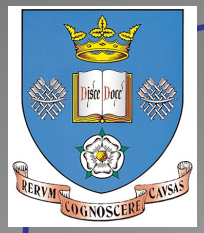

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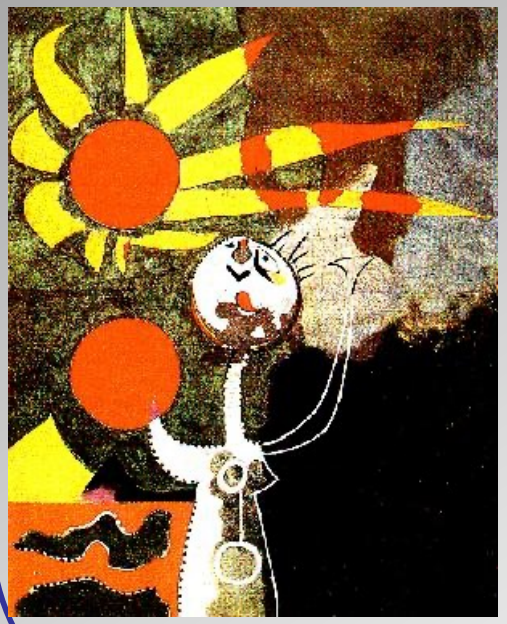
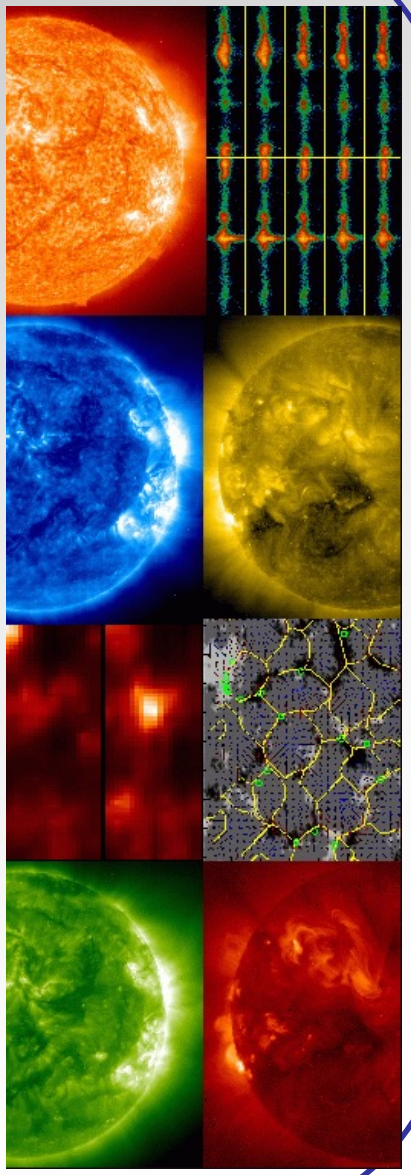
The Solar Atmosphere





Robertus Erdélyi

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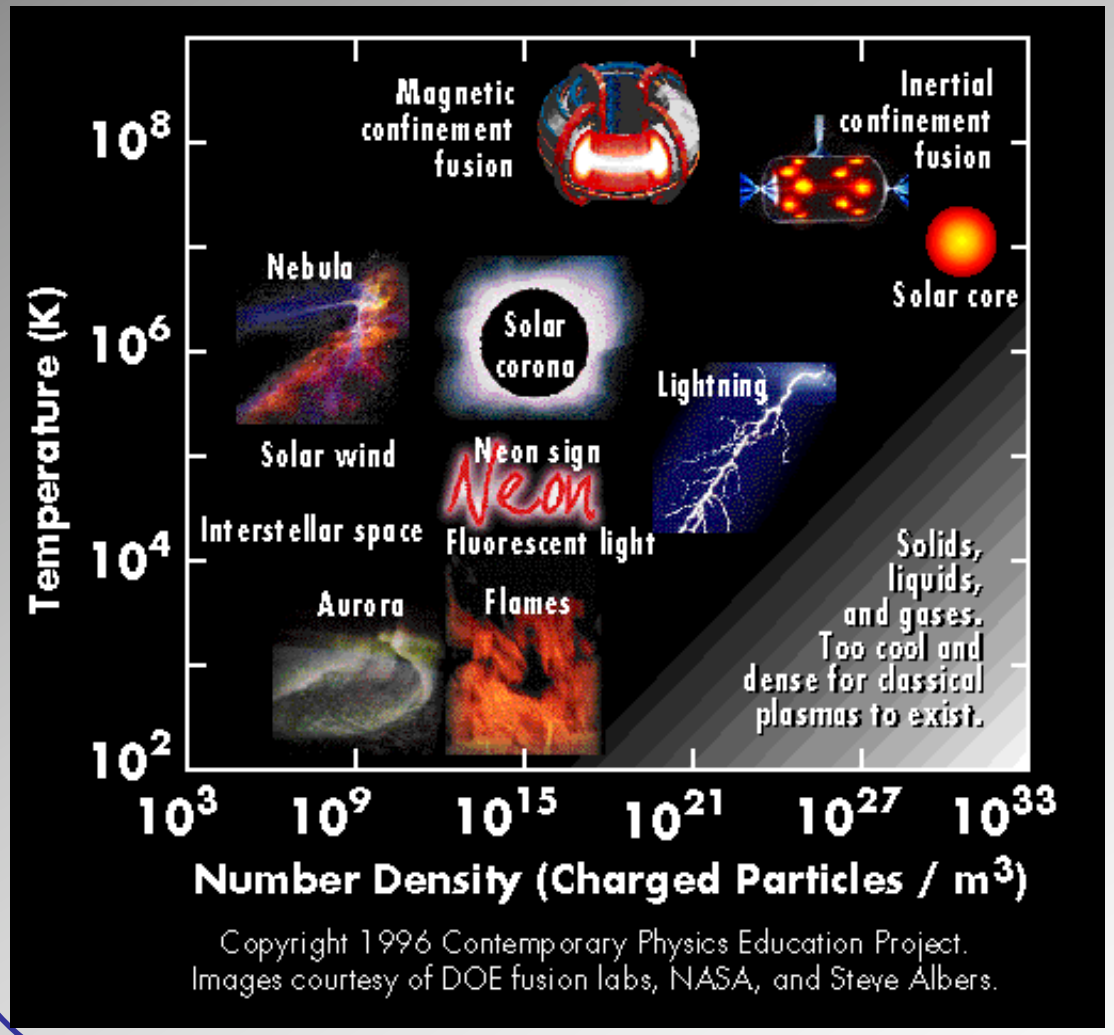
SP²RC, School of Mathematics & Statistics,
The University of Sheffield (UK)

http://robertus.staff.shef.ac.uk

Why Bother?



Modern Physics ➔ Plasma Physics

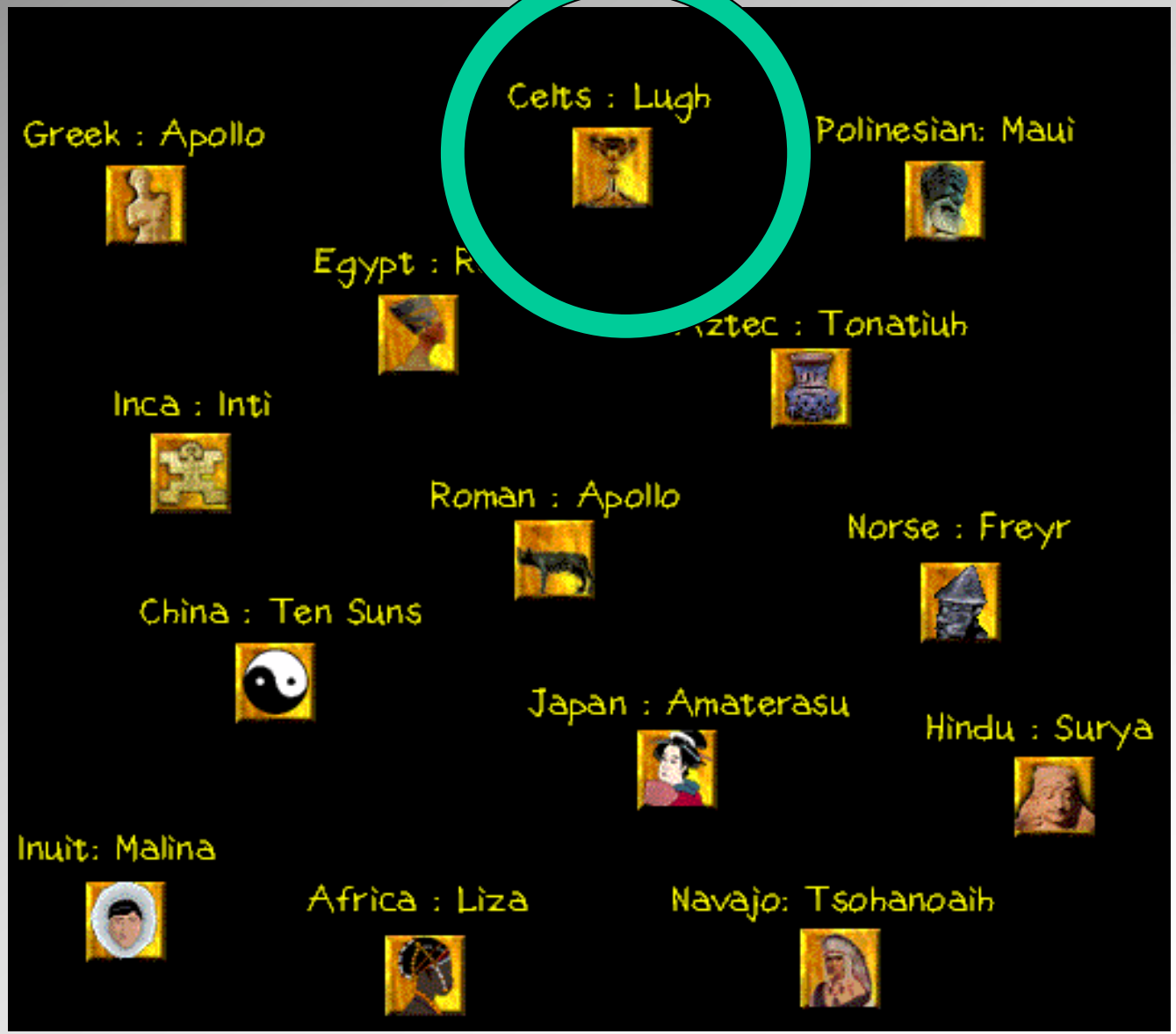
Solar and stellar atmospheres are composed of *ionised plasma* – are excellent conductors of electricity

In fact, [redacted]% 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



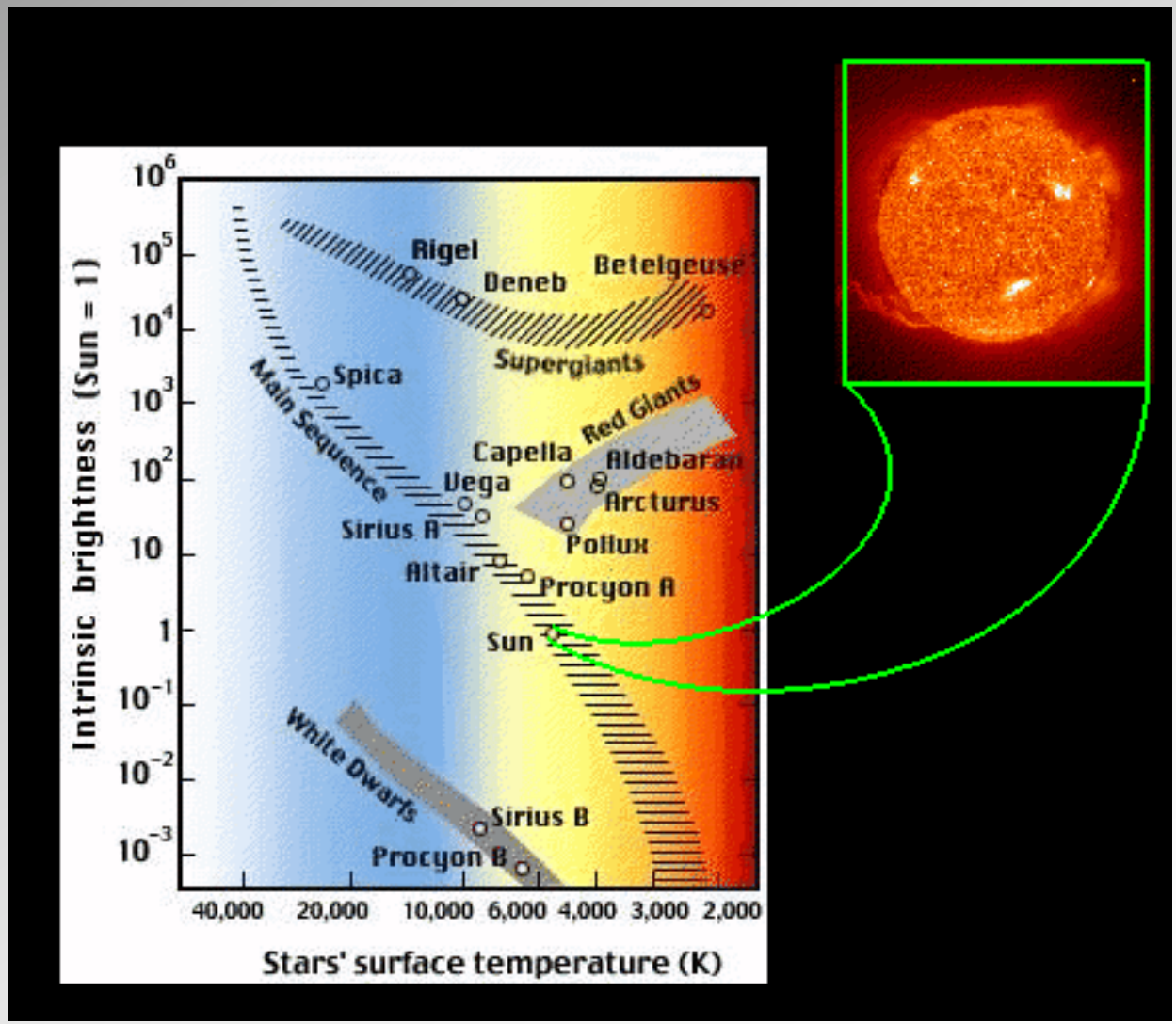
Solar History: High-tech age

And a modern worship of the Sun…

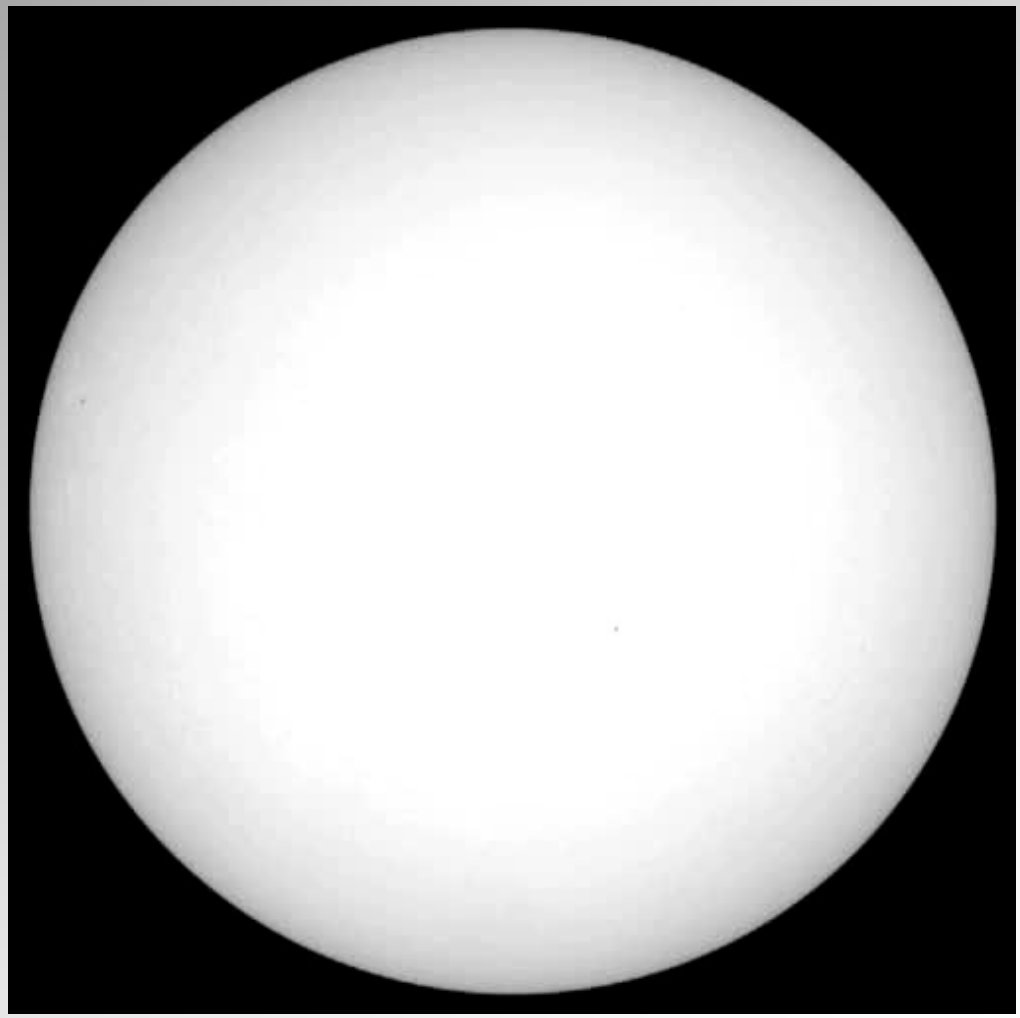
Solar History: Sky's worship continue?

