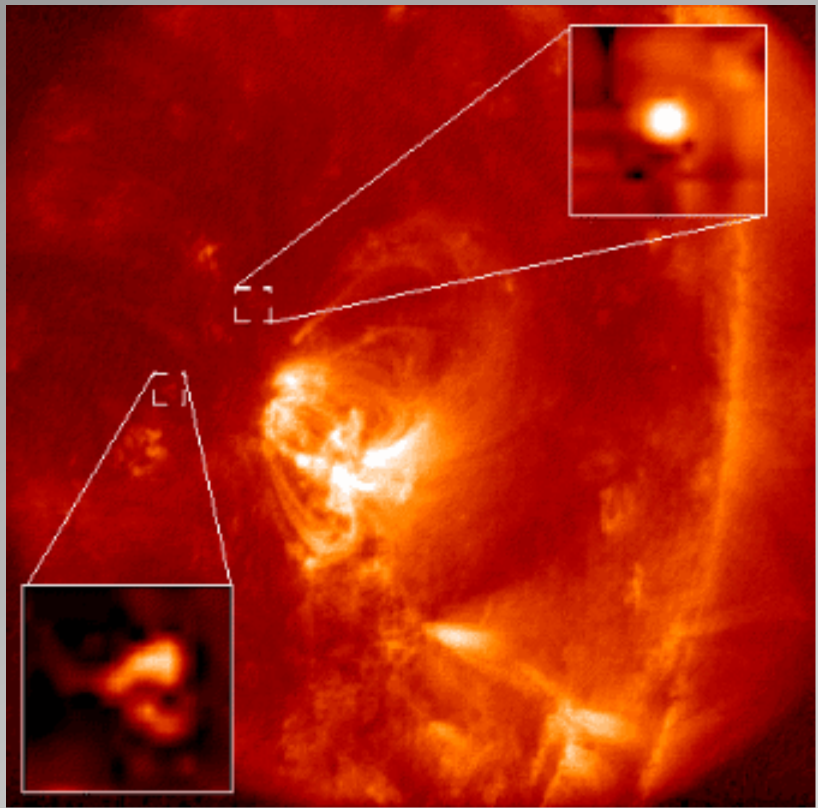


- Most violent explosions in the solar system
- 10^{32} ergs = 5000 atom bombs!



Yohkoh X-ray Image of a Solar Flare, Combined Image in Soft X-rays (left) and Soft X-rays with Hard X-ray Contours (right). Jan 13, 1992.

Nanoflares

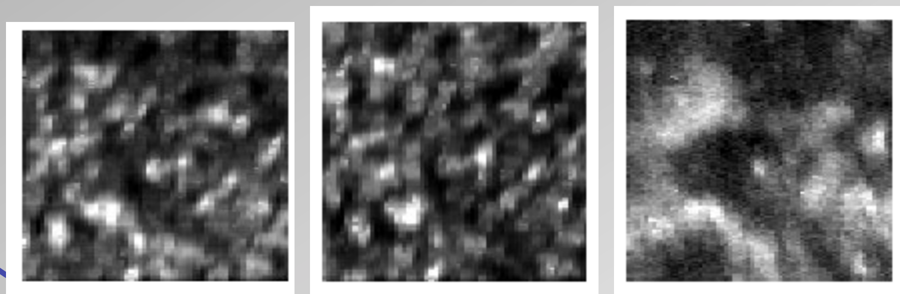


- Much smaller energy release
- At detection limit
- Cumulative effect to heat corona

Transition region blinkers (TRBs)

Observational Characteristics

- Small bright intensity enhancements in the *STR*
- Emission lines: He I, O III, O IV, OV, Mg IX
- Mean lifetime: 16 min.
- Intensity enhancement ratios are around 1.8
- Mean area is around 2.9 x 10^7 km^2
- Temperature remains constant (10^5 – 10^6 K)
- Associated velocity is negligible



He I (left), O V (middle) and Mg IX (right) supergranular network images (**SOHO**/**CDS** NIS raster)

Instrumental Tools

SOHO

Coronal Diagnostic Spectrometer (CDS)

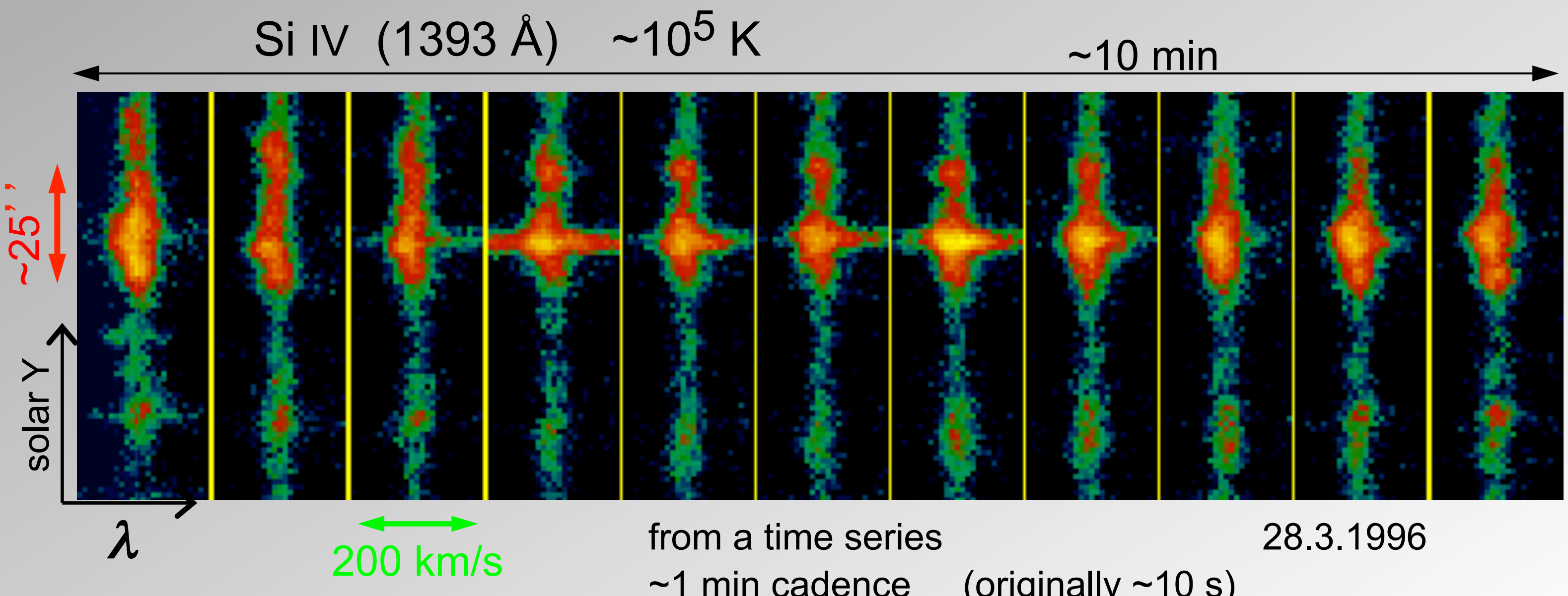
Pixel spatial resolution: 1.7" x 4.0"

Rastered slit exposure time: 10 sec.

Wavelength region: 151 – 785 A

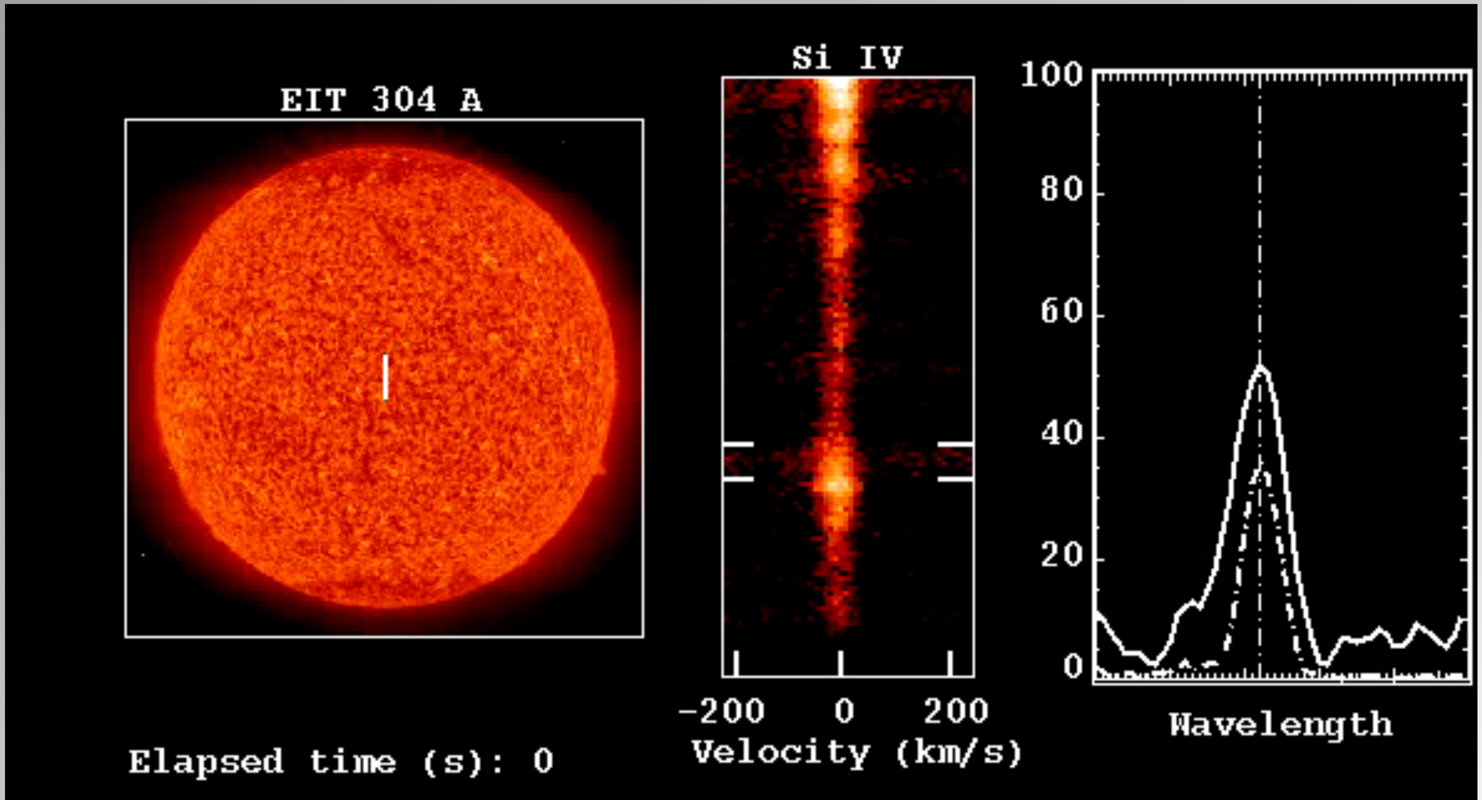
Explosive events

- transient broadening of TR emission lines, sometimes distinct emisison peaks visible
  (e.g. Dere et al.,1989; Perez, Erdélyi,Doyle, 1998)
- interpreted as bi-directional jets after reconnection
  (e.g. Innes et al., 1997; Roussev et al., 2001a,b,c)
- radiated energy might be / is small compared to what is needed to heat the corona
- BUT: conversion of magnetic energy into waves ?!
  new models of reconnection are needed !