The Sun as a star

Hertzsprung-Russell Diagram (HRD)



Our own star: the Sun



The atmosphere

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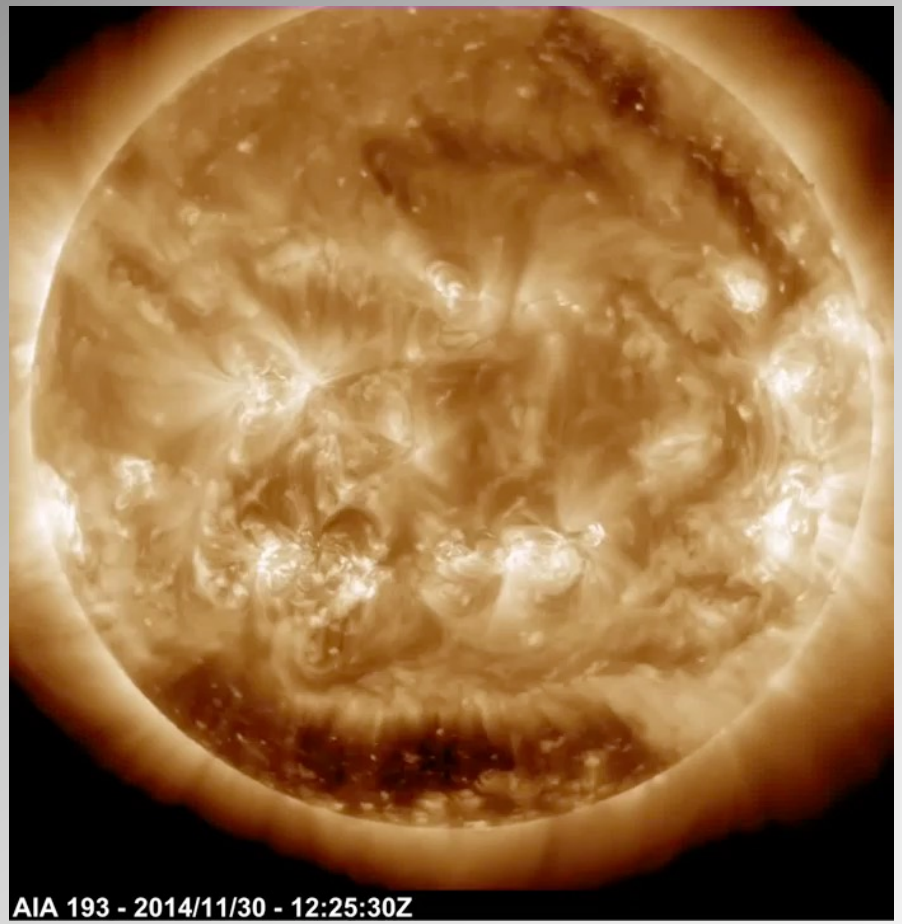
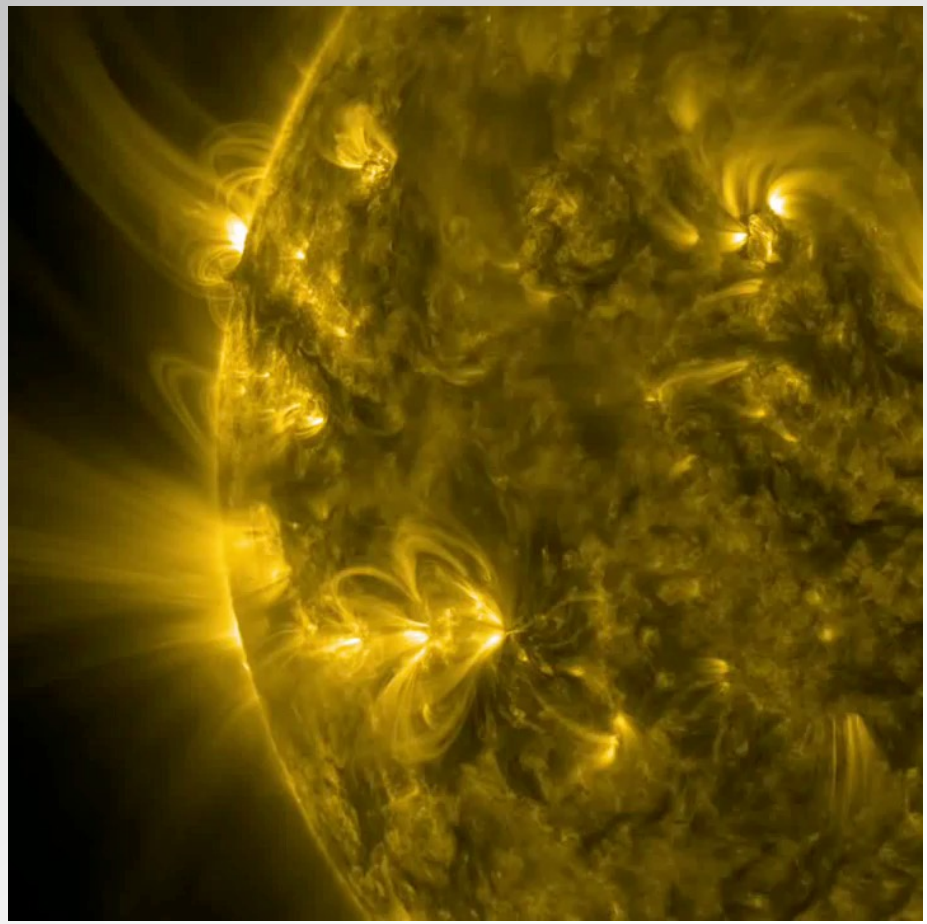
Our own star: the Sun





Why 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?

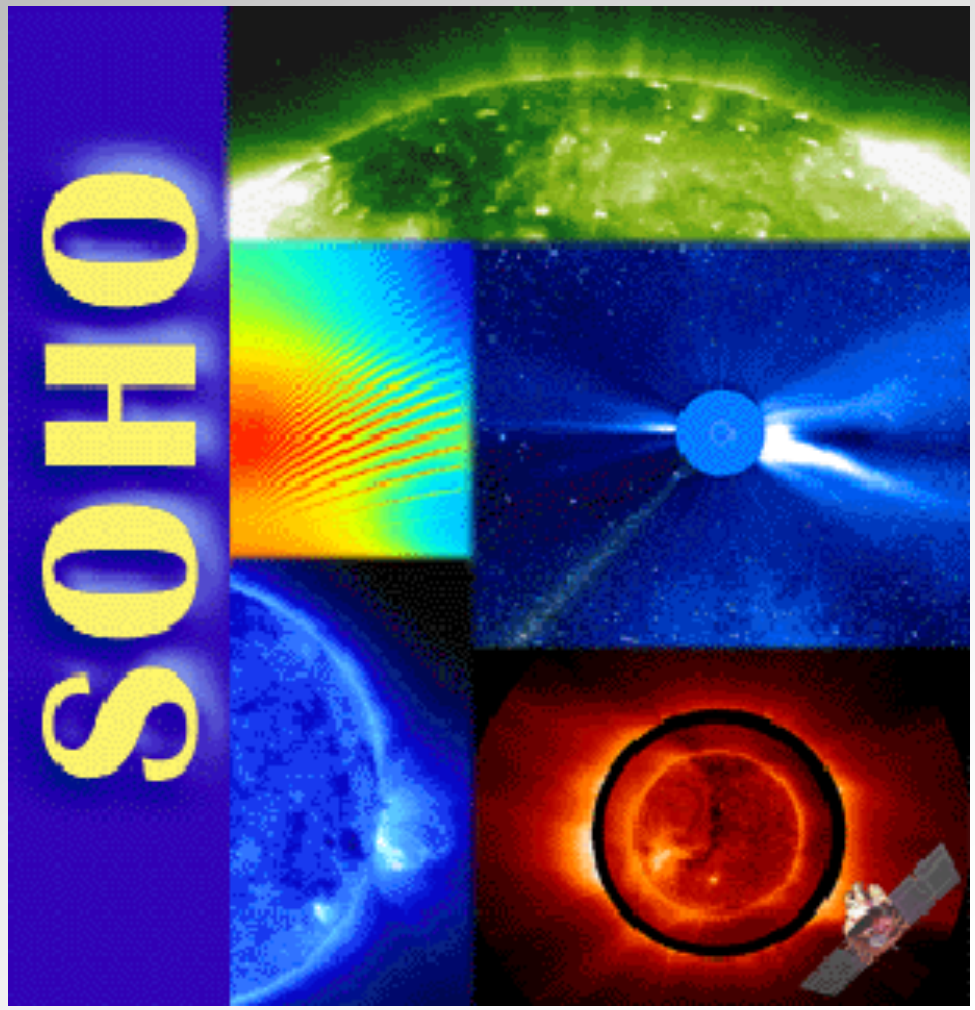
• What accelerates the solar wind up to measured speeds exceeding 700 km/s?

• 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: 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

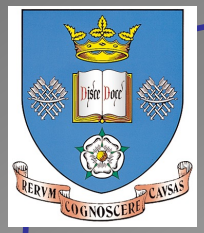
Important limits

- Cold plasma

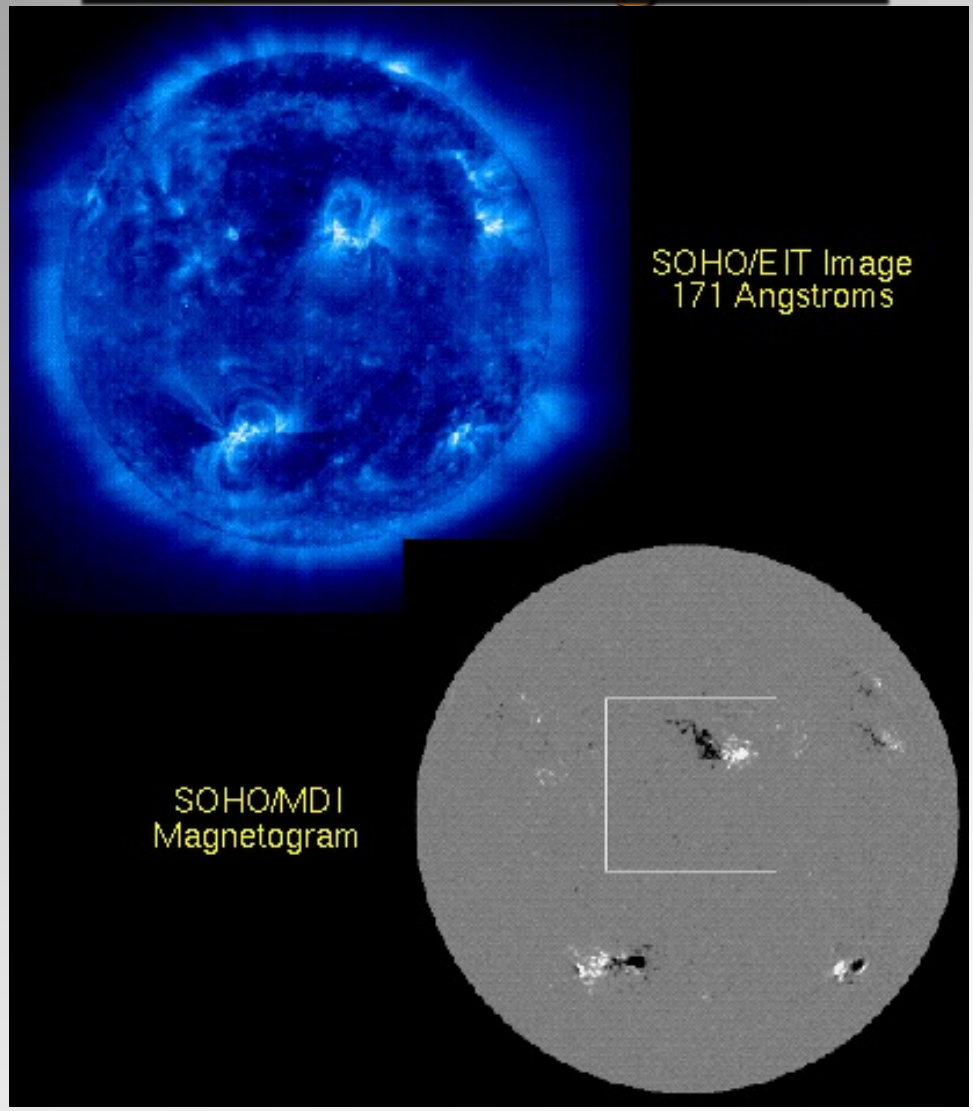
$$\beta = 0$$

- Incompressible plasma

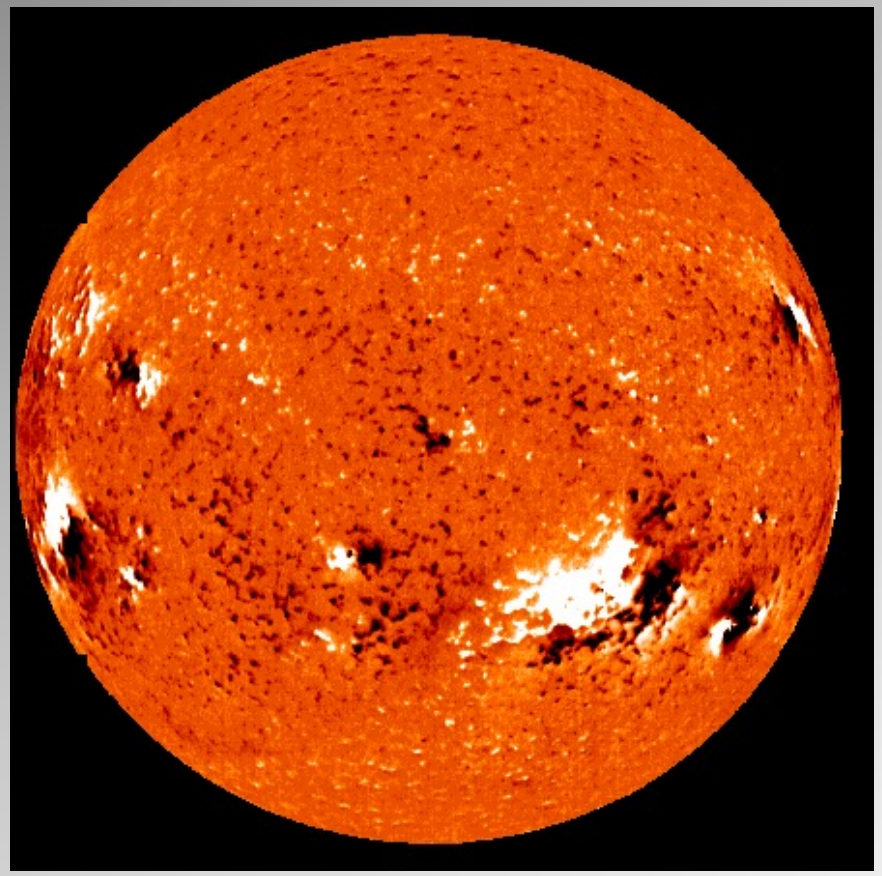
$$\gamma \rightarrow \infty$$



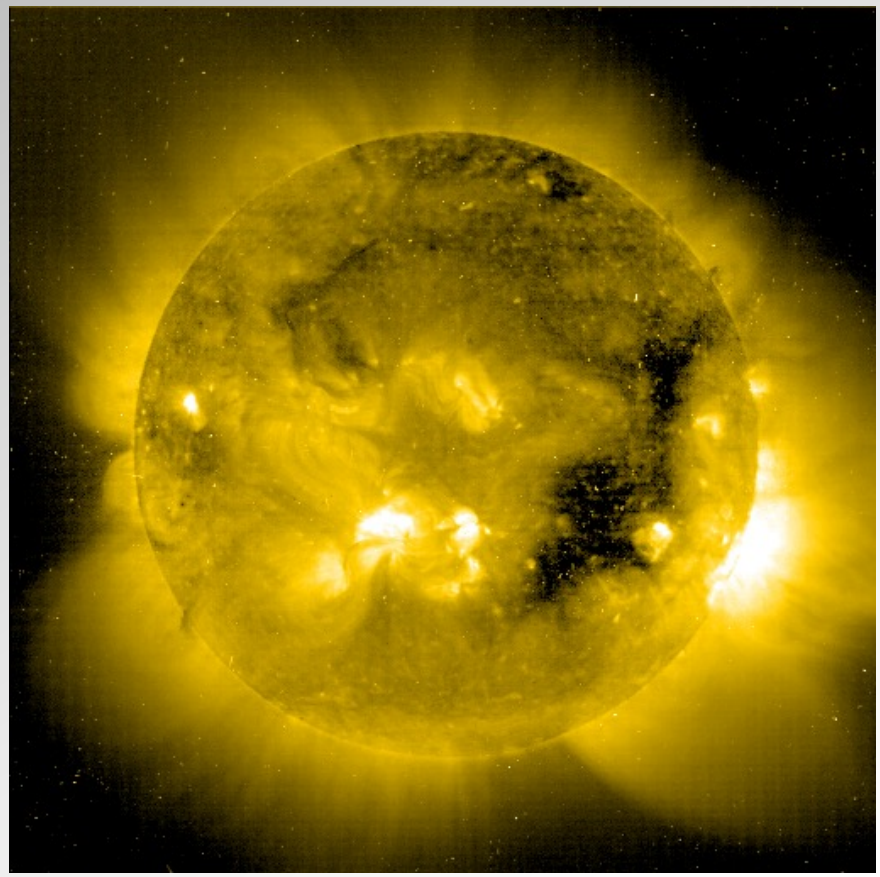
Is the Sun magnetic?



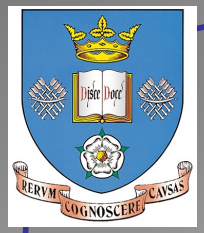
Is the Sun magnetic?