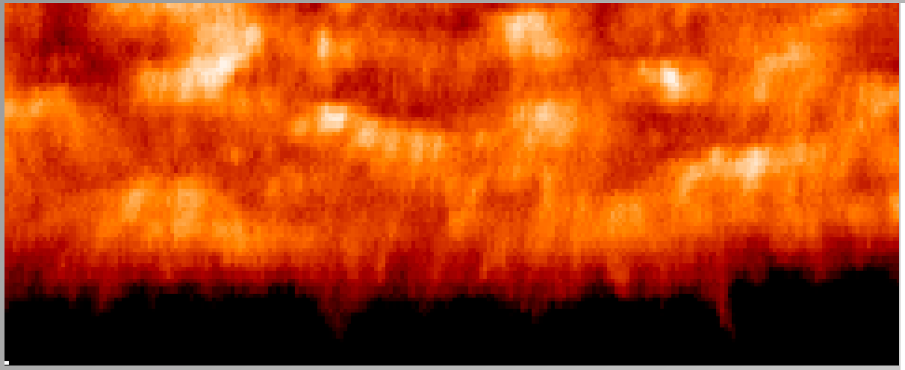


from a time series
~1 min cadence (originally ~10 s)
28.3.1996

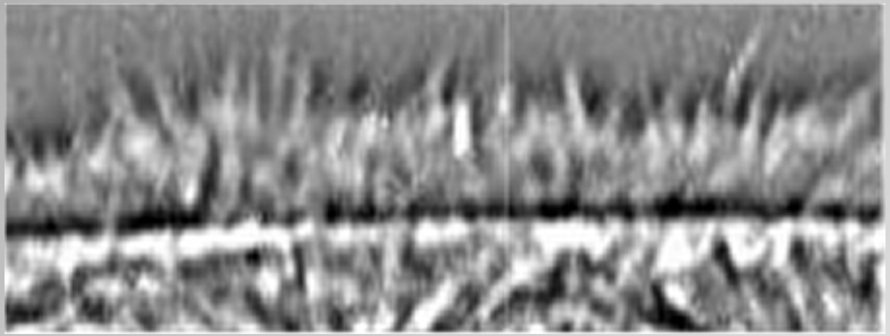
Explosive events



Solar spicules (tornadoes)



SOHO Image of the Solar limb taken March '96



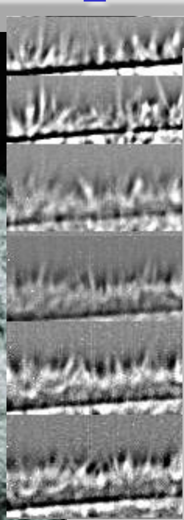
Hα Image from the Big Bear Solar Observatory, California

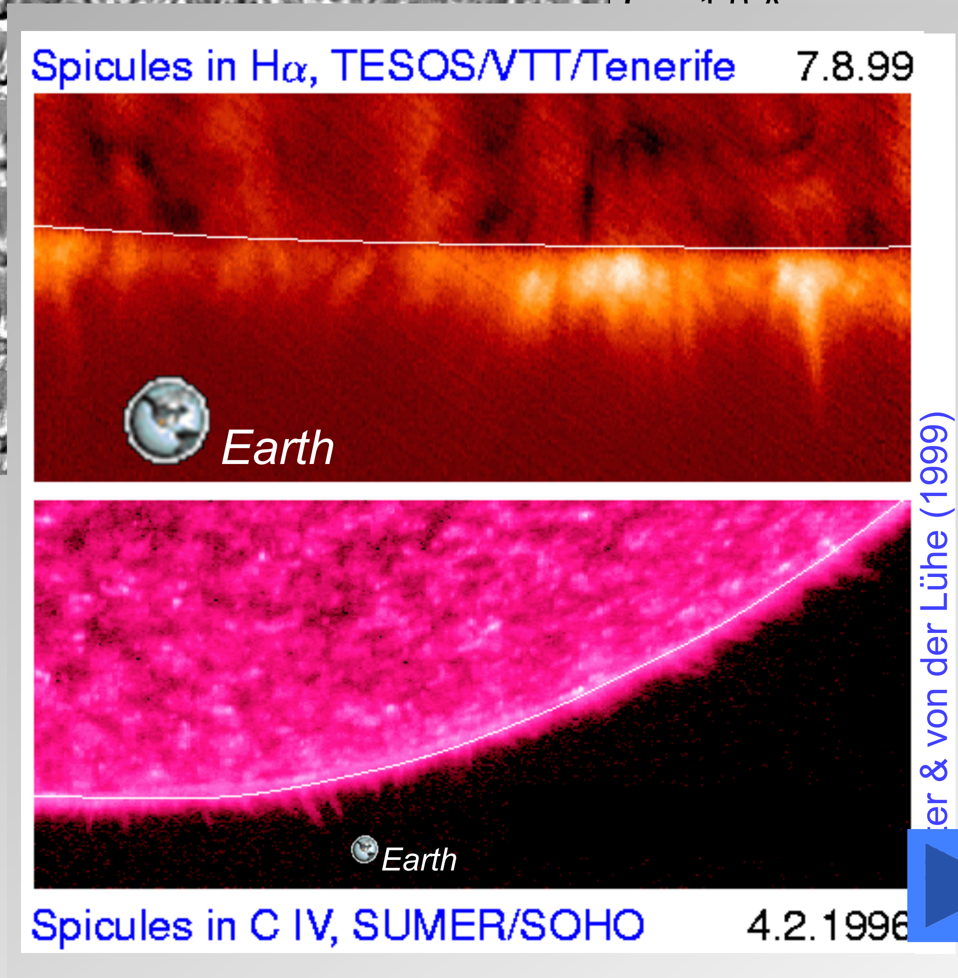
- Solar spicules are thin, hair-like jets of gas seen on the solar limb in chromospheric emission lines
- They occur predominantly at supergranule boundaries and appear to be guided along the intense magnetic flux tubes gathered there
- Typical properties are:

Width	200-1000km
Height	5000-10000km
Lifetime	5-15mins
Axial Velocity	$20 kms^{-1}$
Temperature	5000-15000K
Density	0.5-$2.5 kgm^{-3}$

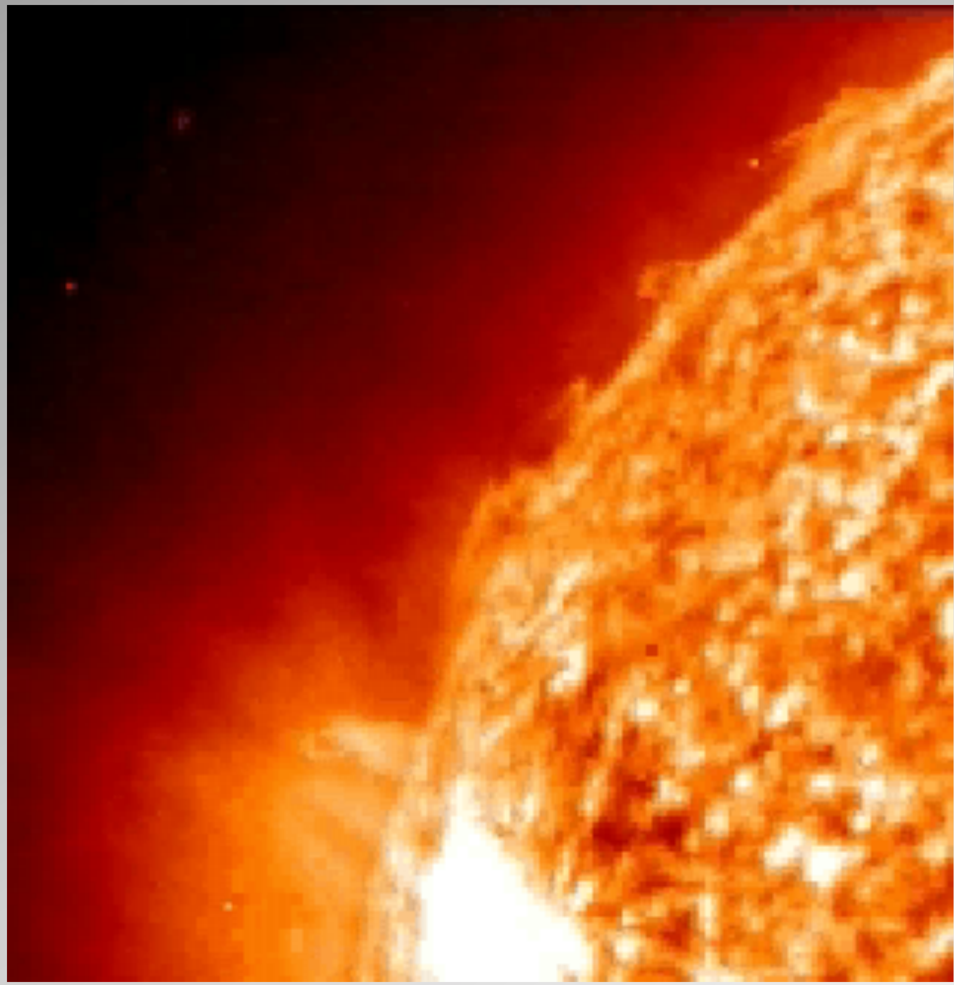
- Some spicules display rapid rotation about their axis, typically of the order of $25 km\ s^{-1}$
- The spicule rise is probably not ballistic, although the evidence for this is not conclusive

Solar spicules (tornadoes)

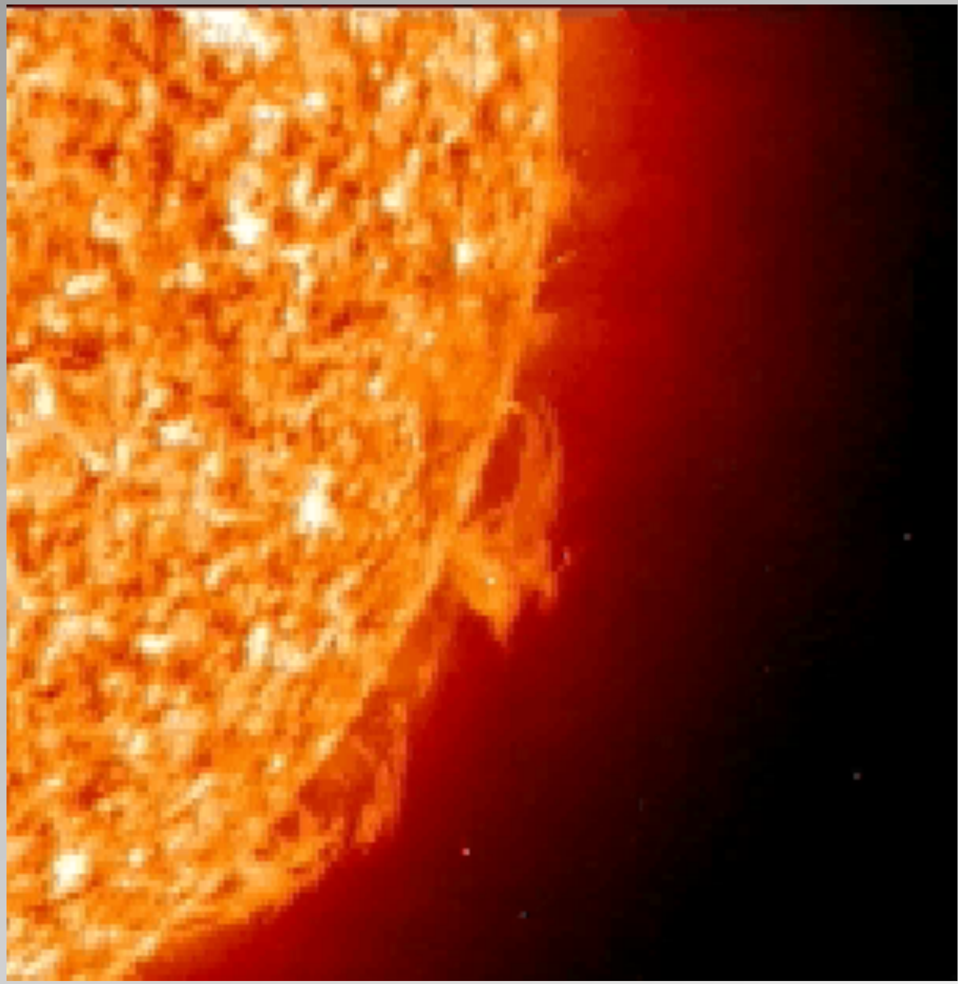




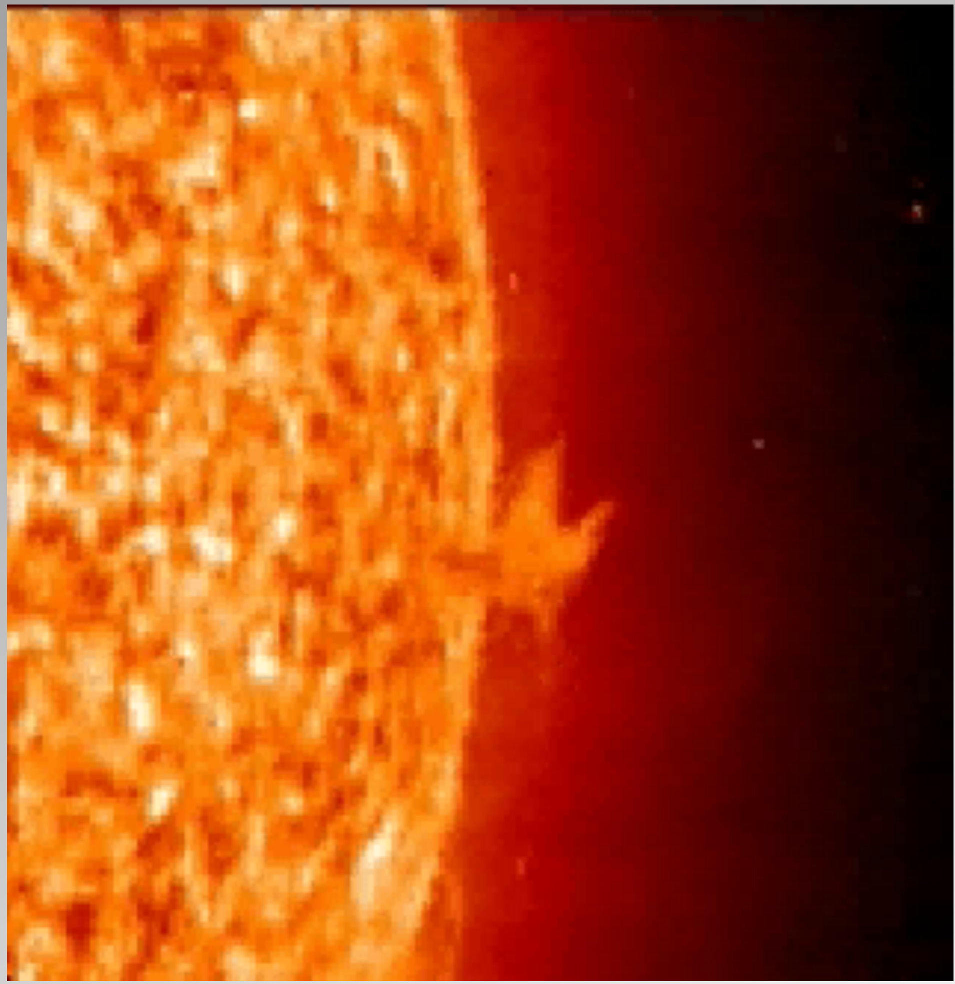
Solar spicules (tornadoes)



Solar spicules (tornadoes)

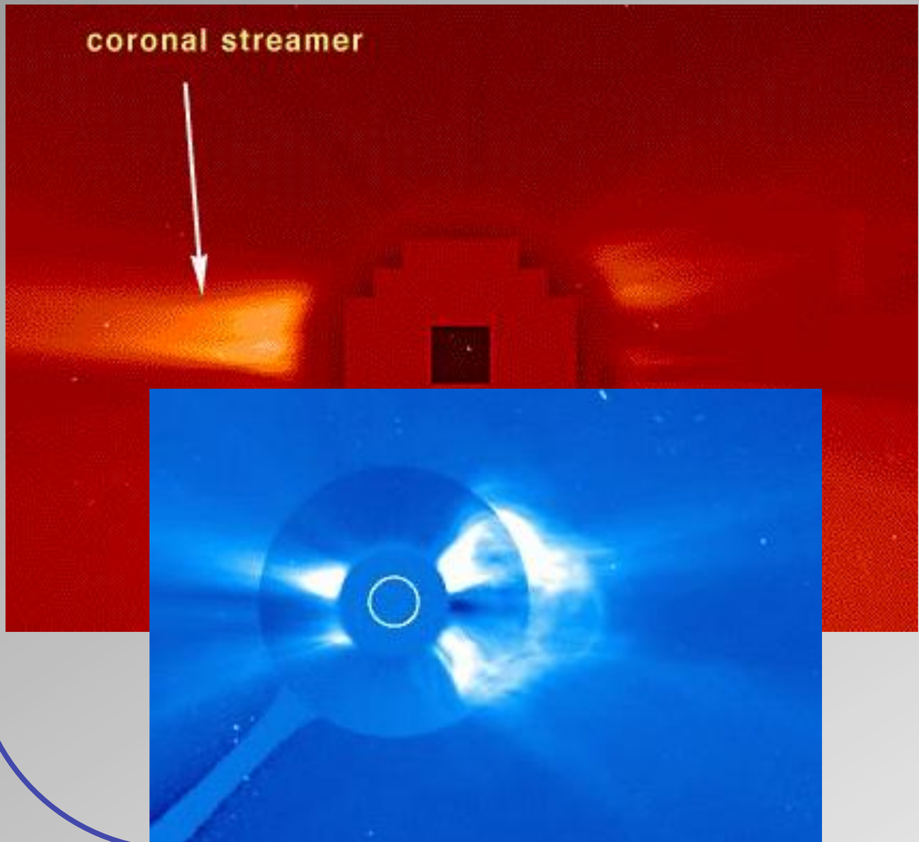


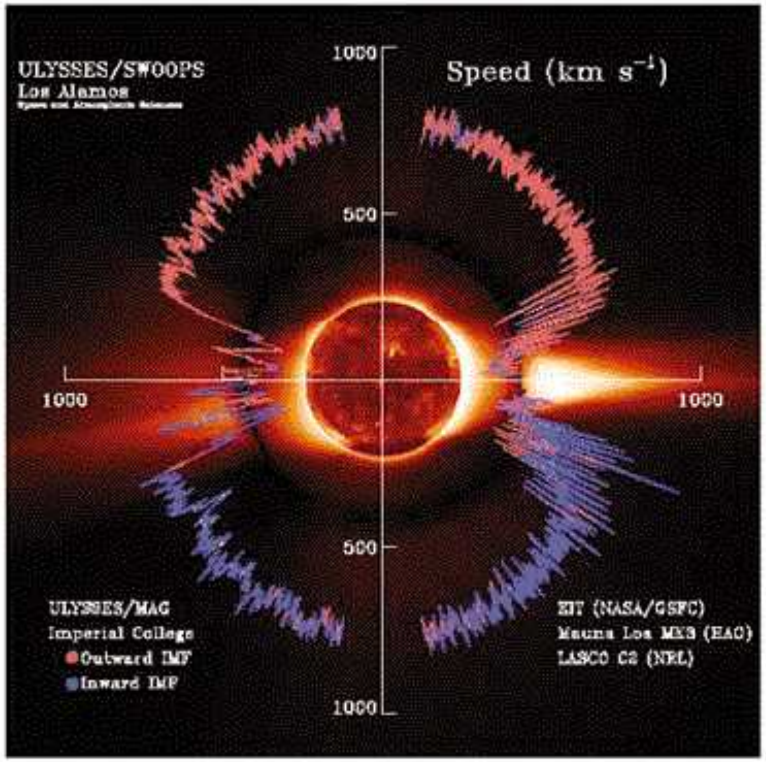
Solar spicules (tornadoes)