Ca II emission



Extreme ultra-violet



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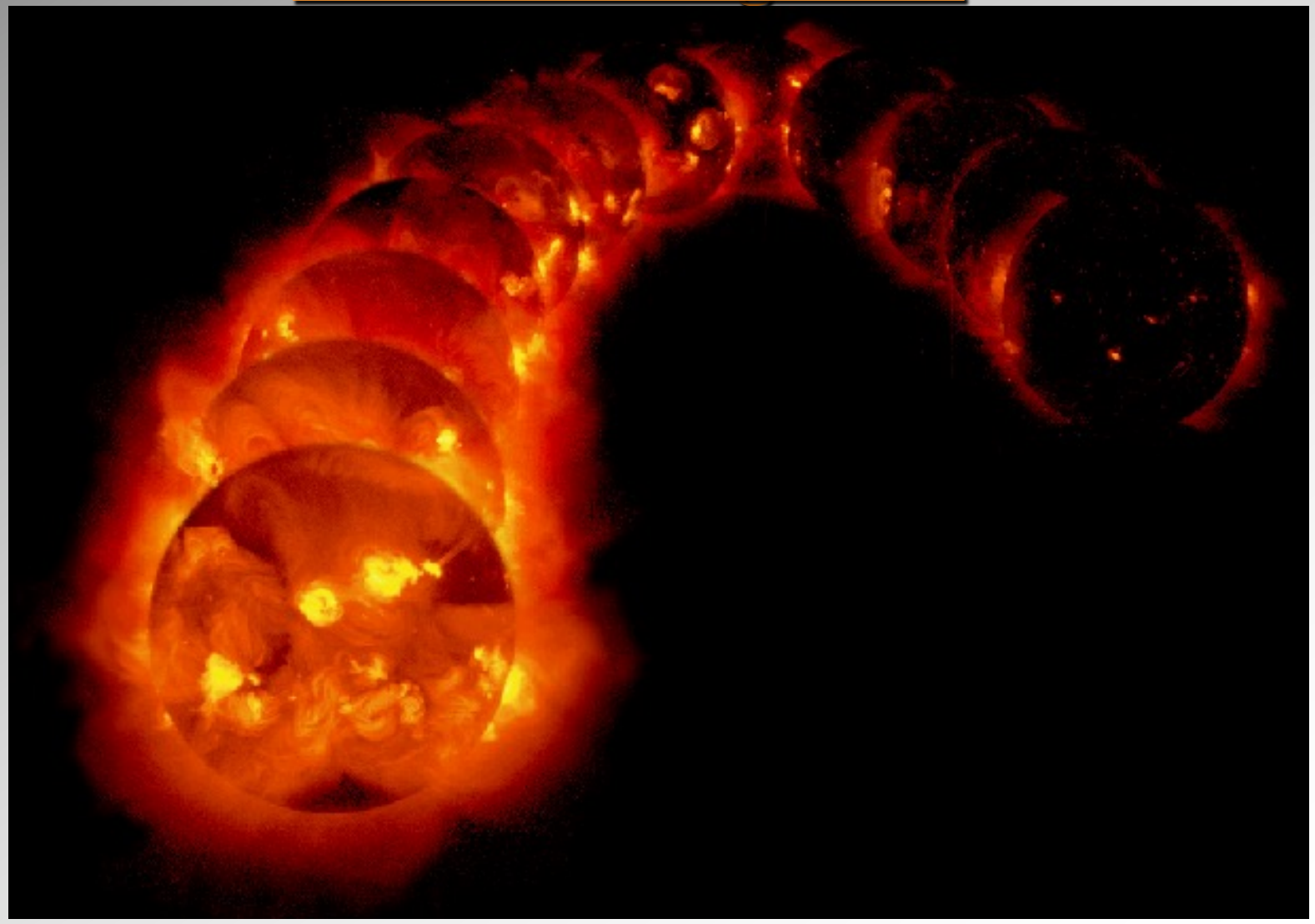
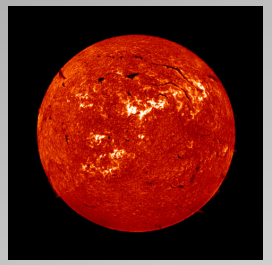
Is the Sun magnetic?

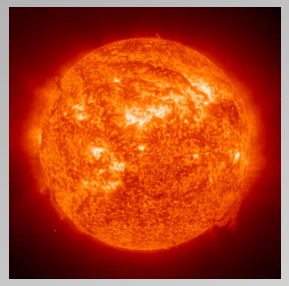


Magnetic coupling: the dynamic Sun

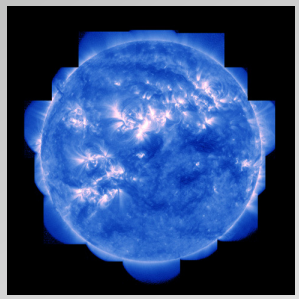
Hα
15,000 K



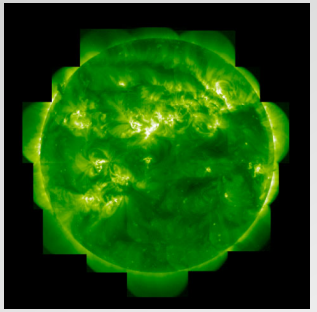
He EUV
50,000 K



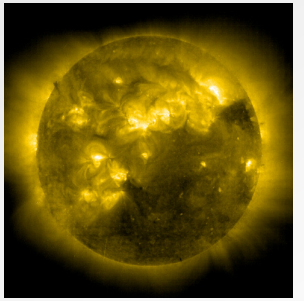
Fe VIII/IX EUV
1 MK



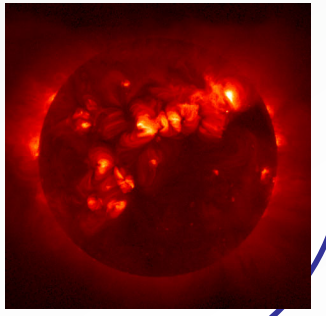
Fe XI
1.5 MK



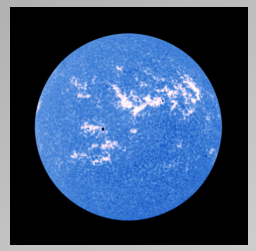
Fe XIV
3 MK



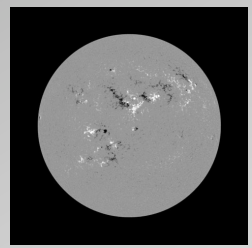
X rays
4-6 MK



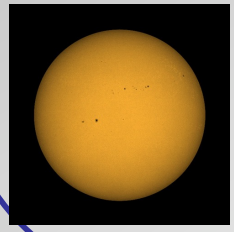
UV 1600 Å
8000 K



Magnetic field
5000 K



Visible
5000 K



- 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**.

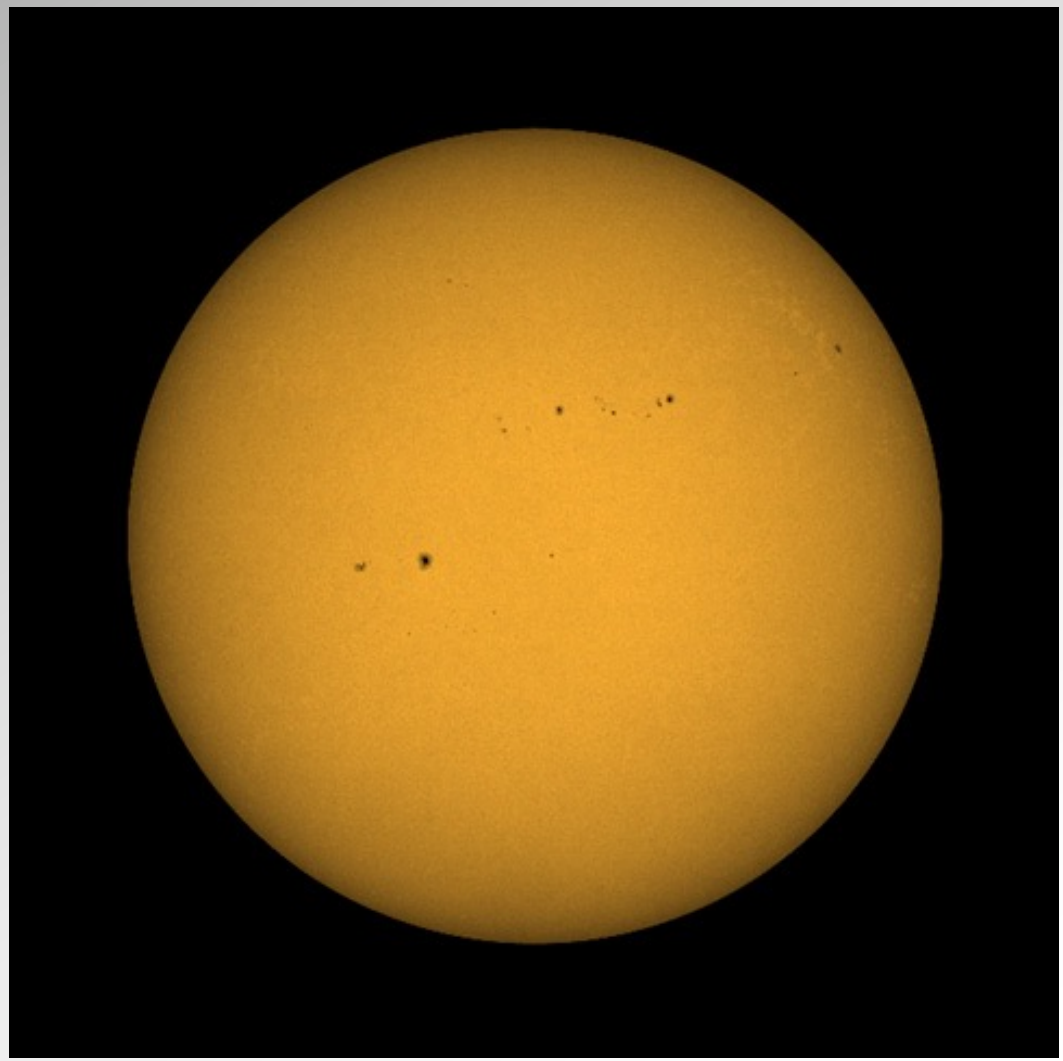
MHD seismology is a perfect tool to study this coupled, dynamic an structured system.

Two (biassed) particularly exciting aspects:

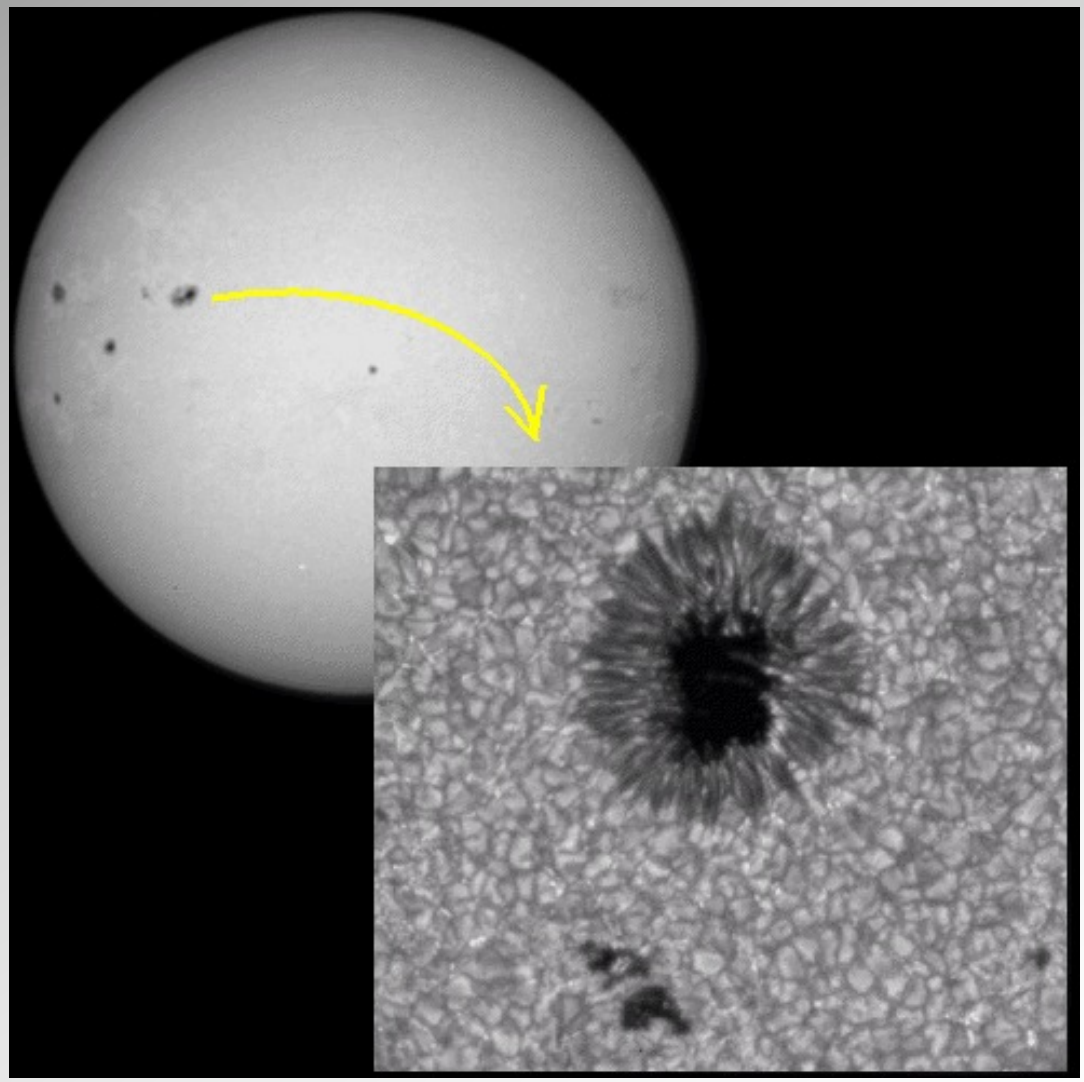
- **Influence of atmosphere** on global oscillations.
- **Role of *p* modes in the dynamics of the atmosphere!** (Not yet explored.)

Photosphere

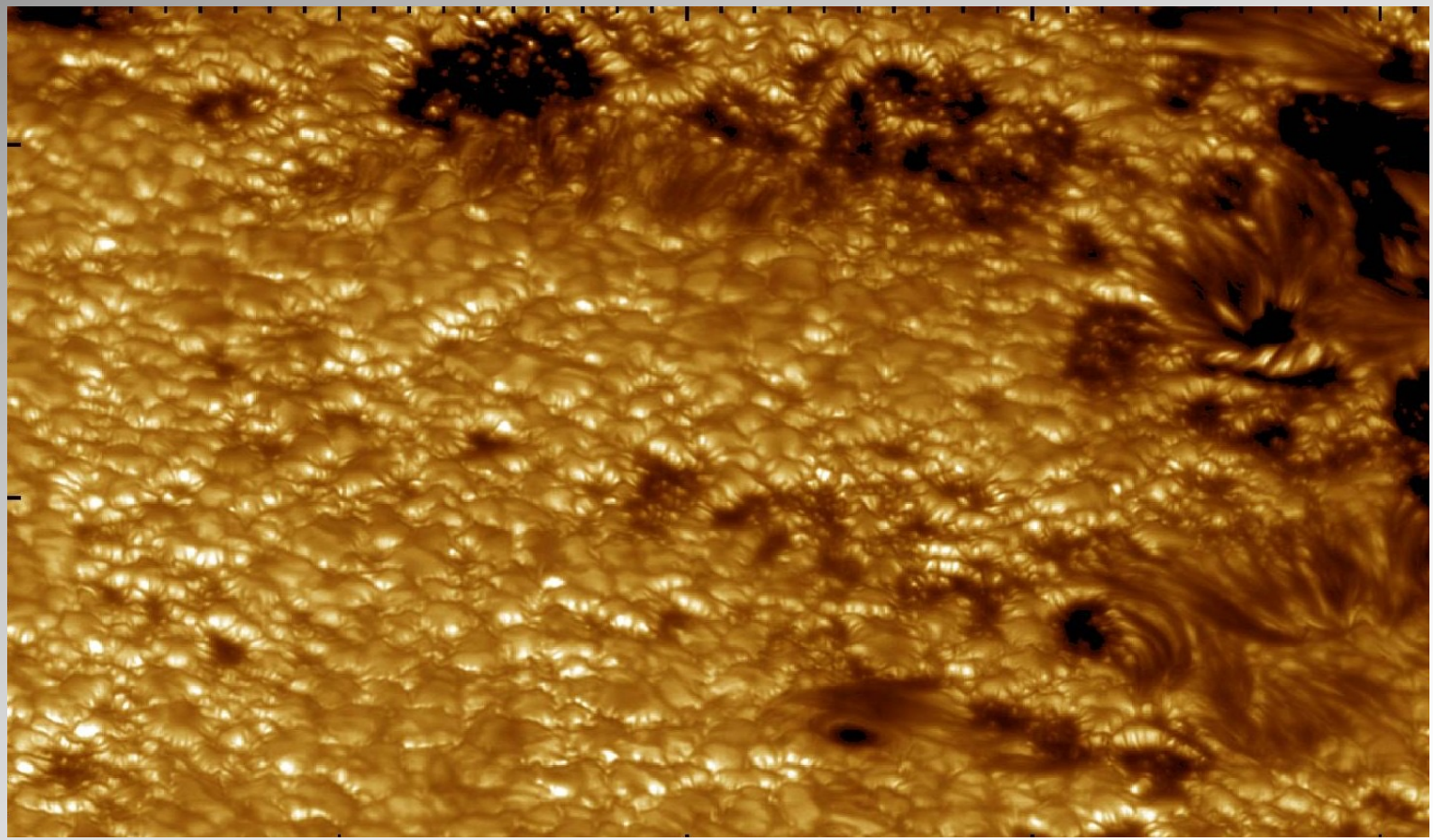
- Visible surface of the Sun
- Only ≈ 100 km thick
- Temperature ≈ 6000 K