Expanding corona

Parker's solar wind



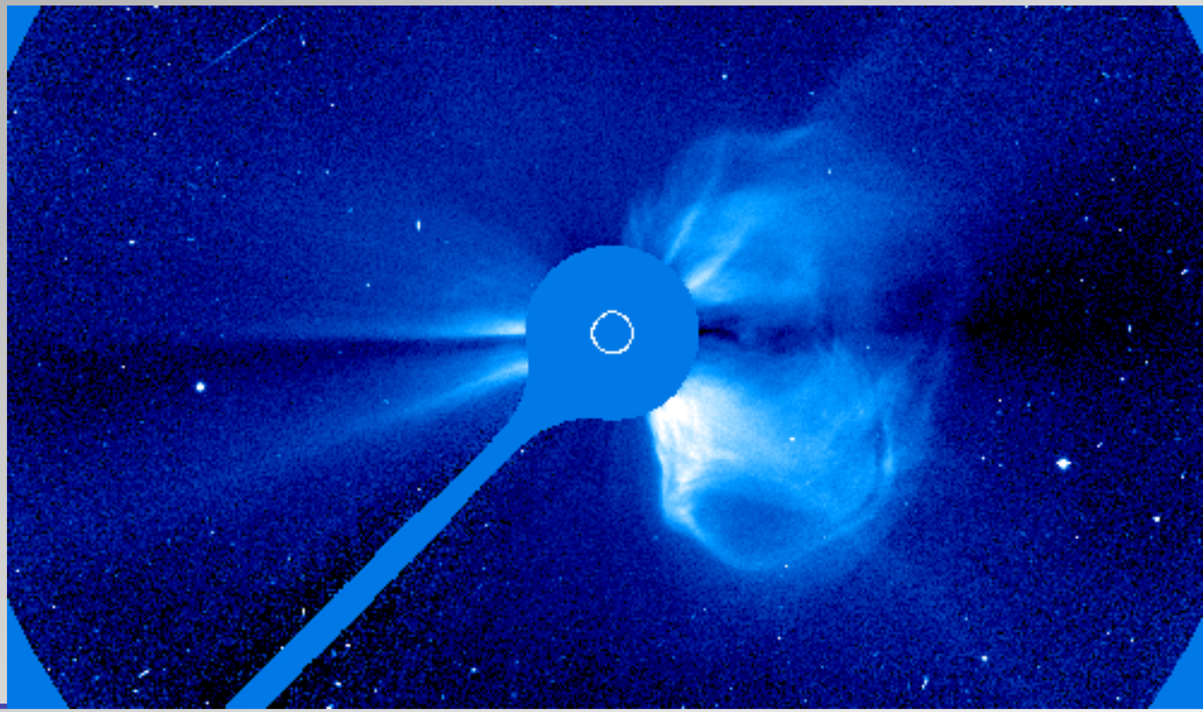


McComas, D.J., et al., Geophys. Res. Lett., 25, 1-4, 1998

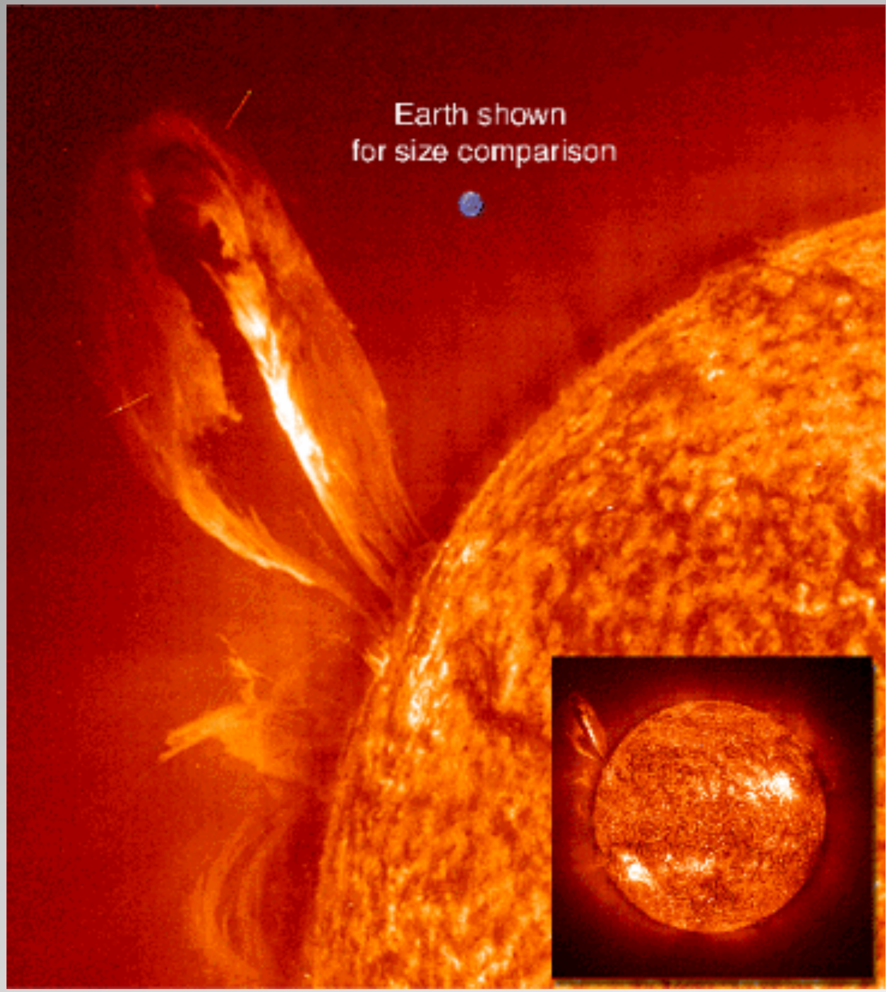
Expanding corona: solar storms

Coronal mass Ejections

- 100 to 1000 km/s
- 1 to 10 billion tonnes (10^{13} kg) released
- 2 to 3 occurring every day at present

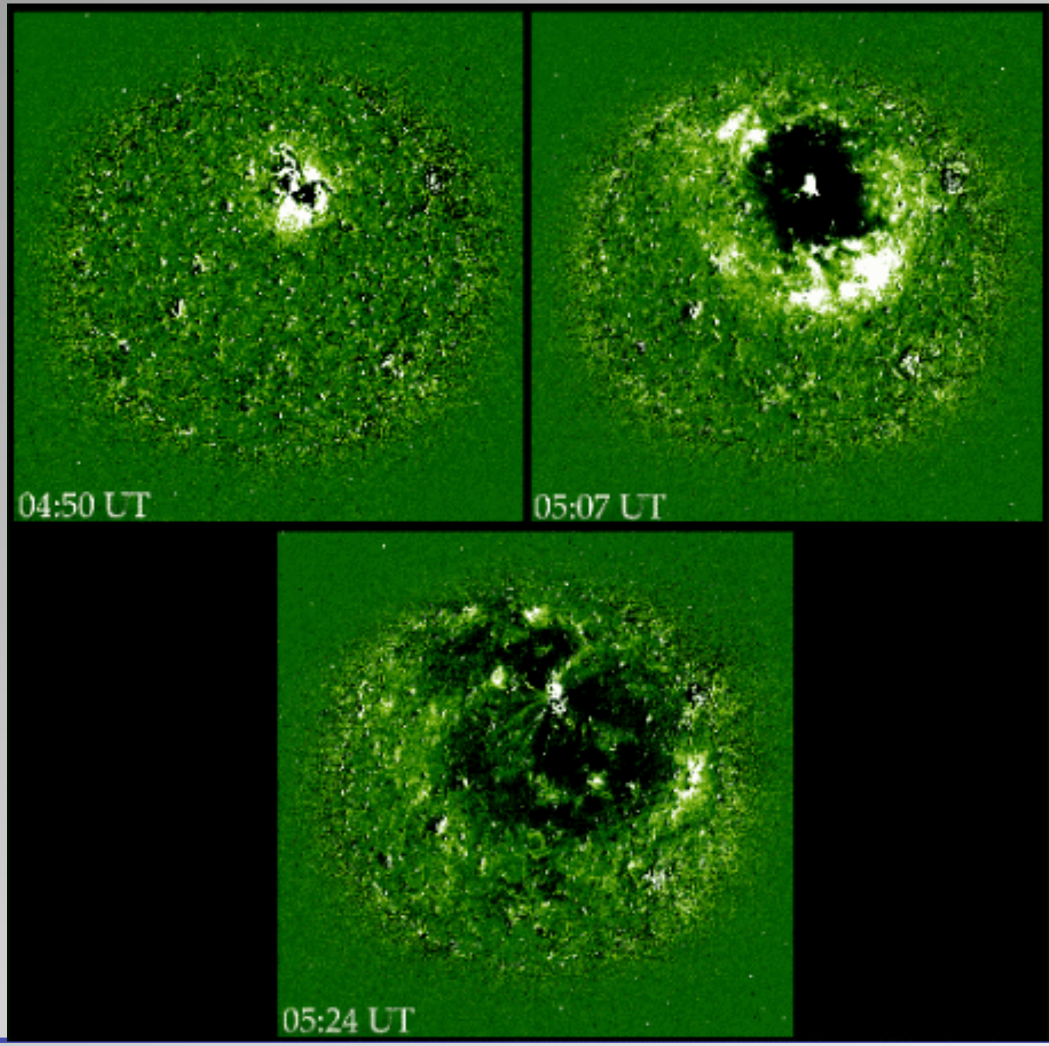


Expanding corona: solar storms (ctd)



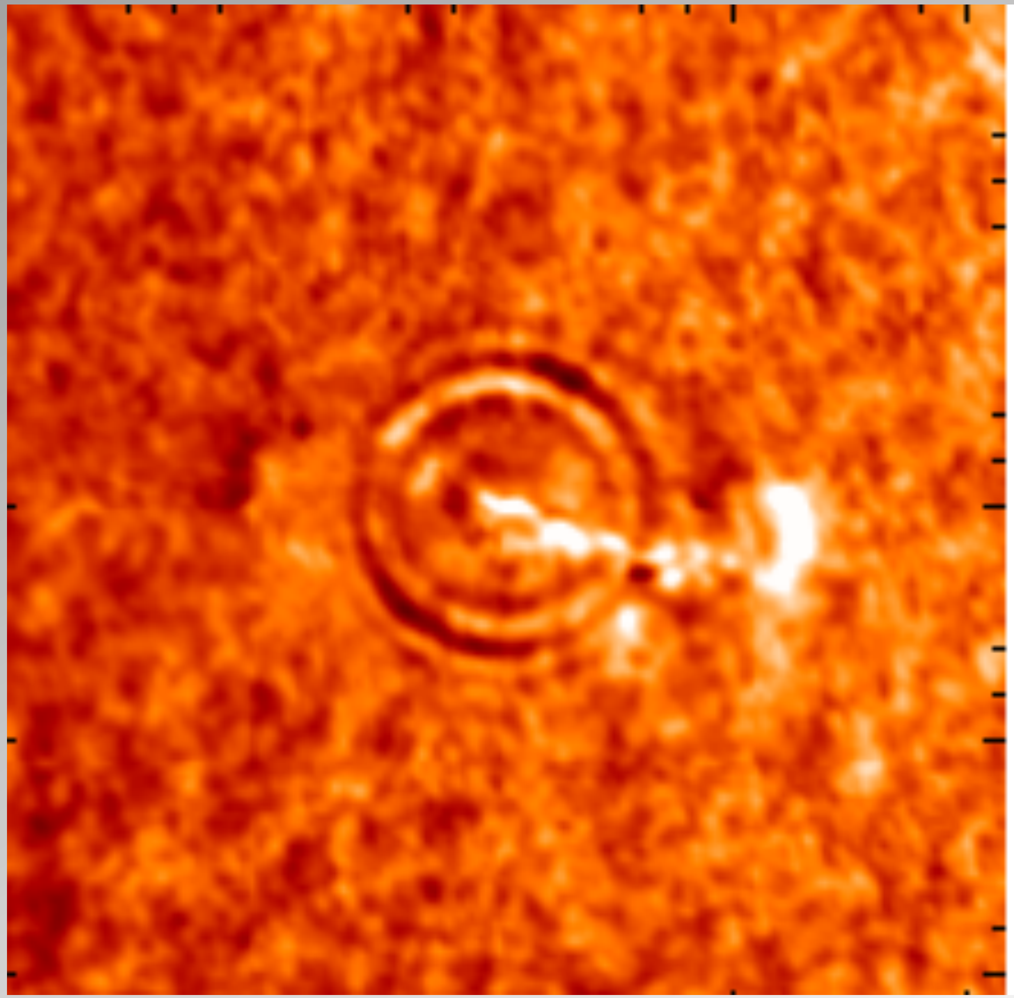
Solar storms: Moreton waves

- Moreton waves on difference images after solar eruption



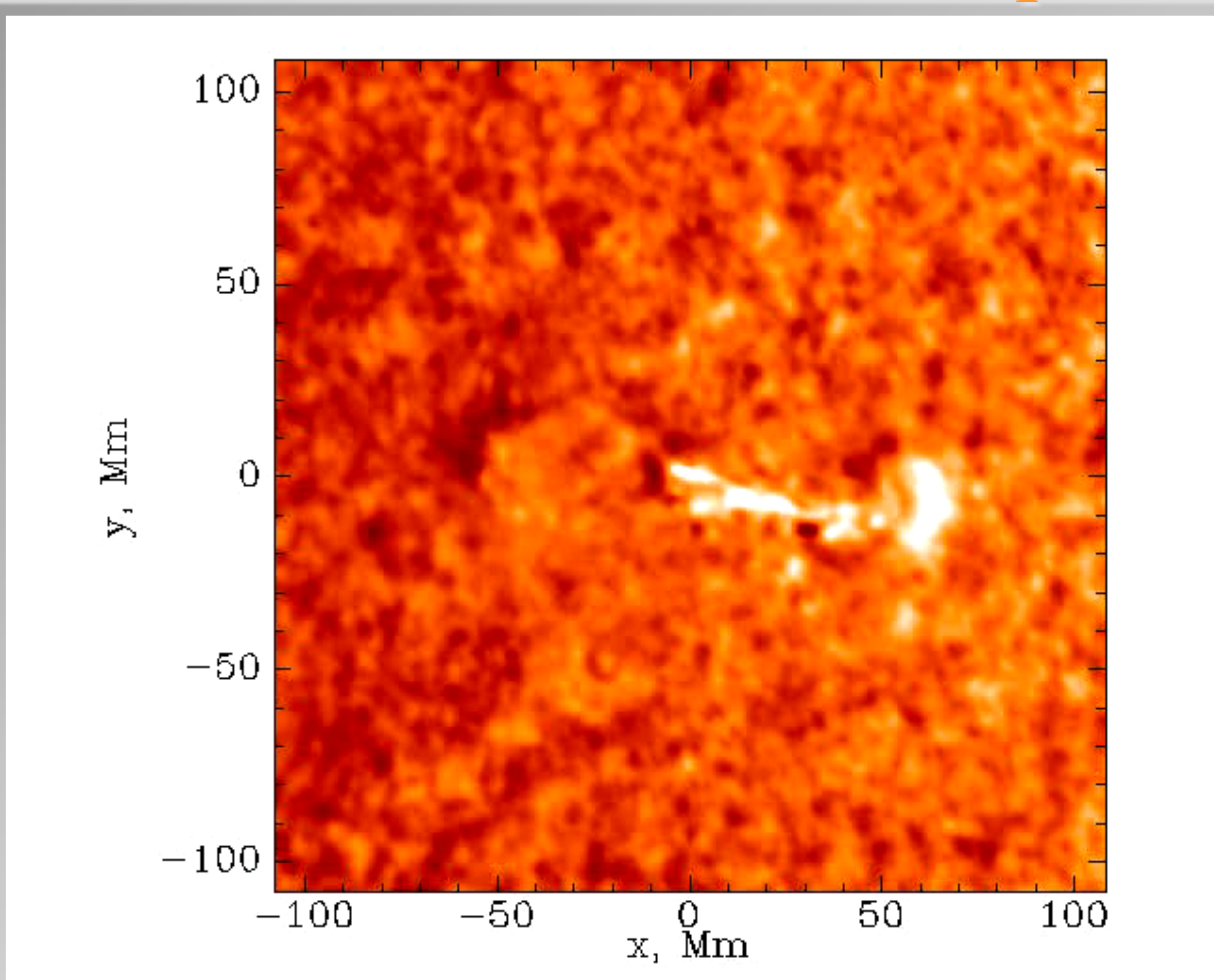
Solar storms: Sun quakes

- Solar quakes: high energy electrons slam the solar surface



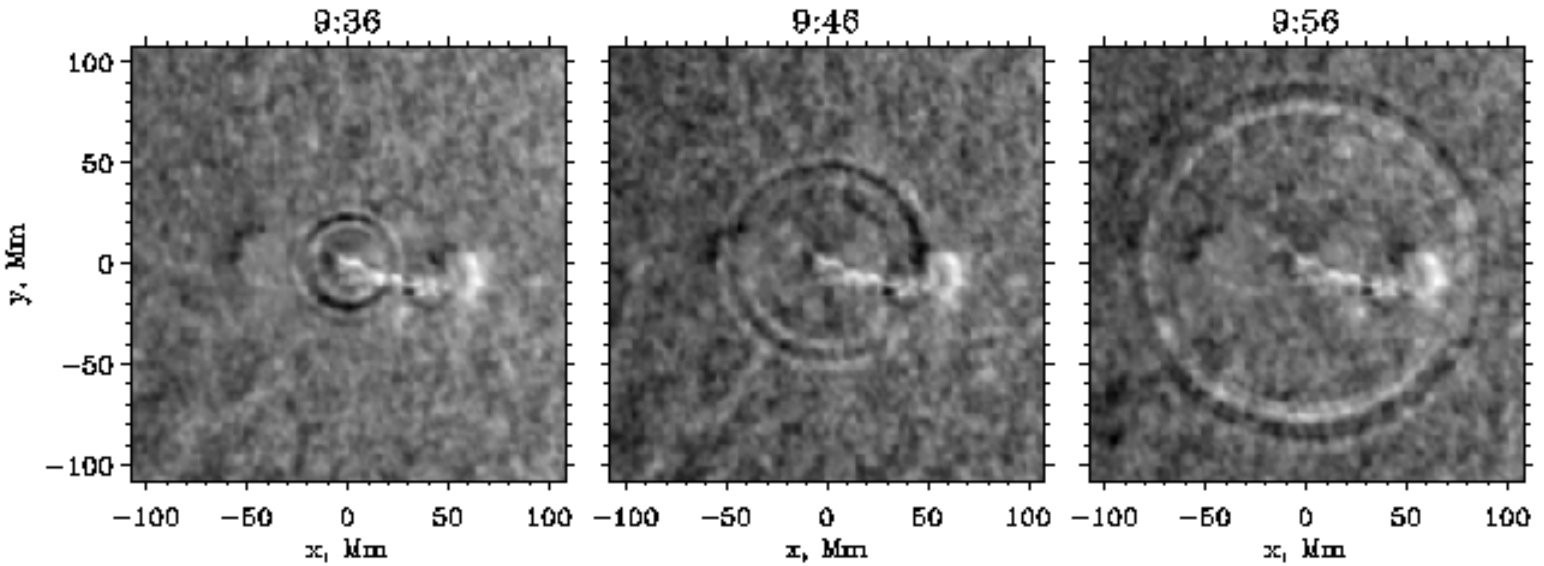