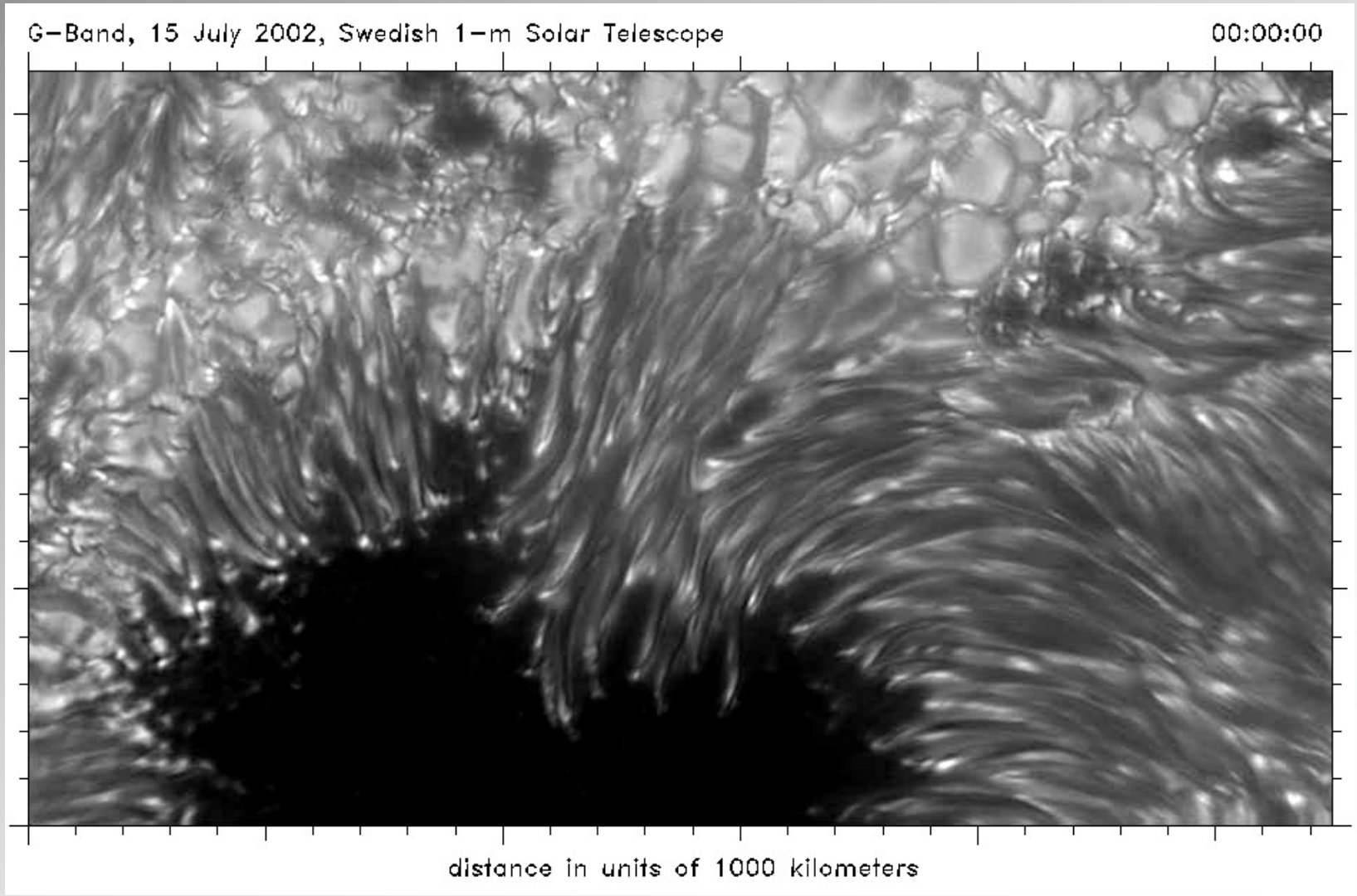
Photosphere: sunspots I



Photosphere: structure of sunspots

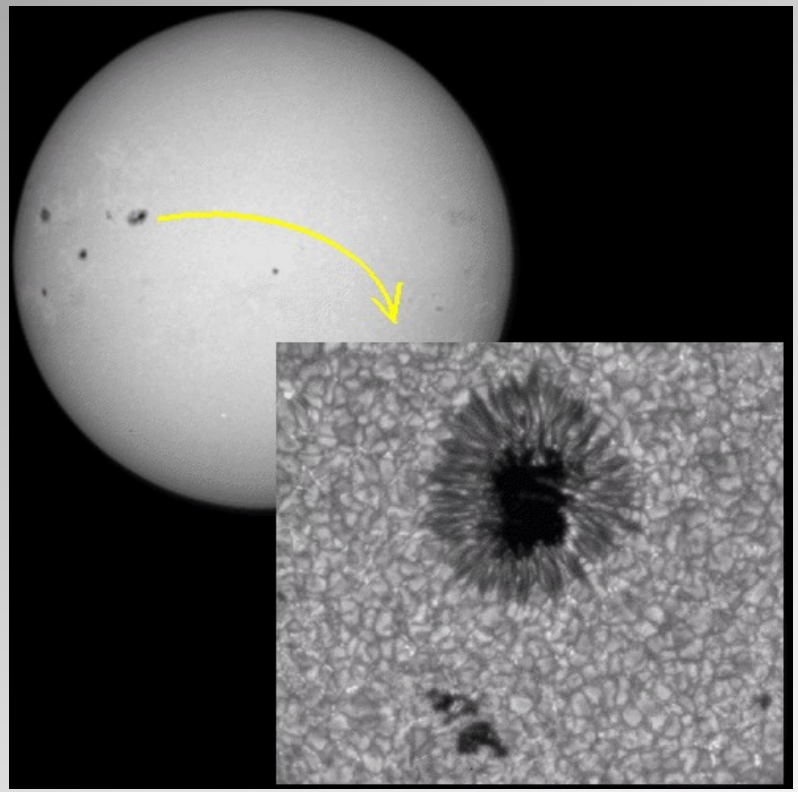


Photosphere: structure of sunspots



Photosphere: structure of sunspots

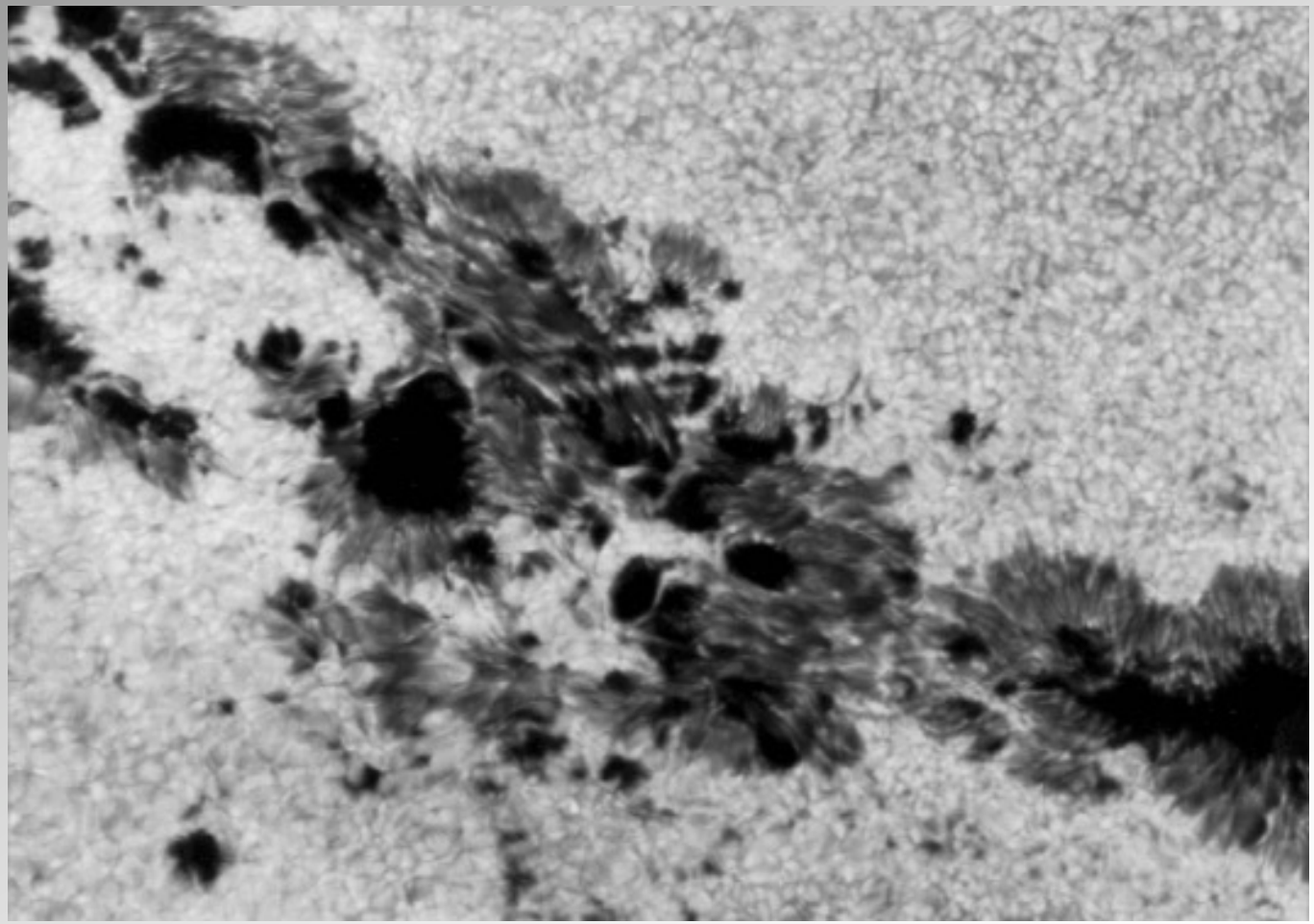
Sunspots are cooler than their surroundings because their strong magnetic field inhibits convection below the level of the photosphere. Hence, internal heat flux F_i, is reduced compared to external heat flux F_e



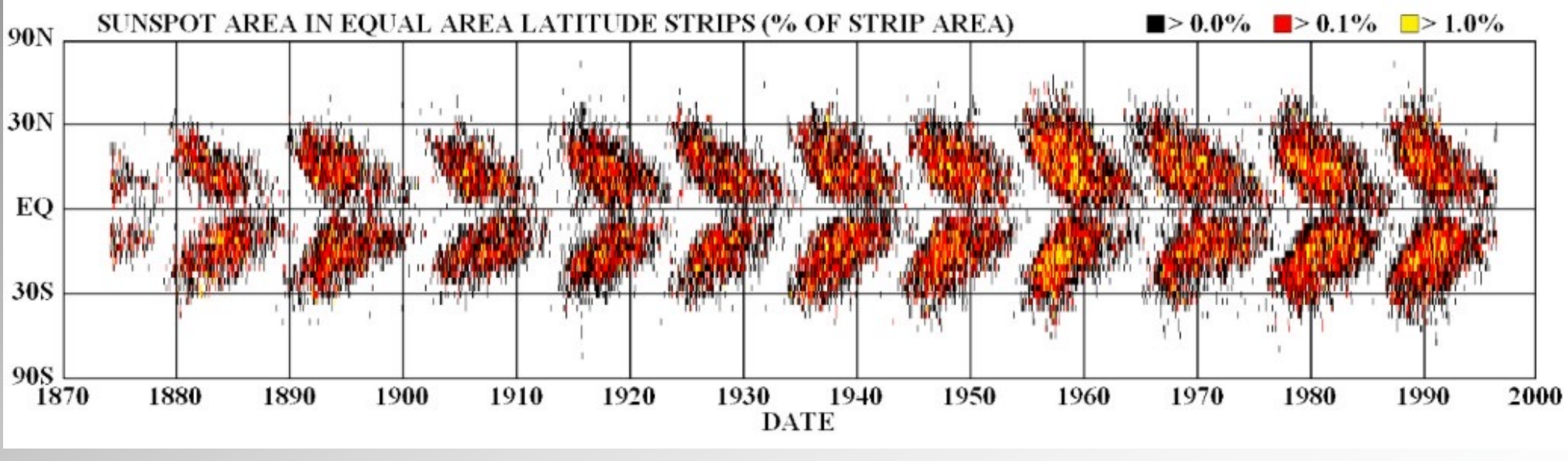
Sunspot field structure determined by lateral pressure balance

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

Photosphere: sunspots II

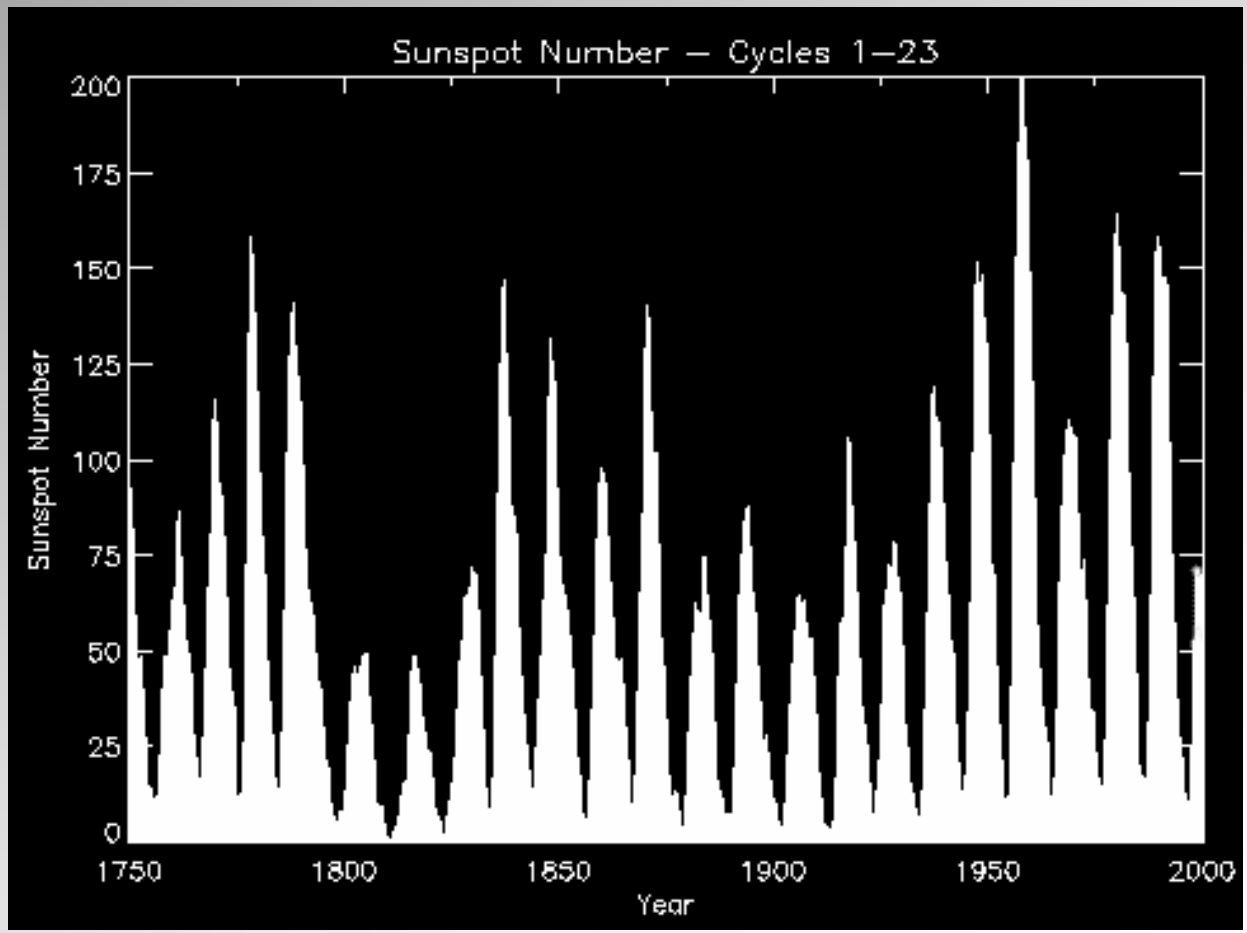


Solar cycle


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

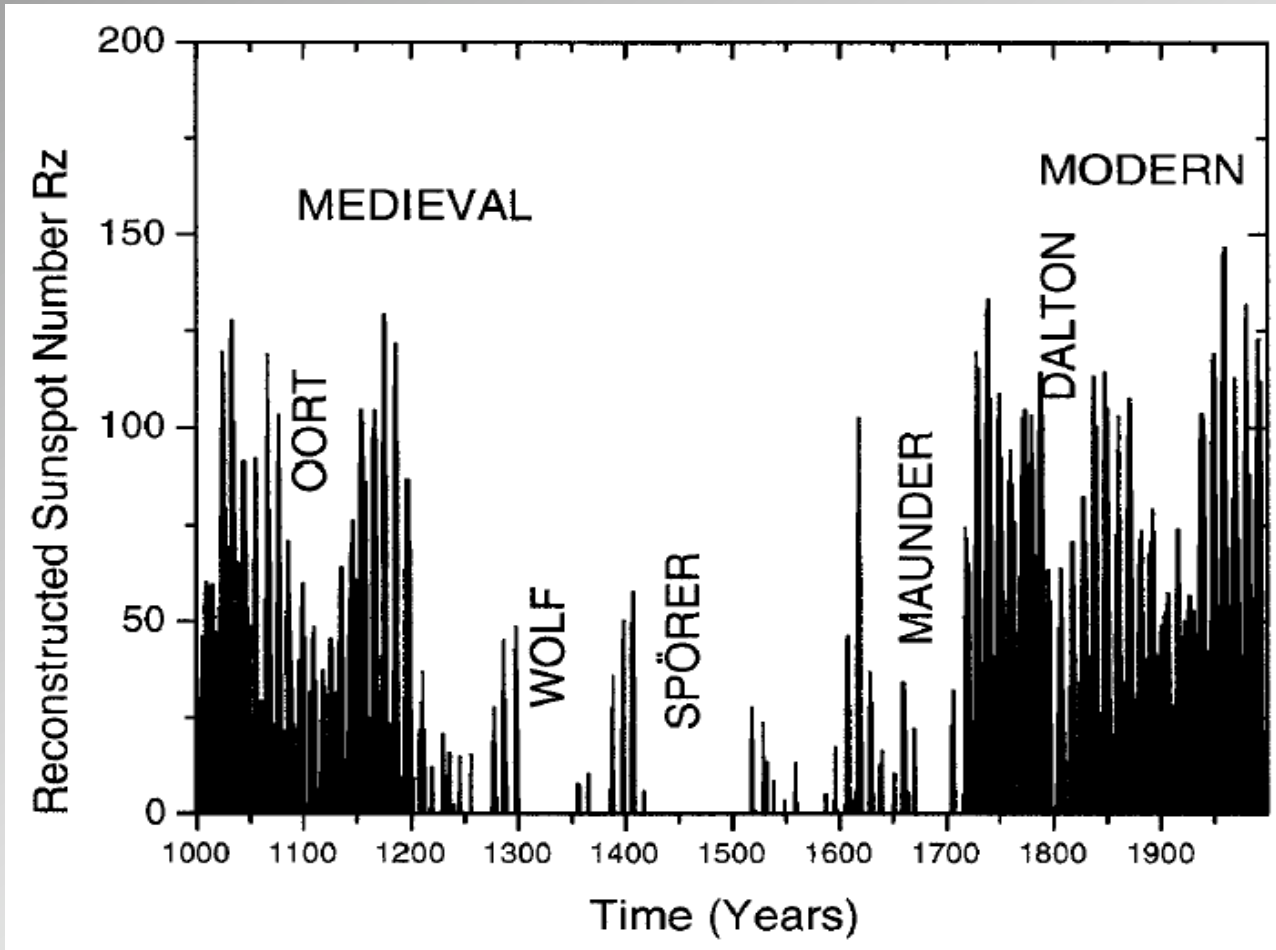
- Approximate 11 year cycle
- Whole magnetic field reverses