Do we see MHD waves? – Sun quakes

- Solar quakes: high energy electrons slam the solar surface

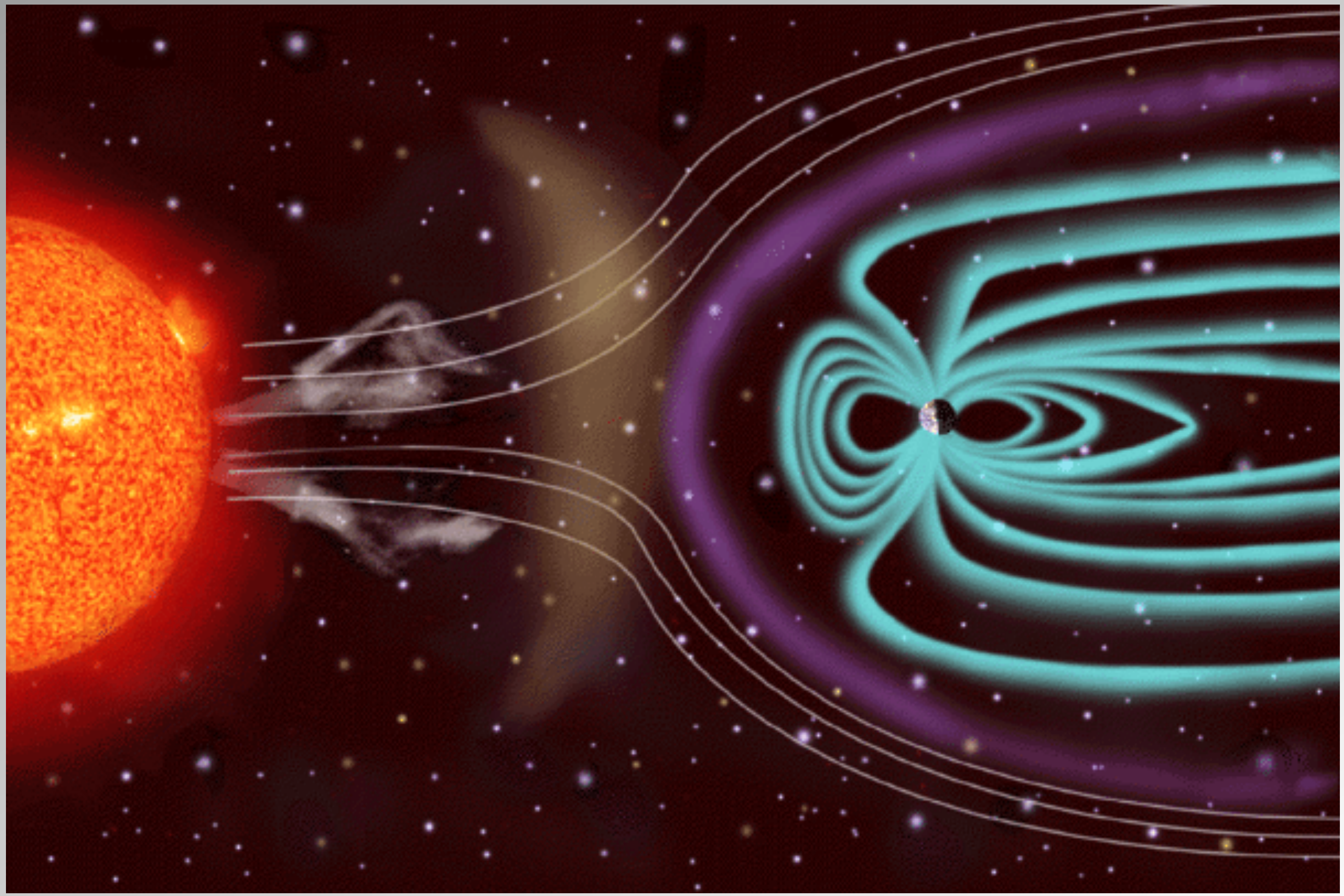


Solar storms: Sun quakes

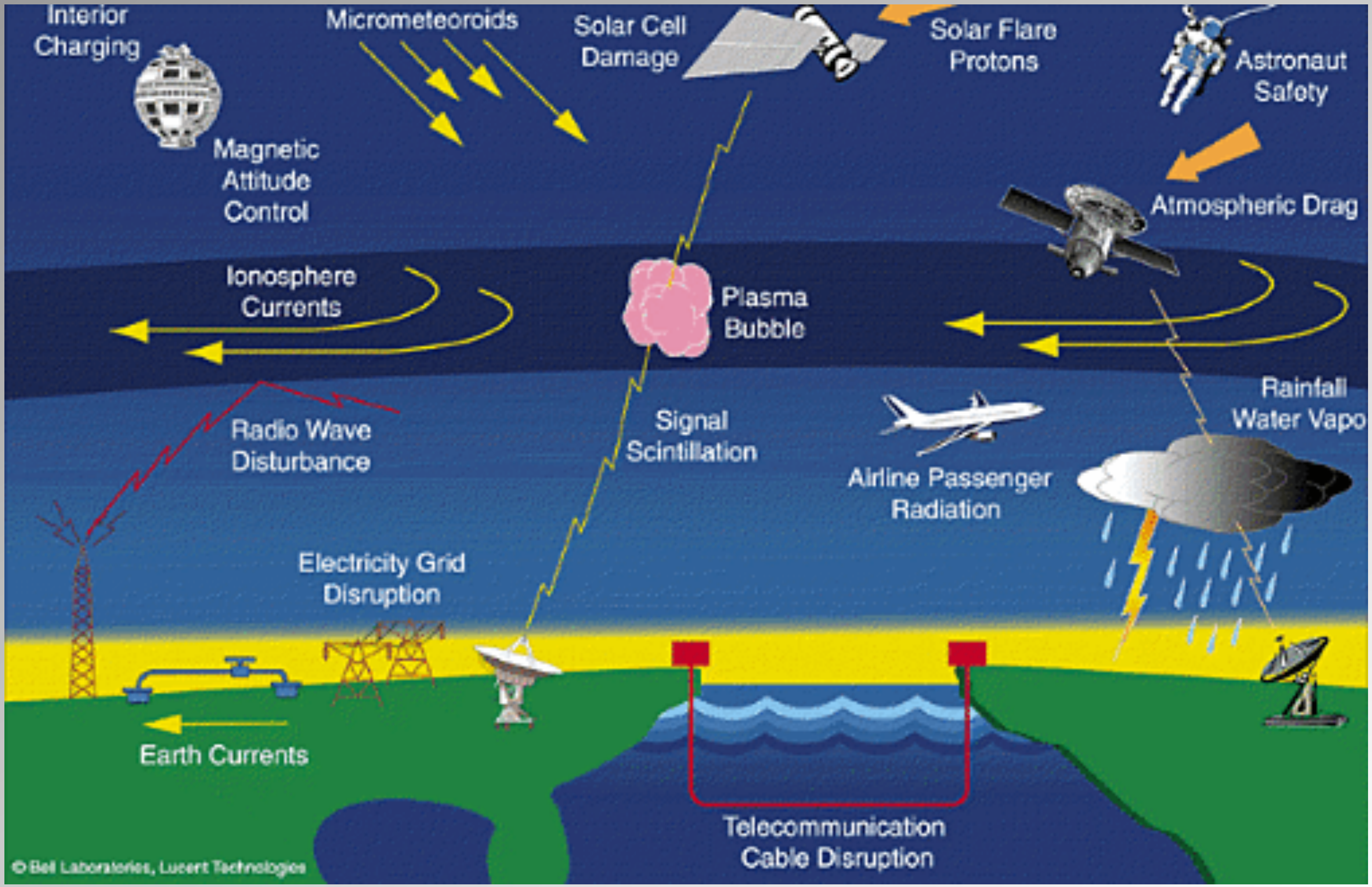
• Solar quakes: high energy electrons slam the solar surface