Solar cycle

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

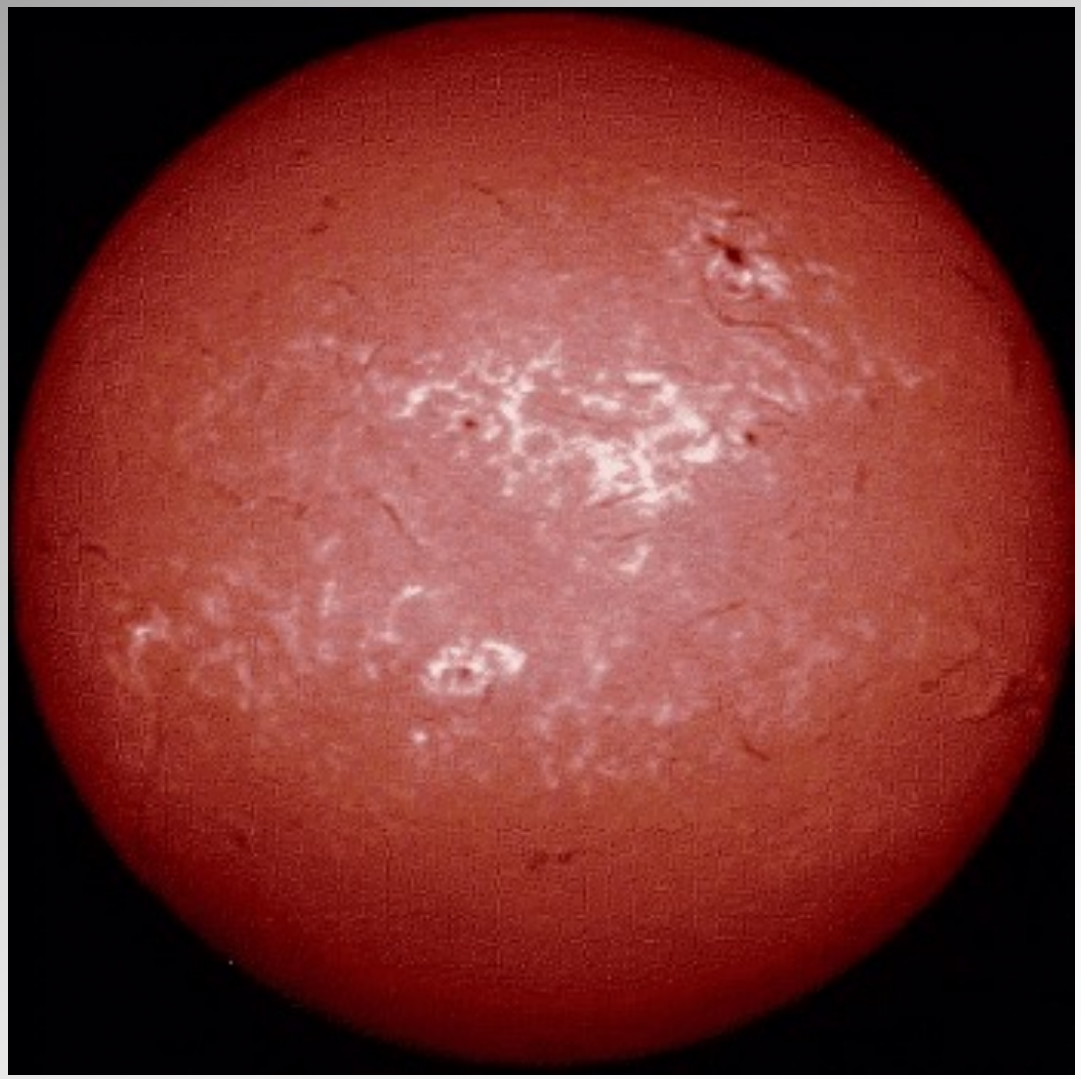
Solar cycle: Grand Minima/Maxima



Rigozo et al., 2001, Solar Physics

Chromosphere

- Hydrogen alpha filter image
- Thickness ≈



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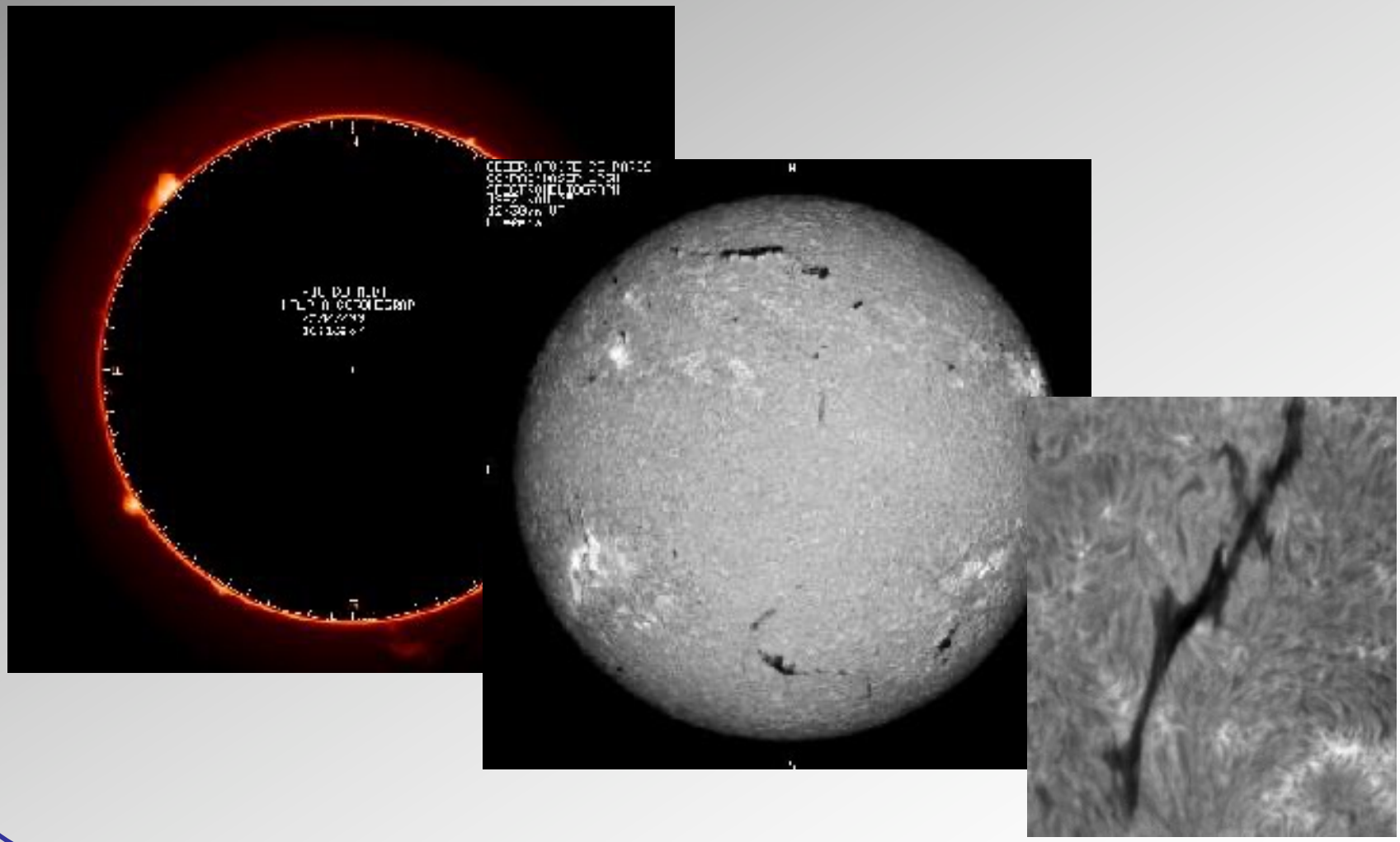
Prominences/filaments

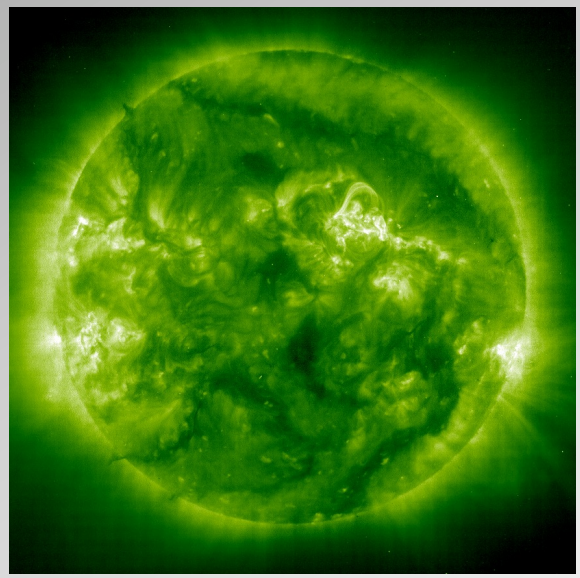


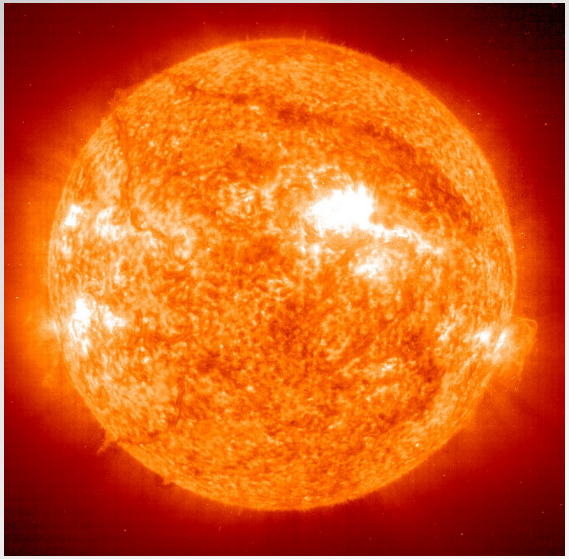
Prominences/filaments

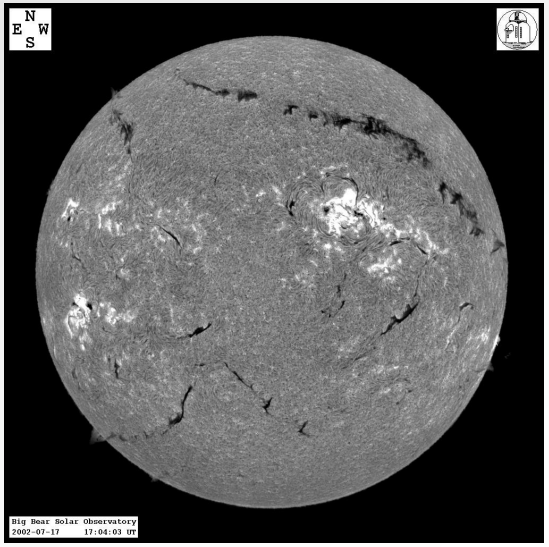
Filaments - called prominences when they appear in emission at the limb - are cool (20,000K) dense ($10^{21}m^{-3}$) gas which is thermally isolated from the surrounding corona.

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

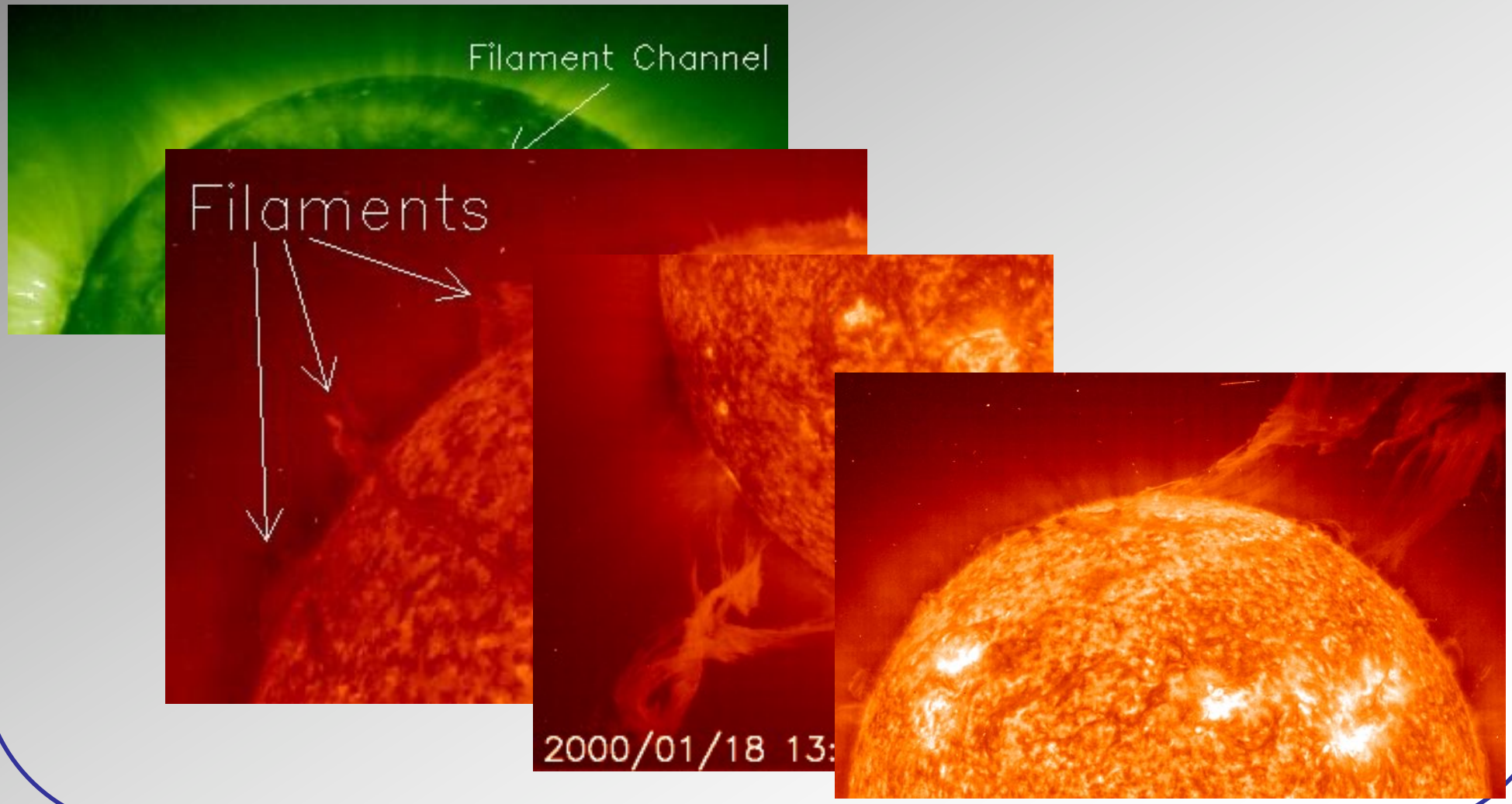
AR filaments tend to erupt within a few days, QS filaments can last and grow for weeks.



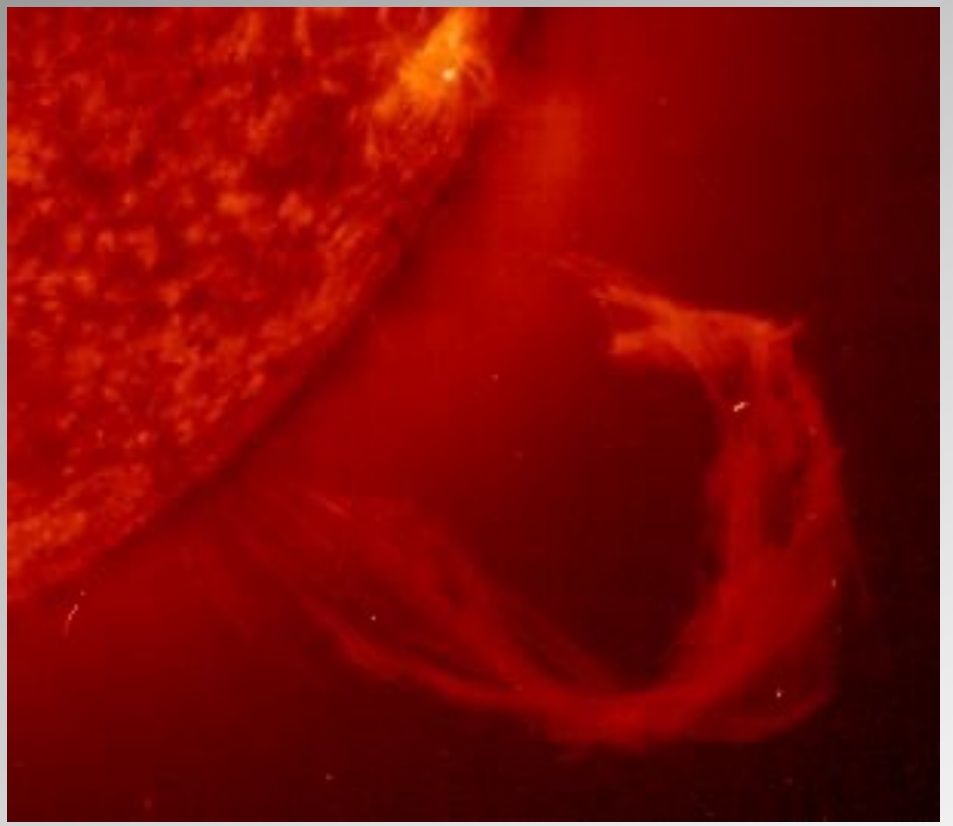


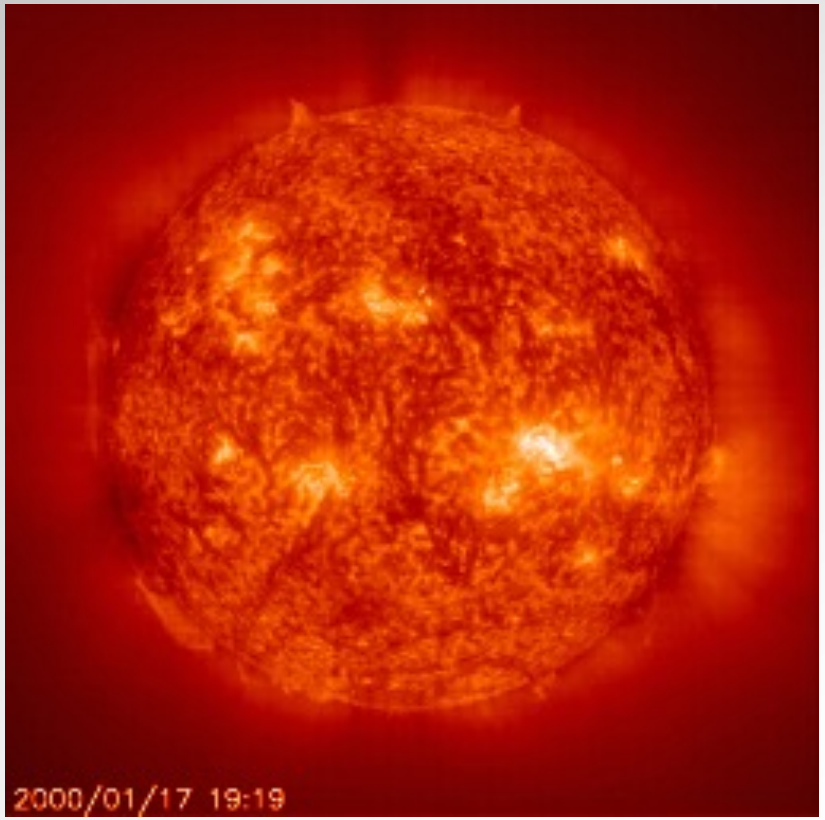


Prominences/filaments (ctd)



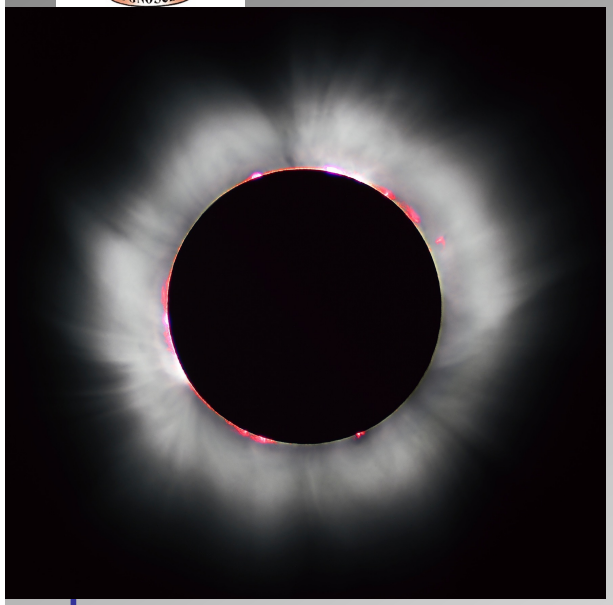
Prominences/filaments (ctd)

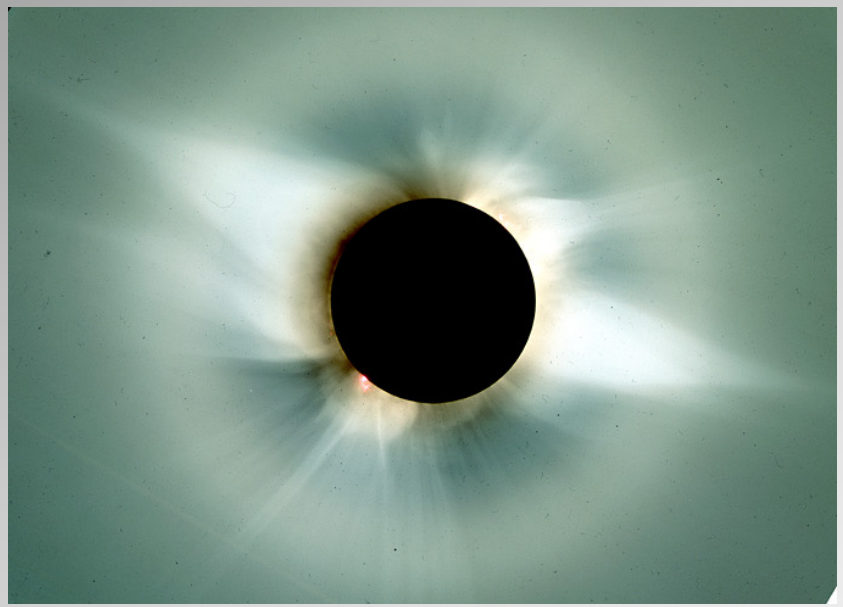




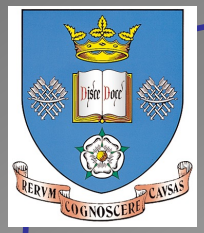
Simple **theory of prominences: they are oscillating!**

The corona at eclipse

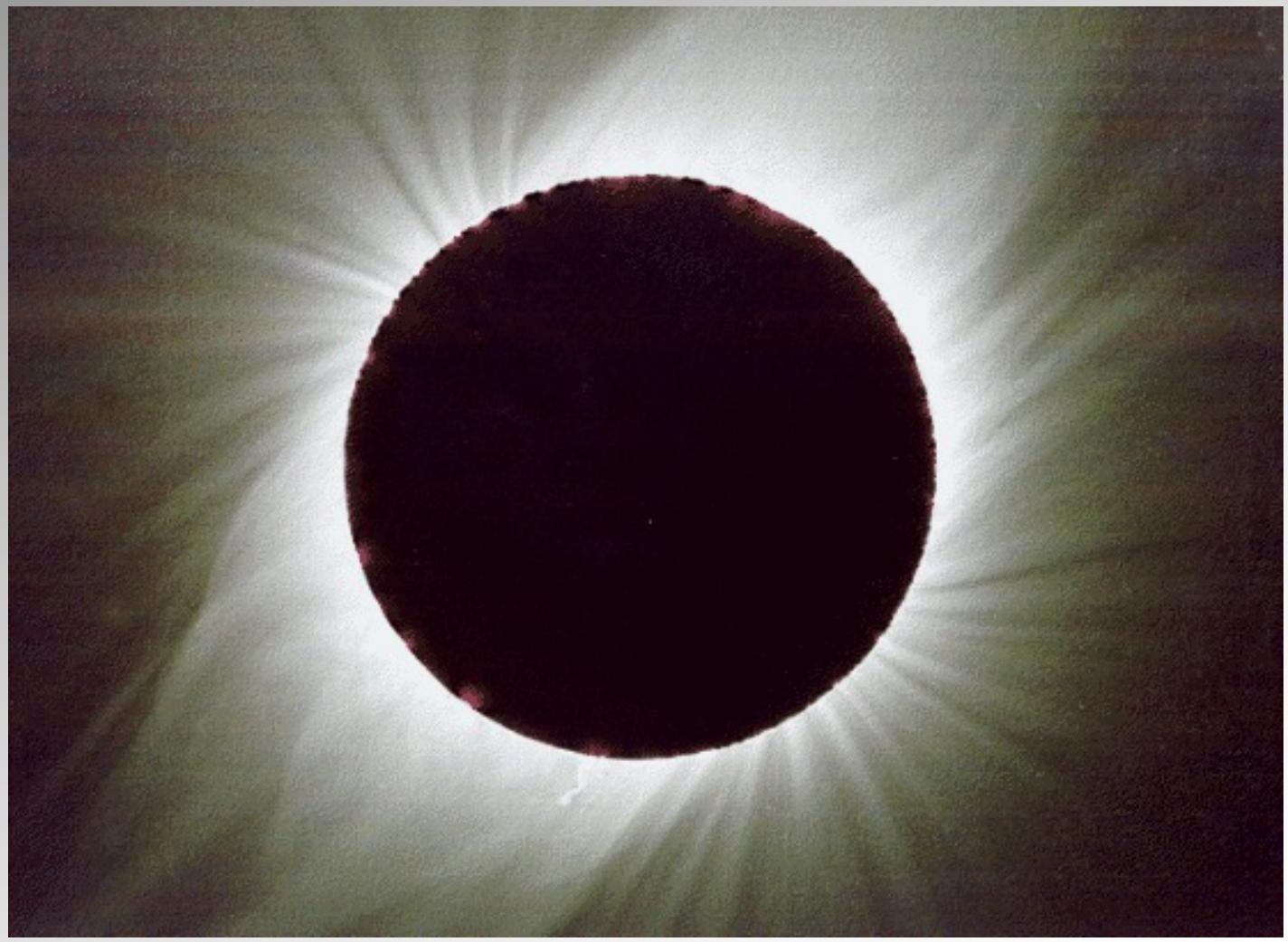




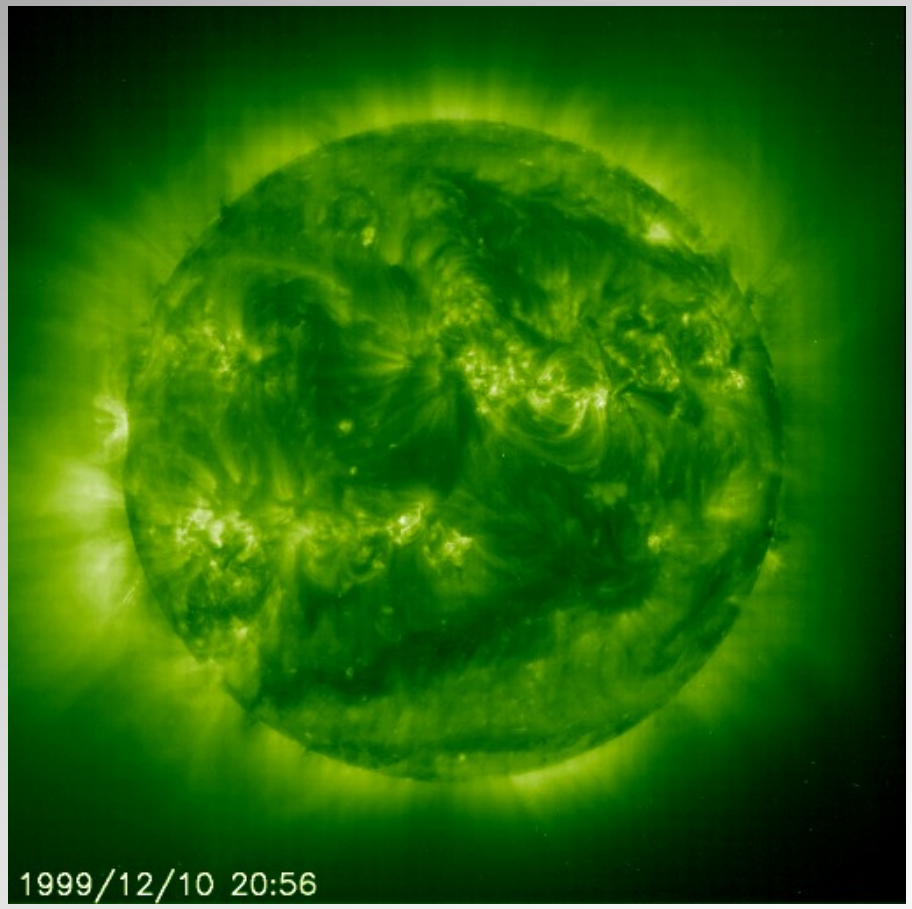
- 1860s – “coronium” discovered
- 1902 – “coronium” has lesser atomic weight than hydrogen (Mendeleev)
- 1930s – spectral lines due to known elements at very high stages of ionisation (Grotrian, Edlén)



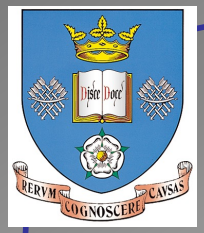
The corona at eclipse



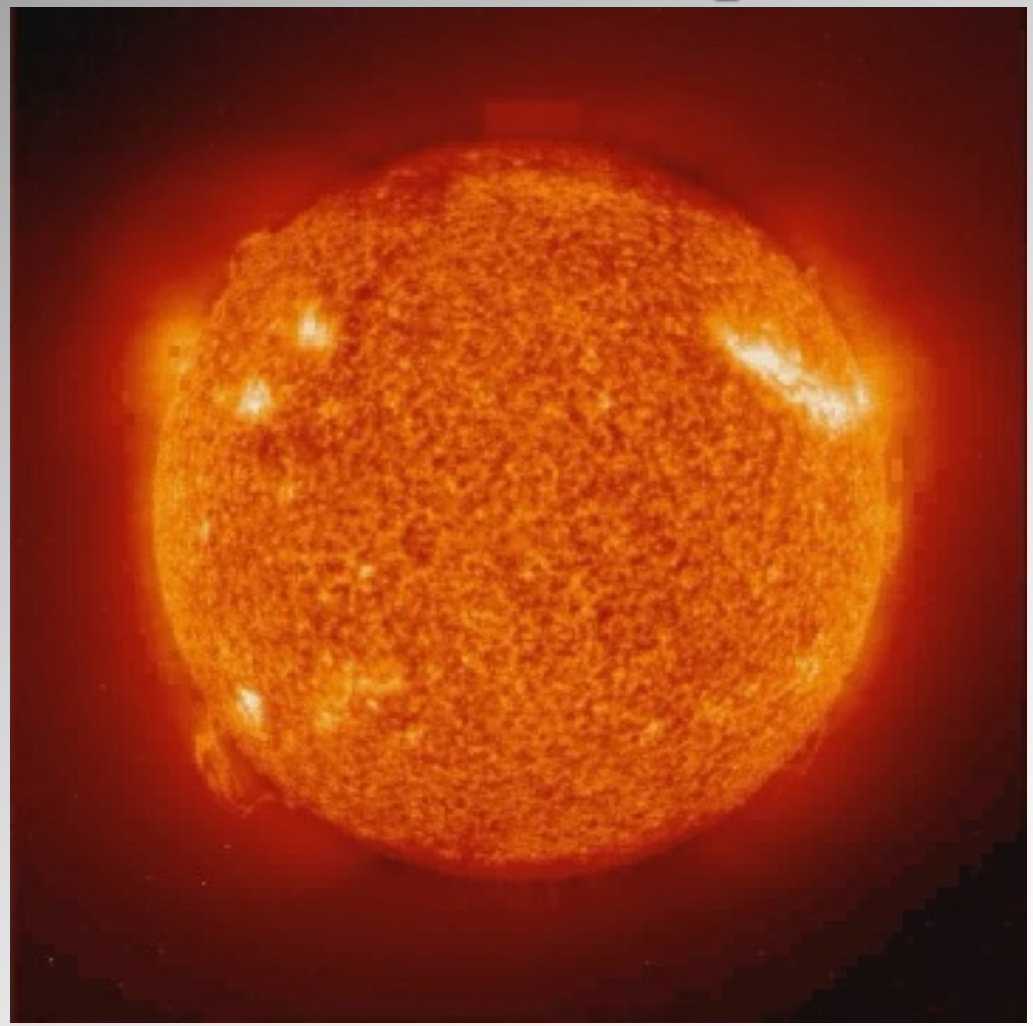
Corona from space

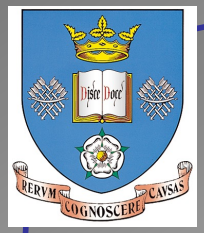


- **Early warning: very rich in structures!**



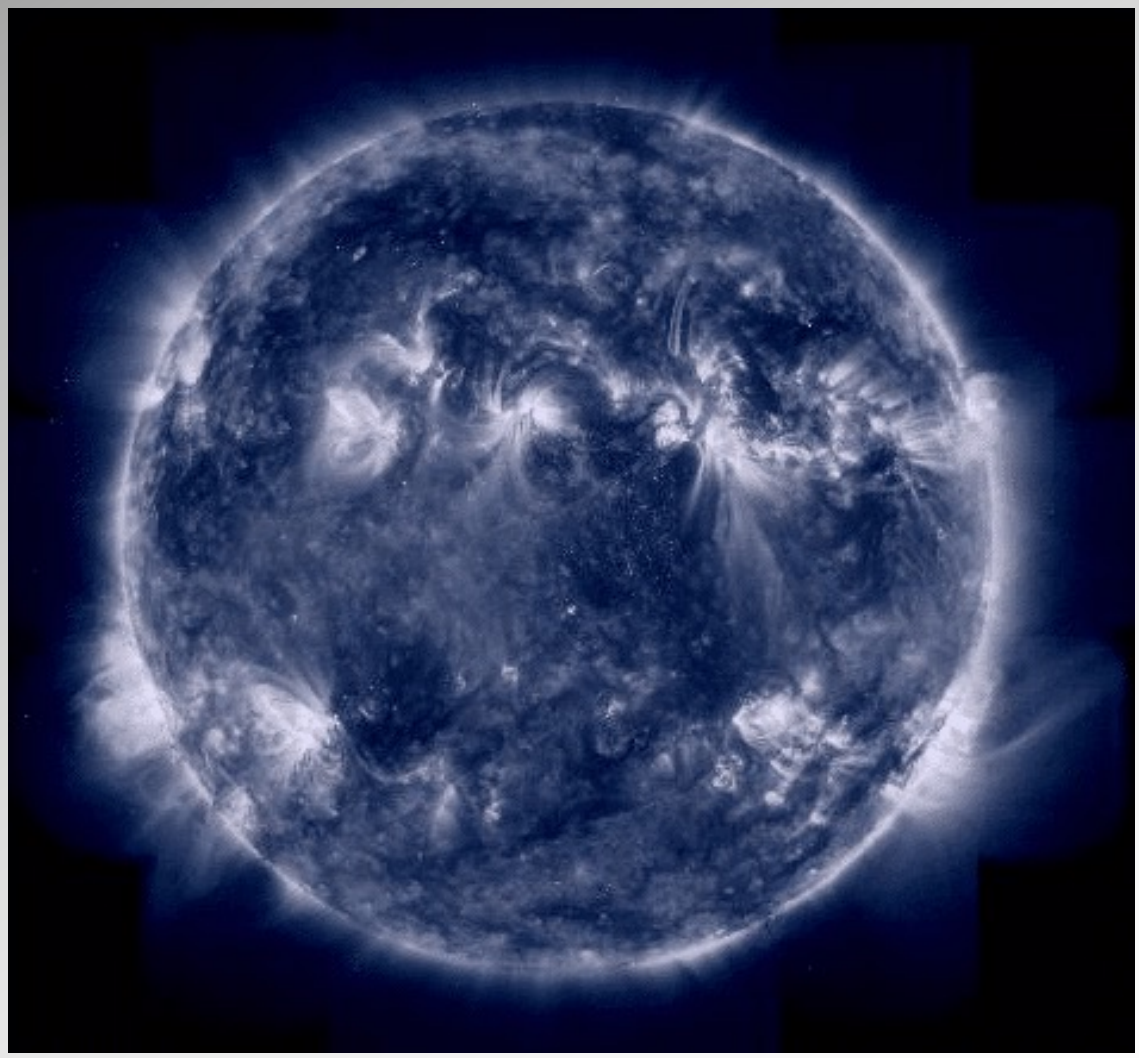
Corona from space





Solar Physics & Space Plasma Research Centre (SP²RC)