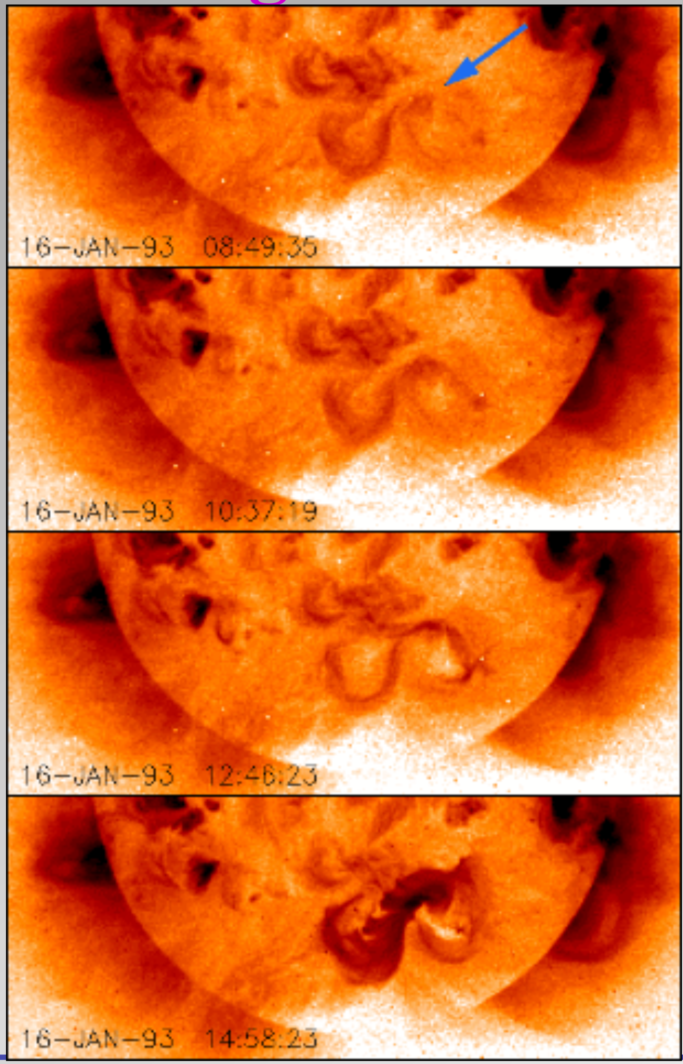
Space Weather



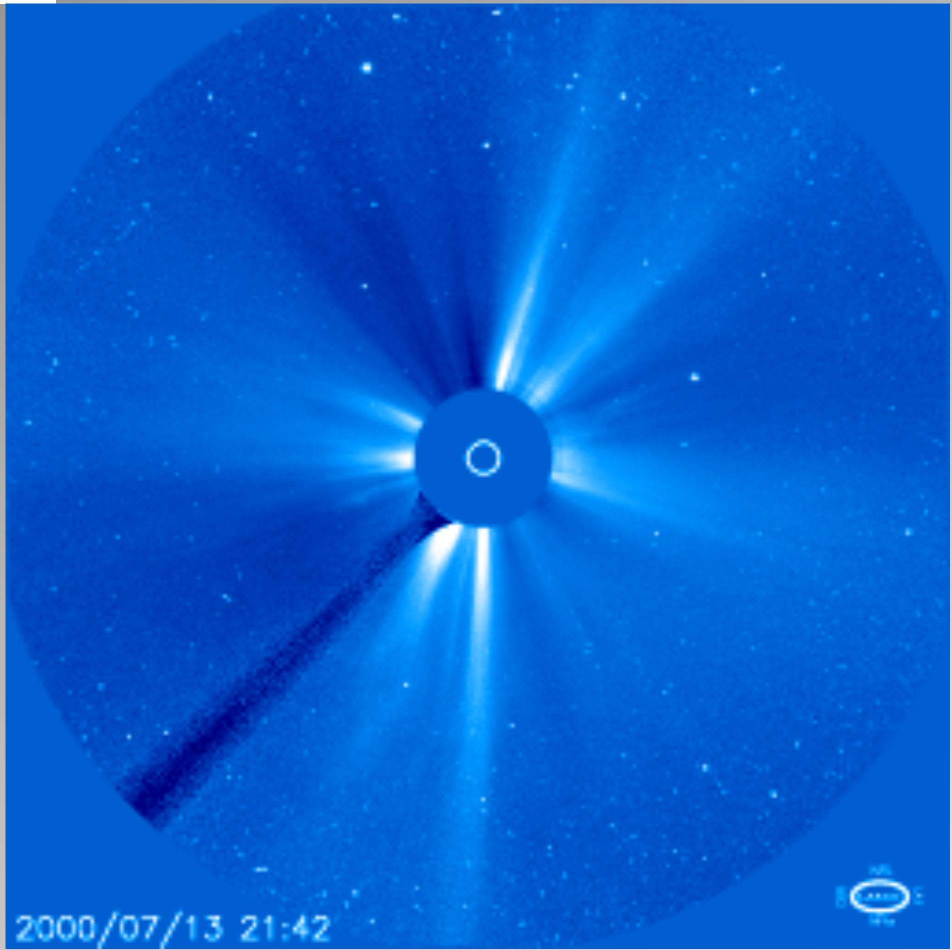
Blackouts and burnouts



Predicting solar storms



X-flare : 14th July 2000

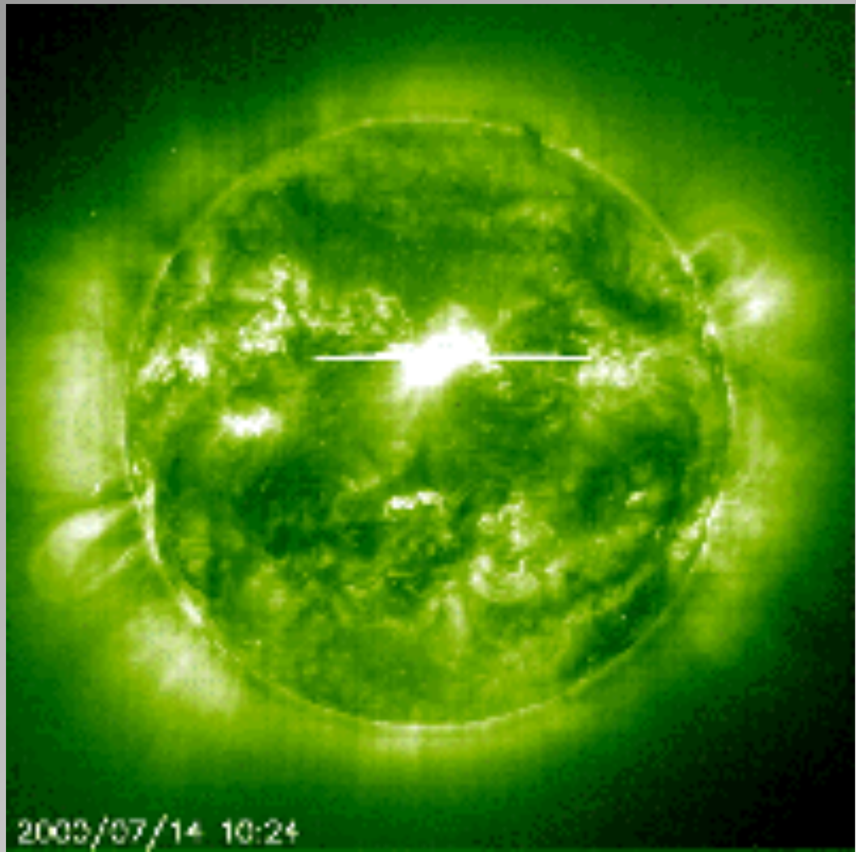


Bastille day flare

- 10.03 am Friday 14th July 2000
- X5.9 Solar Falre and associated CME
- Largest solar eruption in last 11 years!

SOHO had to baton down the hatches

Effect on the Earth

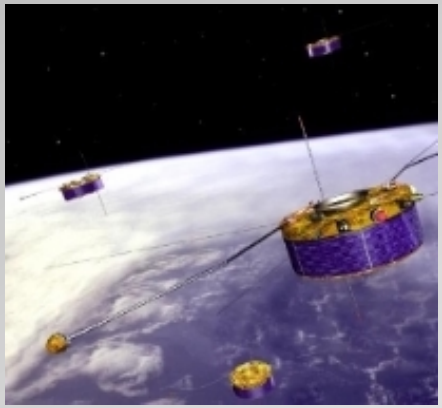


Space Environment Center (USA)

- issued G5 geomagnetic storm warning
- operator or fleet of communication satellites having trouble orienting their spacecraft
- loss of radio communication on Earth' day-side

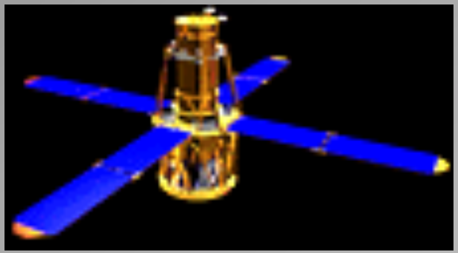
Astronaut radiation exposure quadrupled

Future space observatories



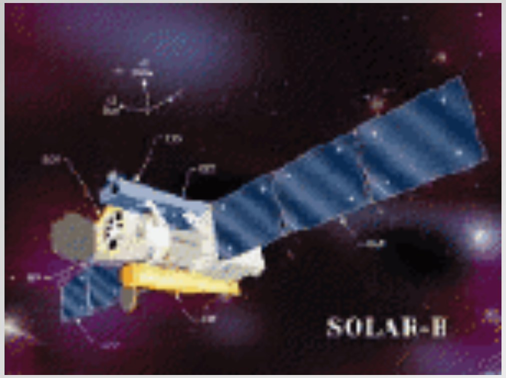
CLUSTER II

- Four satellite
- 3D magnetosphere
- July & August 2000



HESSI

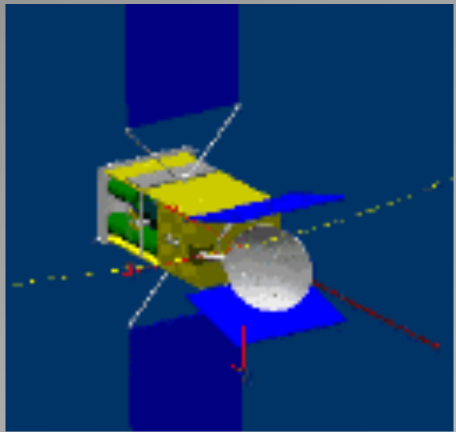
- Solar flare X-ray mission
- March 2001



Solar-B/Hinode

- Japan/UK/USA Mission
- Successor of Yohkoh
- Autumn 2006

Future space observatories (ctd)

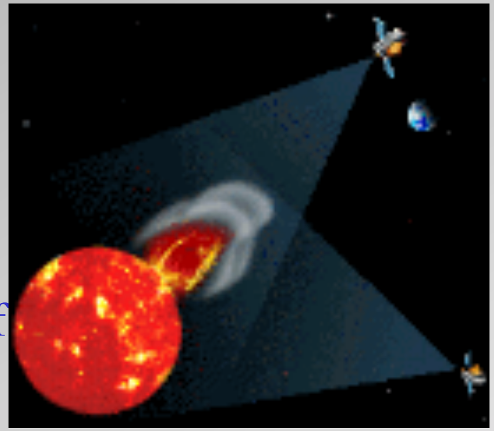


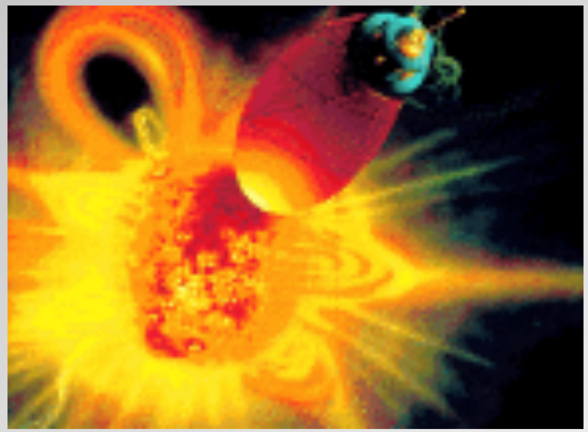
Solar Orbiter

- ESA mission
- 20 million km (3 times closer than Mercury)
- Stays over one position
- 2015 - 2017