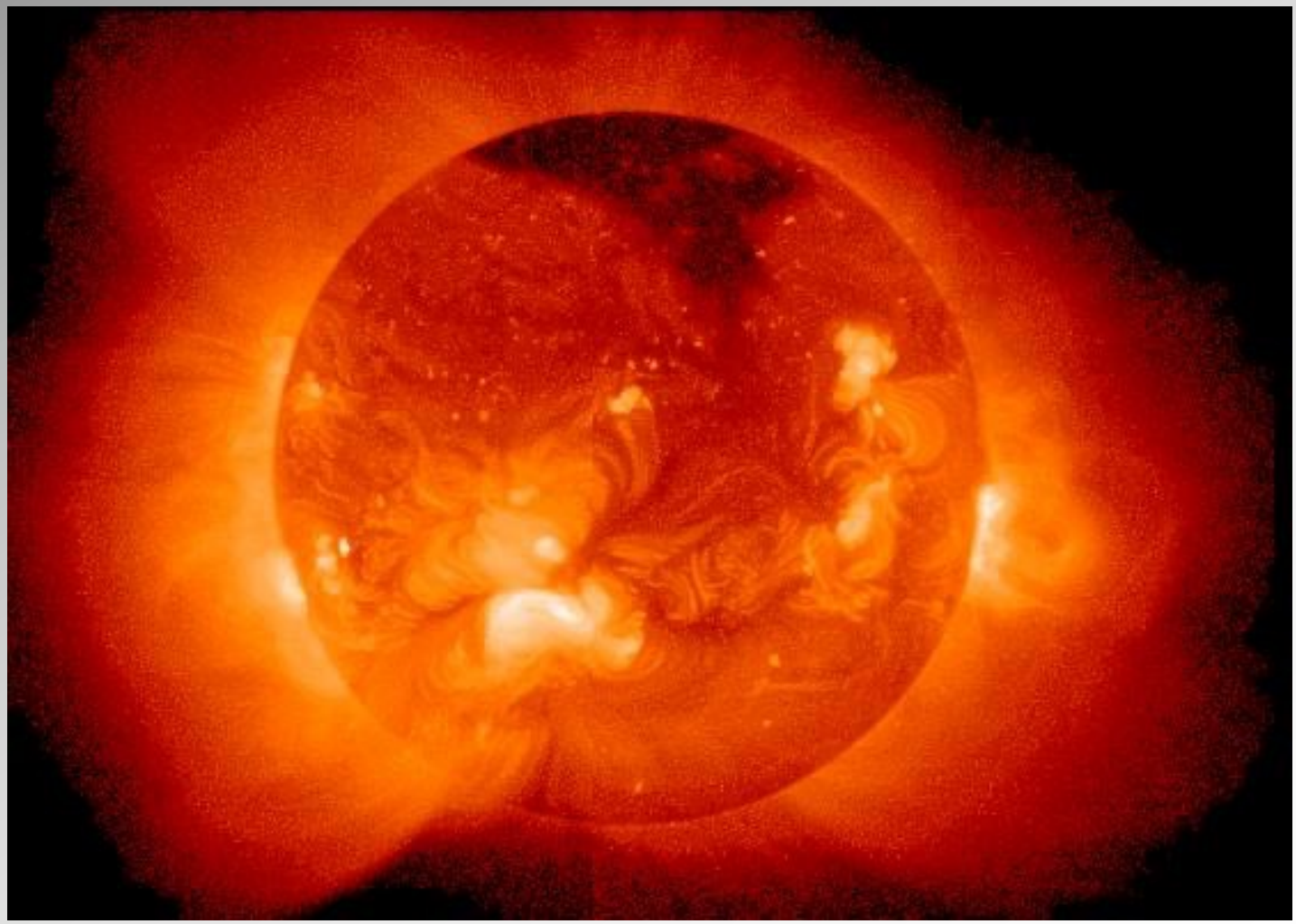
Corona from space



• TRACE Fe IX/X 171 Angstrom line

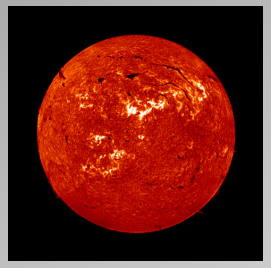
The X-ray corona

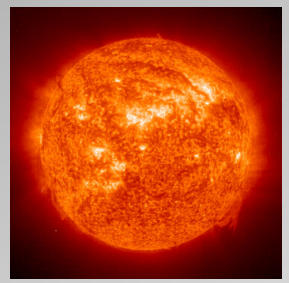
- An atmosphere of hot ionised gases
- Average temperature ≈ 2 million K!