STEREO

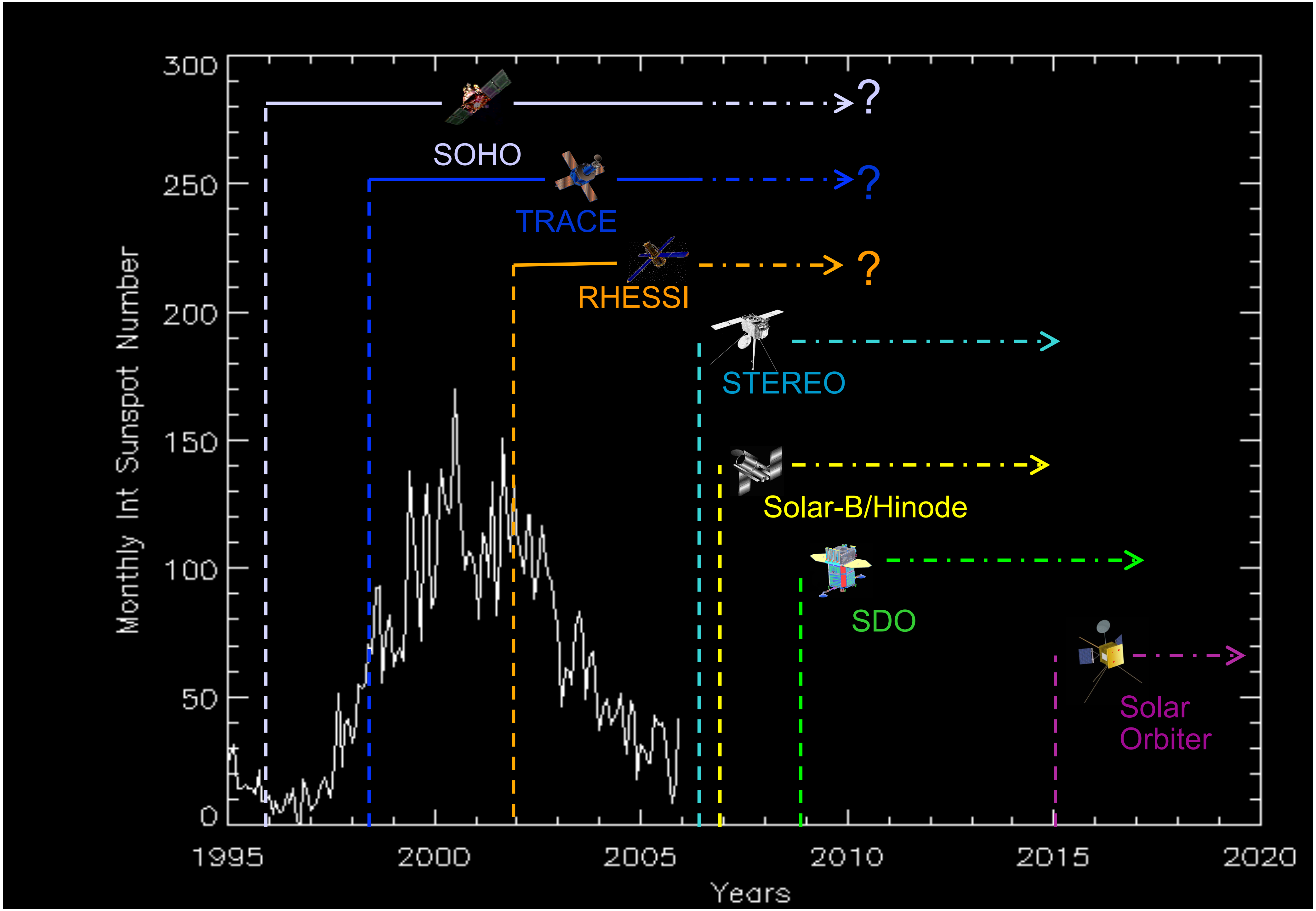
- NASA Mission
- Two satellites
- Stereoscopic images of the corona

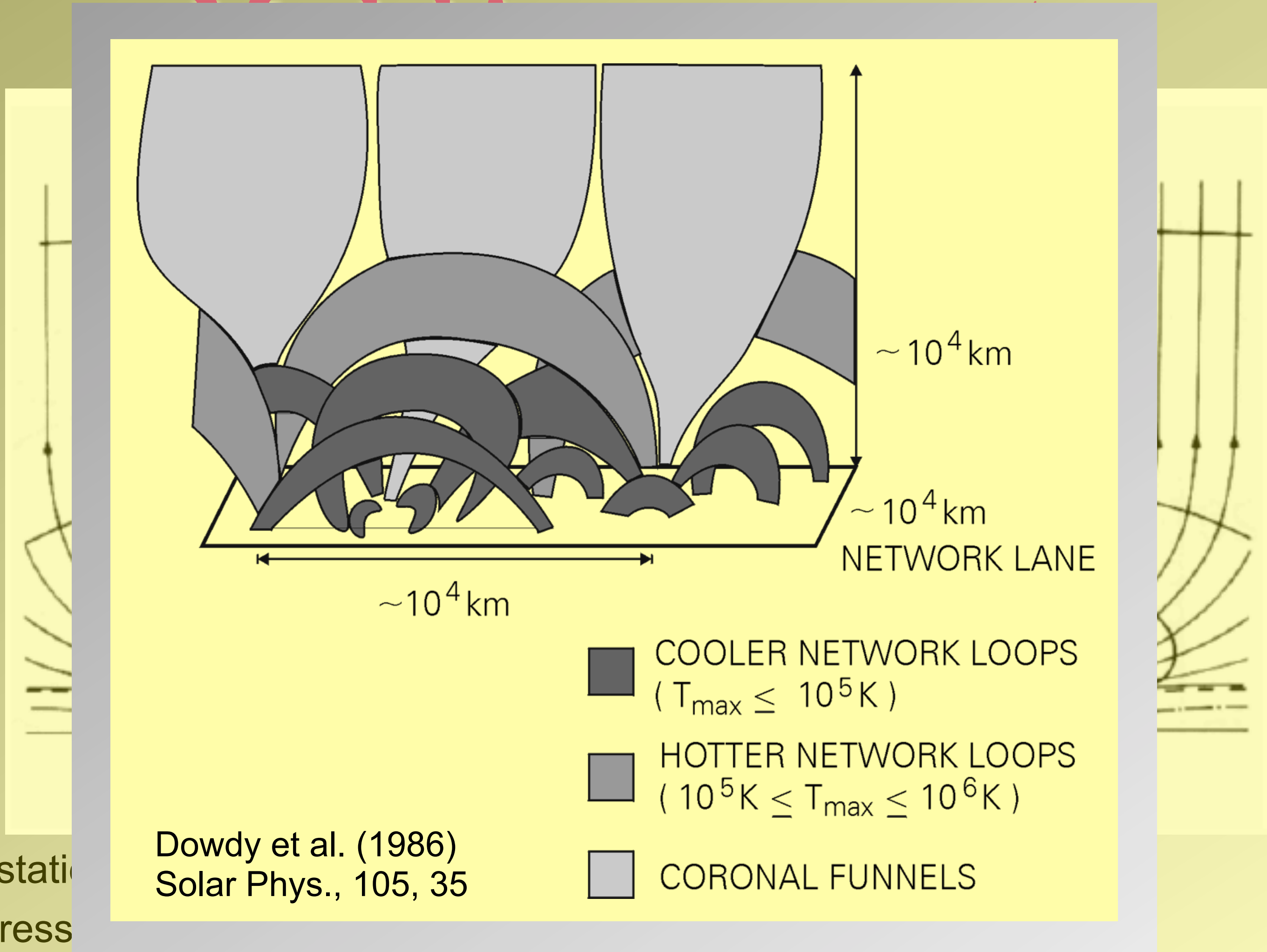




Solar Probe

- NASA Mission
- Fly through the corona at 2 million km at 2000 K
- Lasts only 24 hours
- 201?


SOHO
TRACE
RHESSI
STEREO
Solar-B/Hinode
SDO
Solar Orbiter
?
?
?
Monthly Int Sunspot Number
Years
300
250
200
150
100
50
0
1995
2000
2005
2010
2015
2020



Dowdy et al. (1986)
Solar Phys., 105, 35

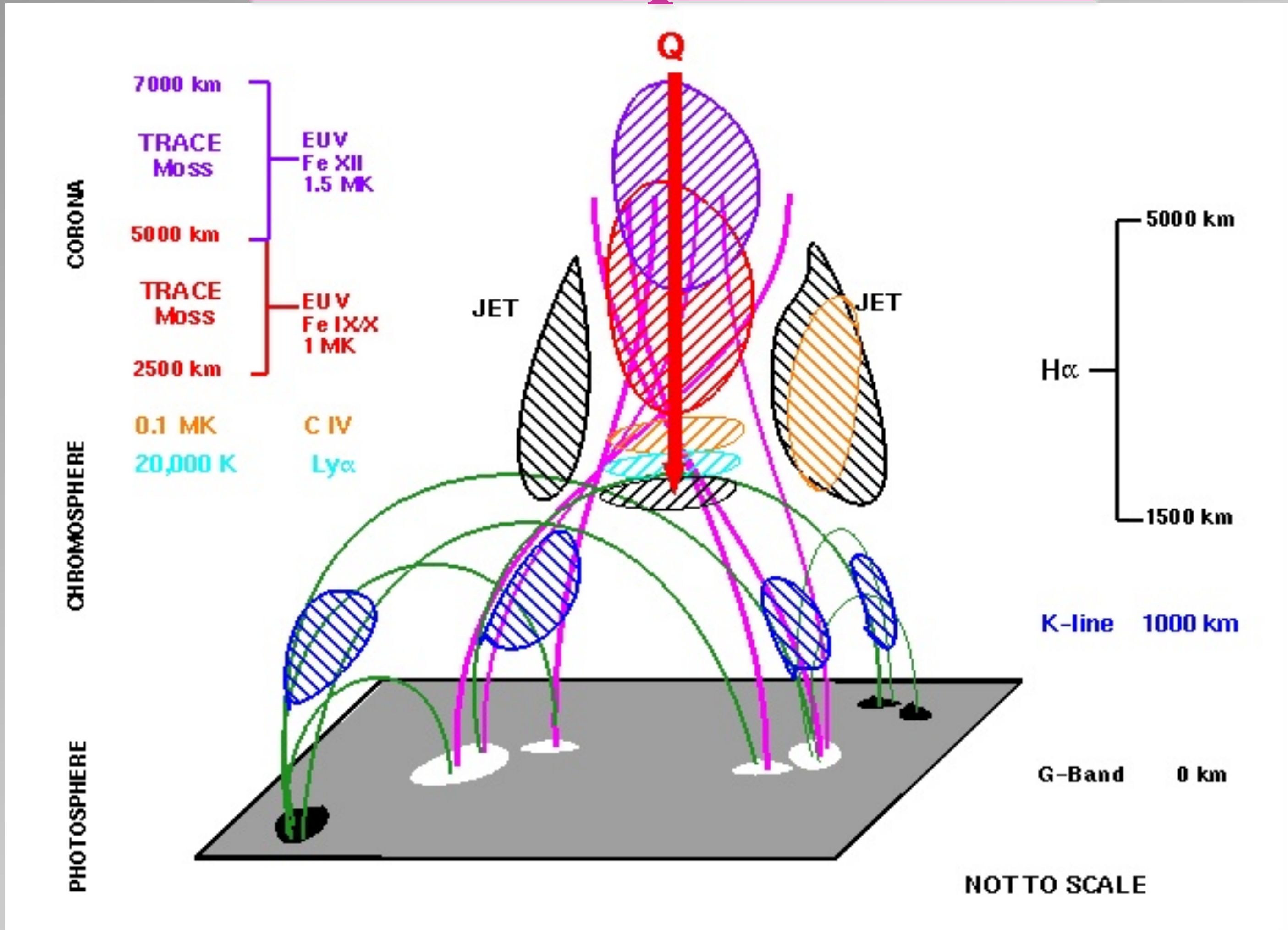
2D stati

- press

Gabriel (1976), Phil. Trans. A281, 339

Solar Physics & Space Plasma Research Centre (SP²RC)

Model improvement



(De Pontieu, Tarbell, Erdélyi, ApJ 590, 502, 2003)

The end