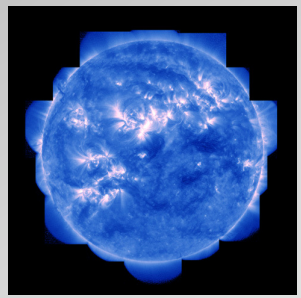
Solar interior - atmosphere

Hα
15,000 K

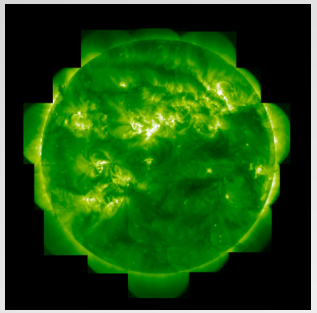




He EUV
50,000 K

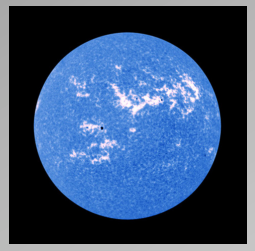


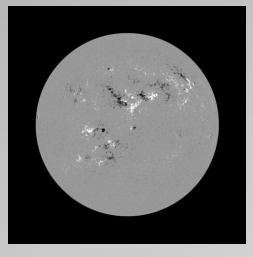
Fe VIII/IX EUV
1 MK



Fe XI
1.5 MK

UV 1600 Å
8000 K

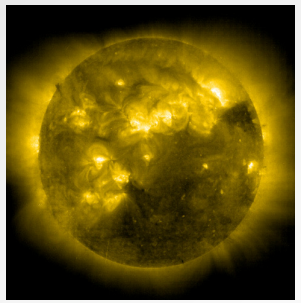


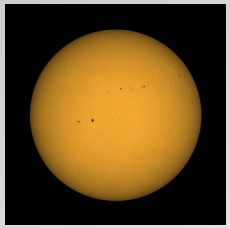


Magnetic field
5000 K

- Highly inhomogeneous
- Ubiquitous magnetic field

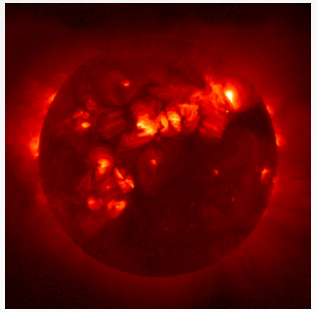
Fe XIV
3 MK

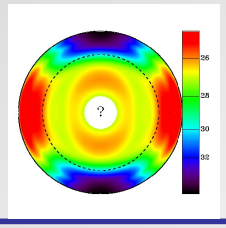




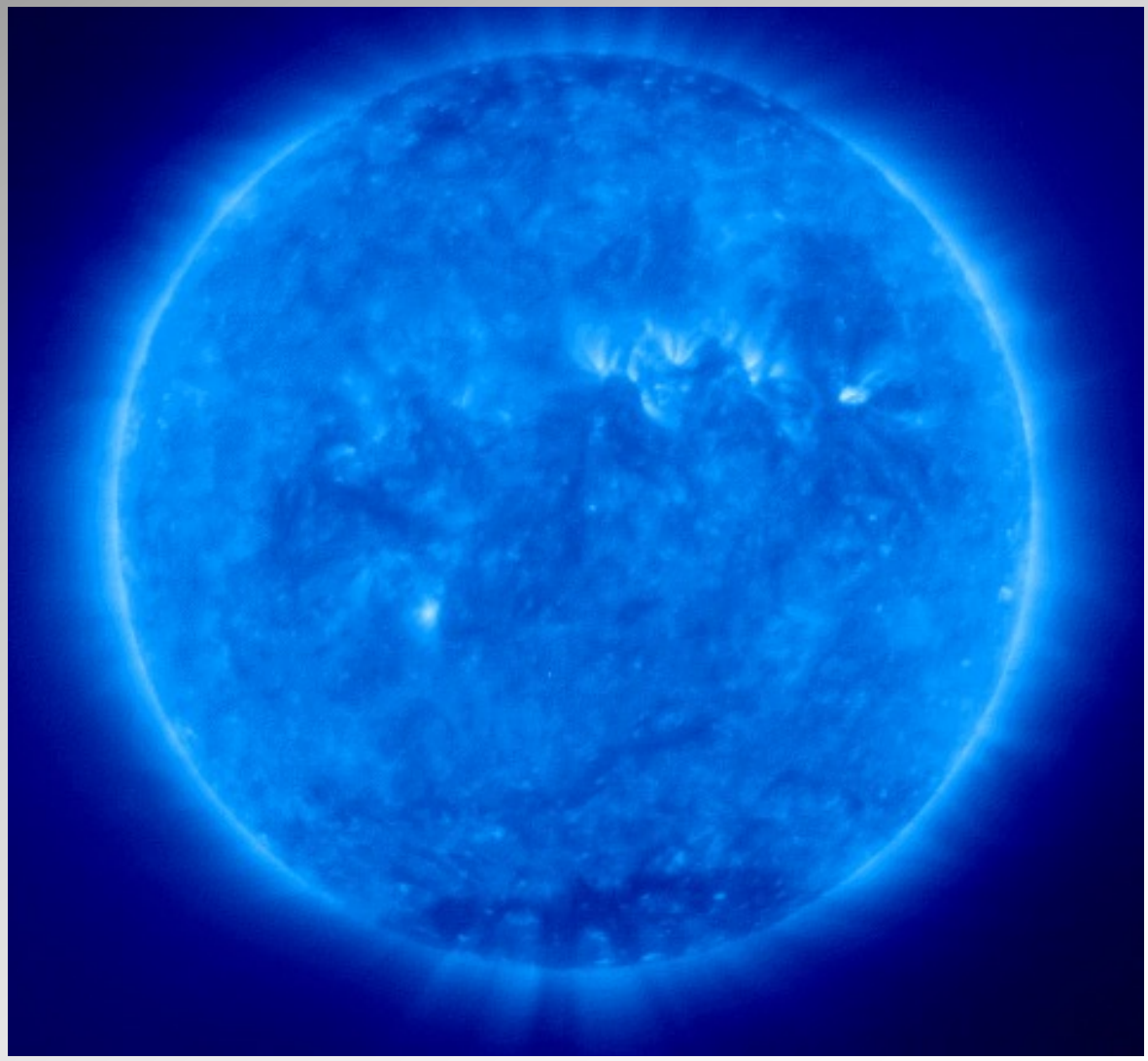
Visible
5000 K

X rays
4-6 MK

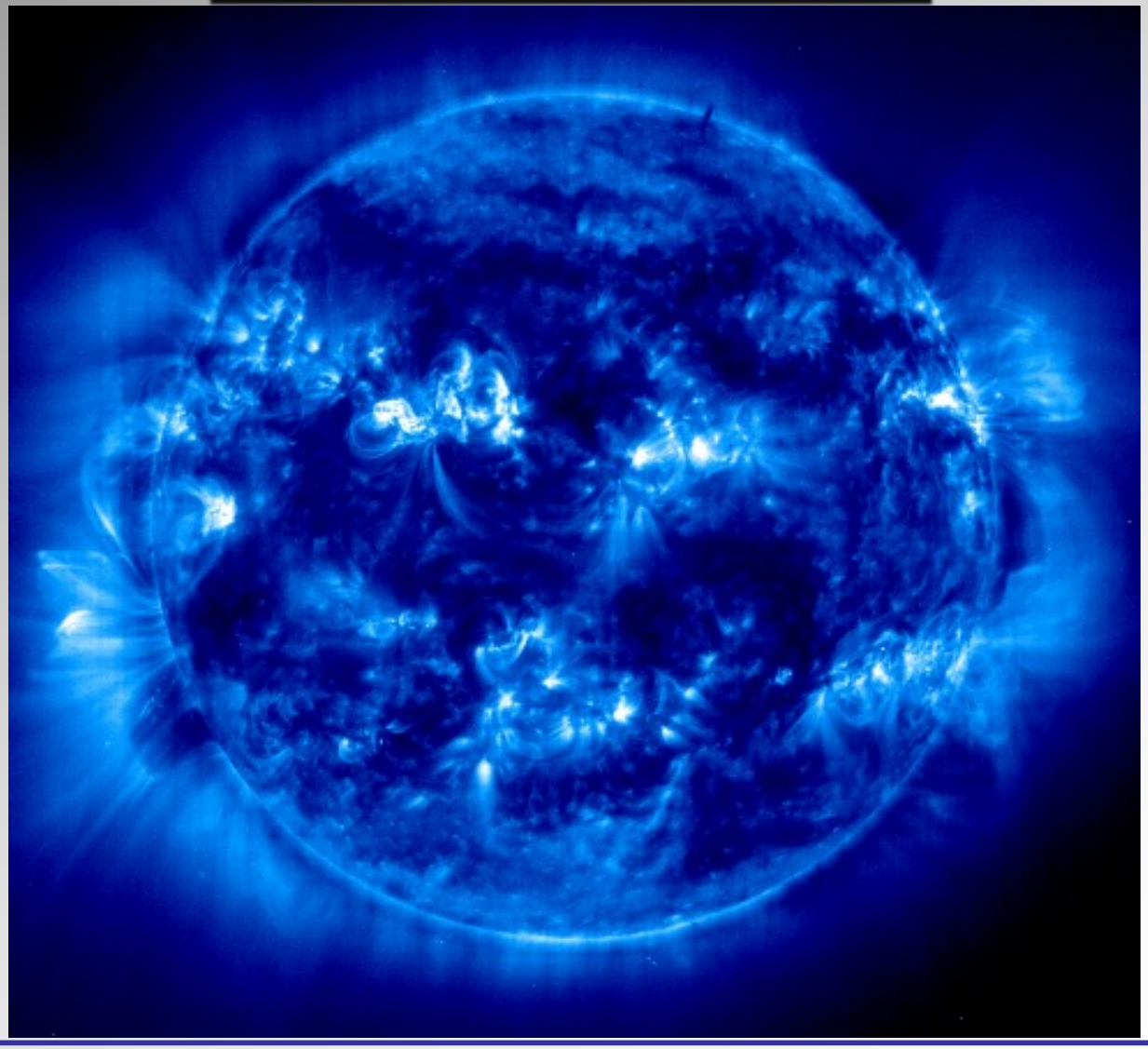


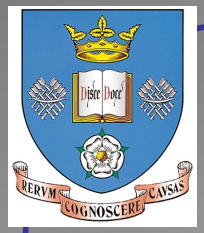


EUV corona in 1995

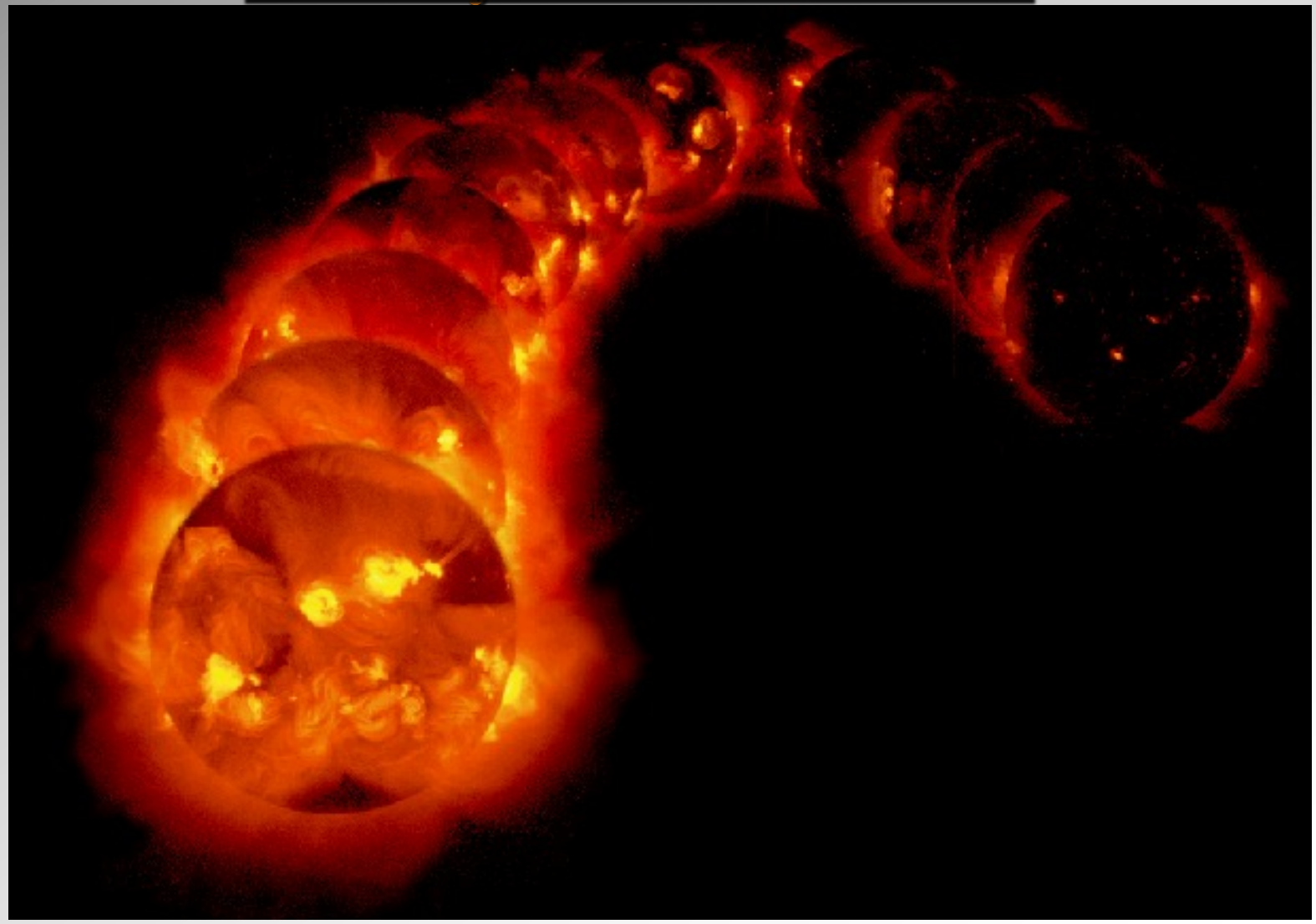


EUV corona in 2000

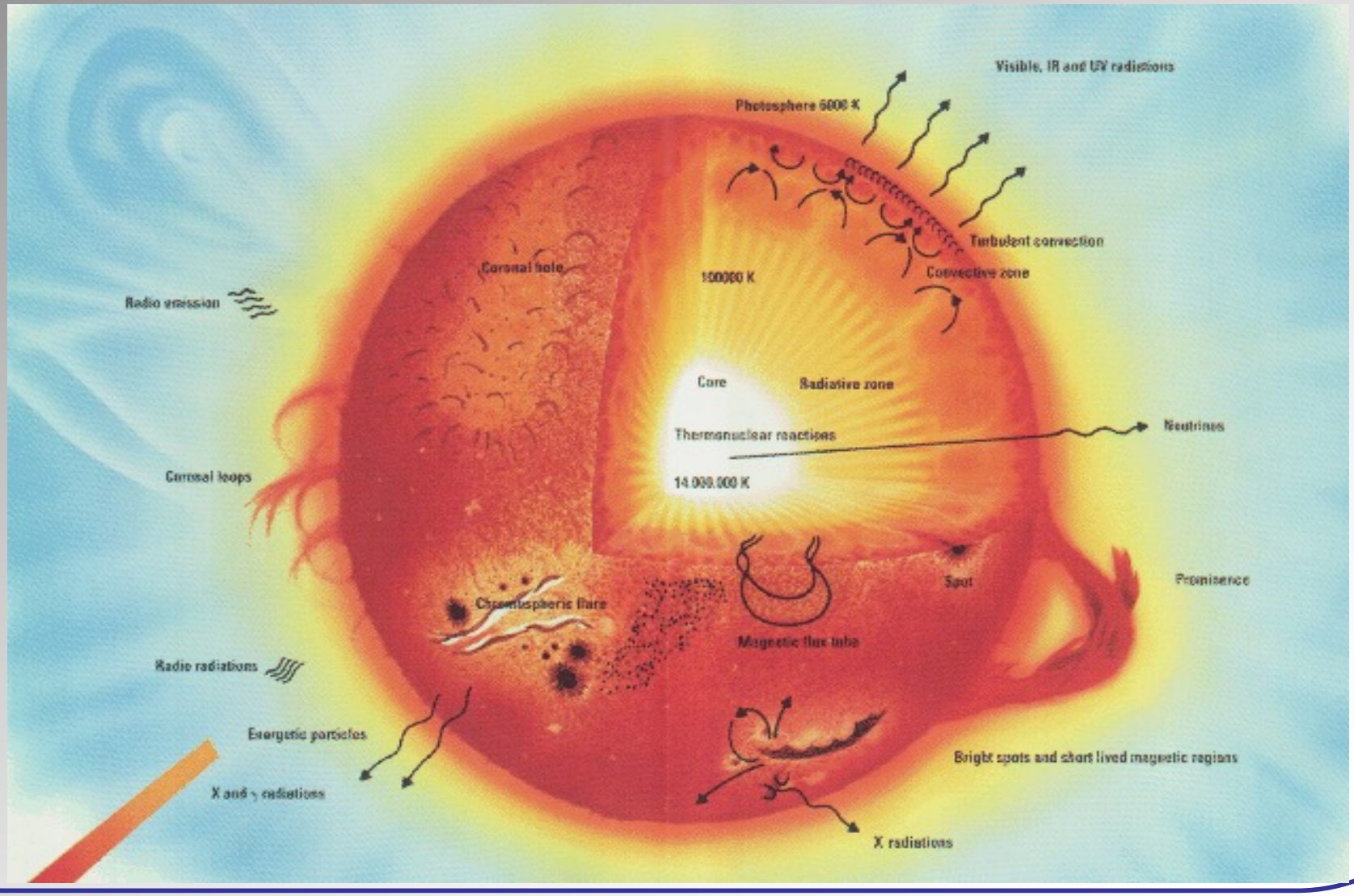




Solar cycle in the corona



Solar atmosphere at my desk



Atmopsheric structures

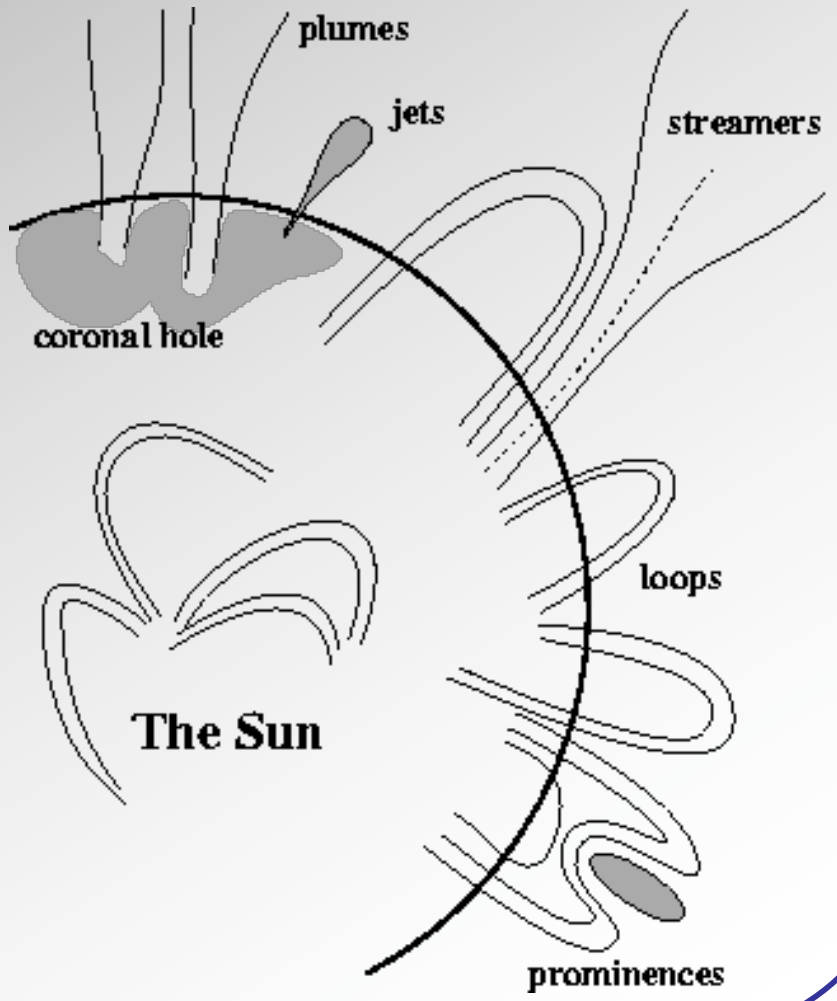
The atmosphere is highly structured in magnetic field, in plasma density and in temperature.

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.

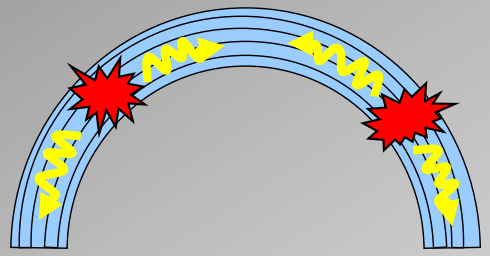
• **Open structures**: coronal holes, streamers, plumes inside the holes. Life time: days-weeks.

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

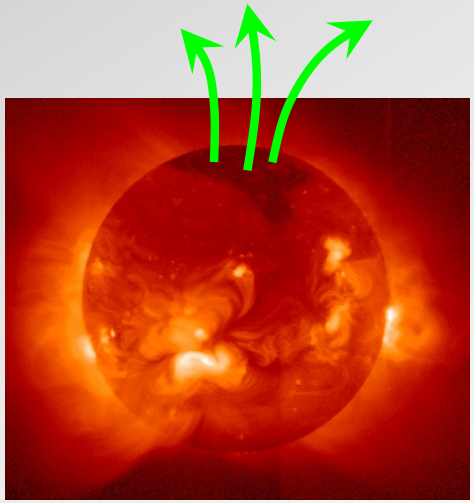


Atmopsheric structures (ctd)

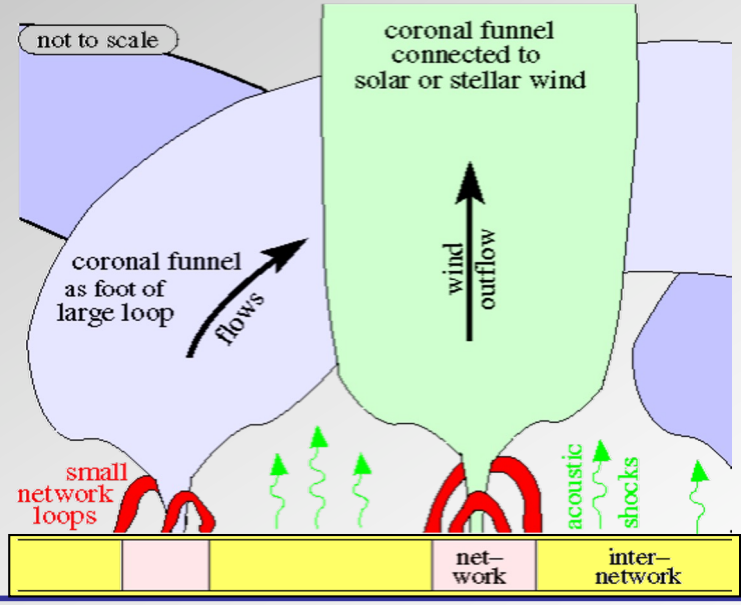
Magnetically closed regions:
network & active regions



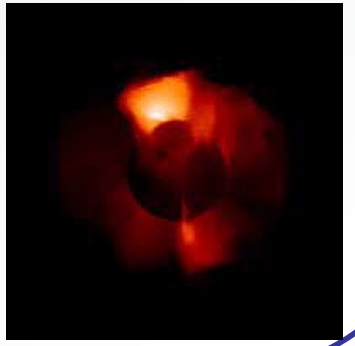
open regions:
coronal holes



"coexisting" open and closed regions



stellar coronae



Characteristics of corona

Main physical facts about the corona:

- Temperature is over 1 MK (c.f. $T_{photosphere}$~ 6000 K).
- Plasma is mainly hydrogen and is almost fully ionised, $n < 10^{15}$ m^{-3}.
- The plasma is magnetized, B = 5-100 G.
- Plasma-β (ratio of kinetic and magnetic pressures) is low (0.001-0.01). The plasma is "cold"!
- Plasma is gravitationally stratified ($g_\odot$=274 m/s^2), the scale height H is about 50-60 Mm (c.f. $R_\odot$=696 Mm).
- The acoustic cut-off frequency [~$C_S(4\pi H)^{-1}$] is about 0.2 mHz (Period is about 60 min).
- The origin of the solar wind. (Speeds are up to several hundred km/s at a few $R_\odot$).
- Typical Reynolds numbers are higher than 10^6.

Characteristics of corona

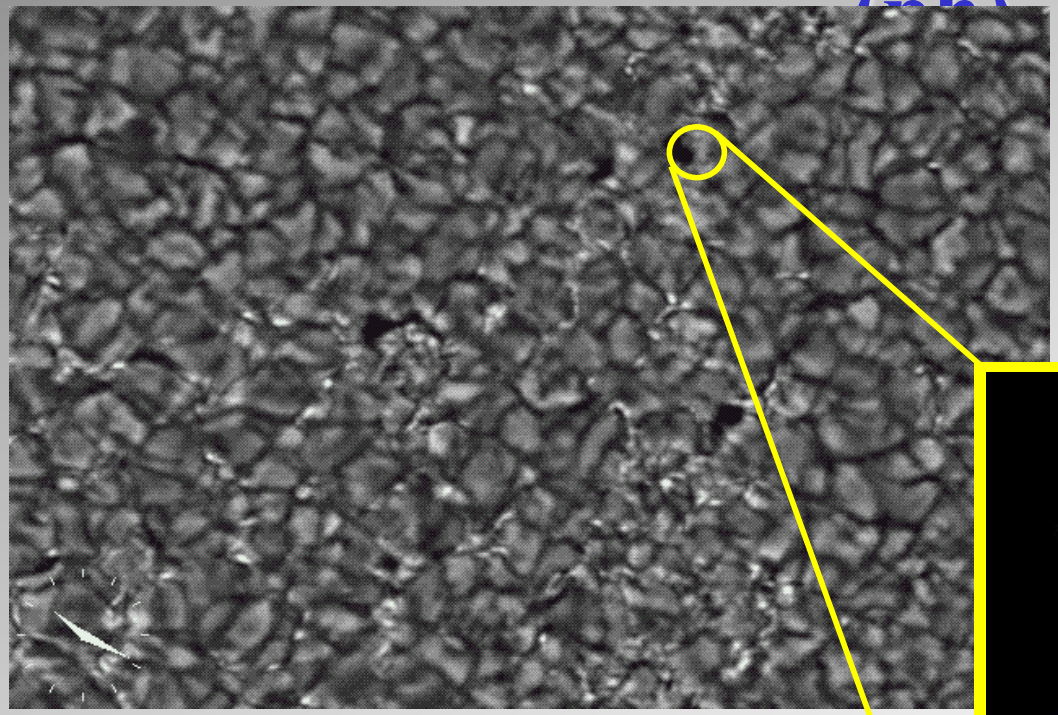
Fundamental puzzles of the corona:

• 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).

Atmopsheric structures: the underlying driver (p.h.)

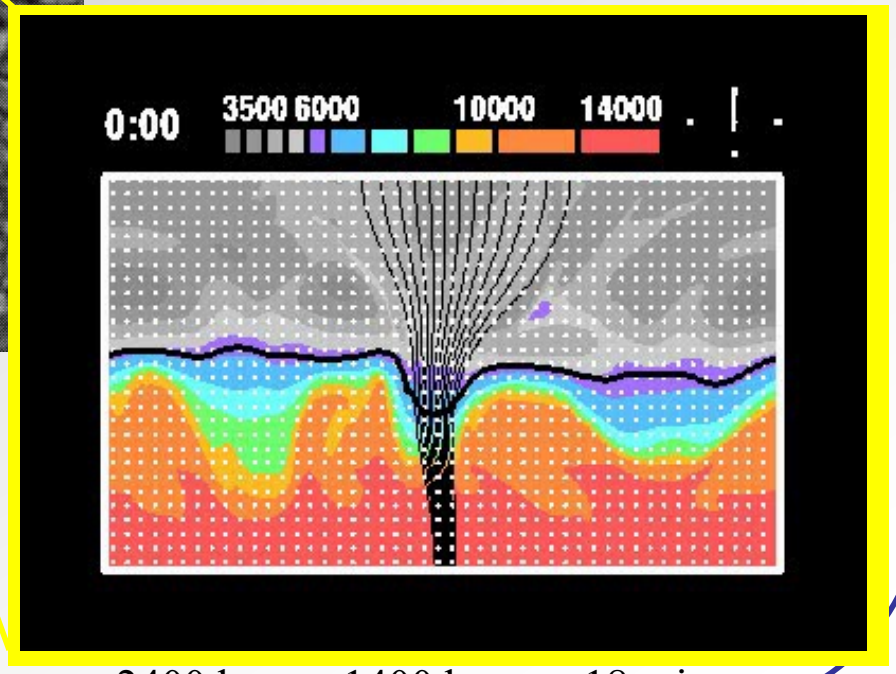


Dutch Open Telescope, La Palma
12. Sept. 1999 [Sütterlin & Rutten]

≈ 25 000 km x 38 000 km

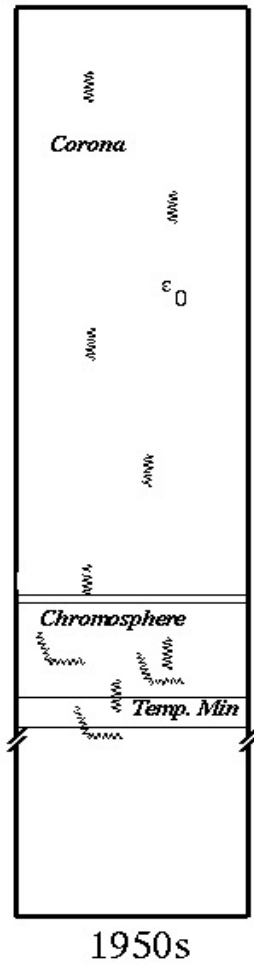
observation in G-Band ≈ 430 nm
granulation (Ø ≈1000 km)
G-band bright points:
small magnetic flux tubes, which
are brighter than their surrounding

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



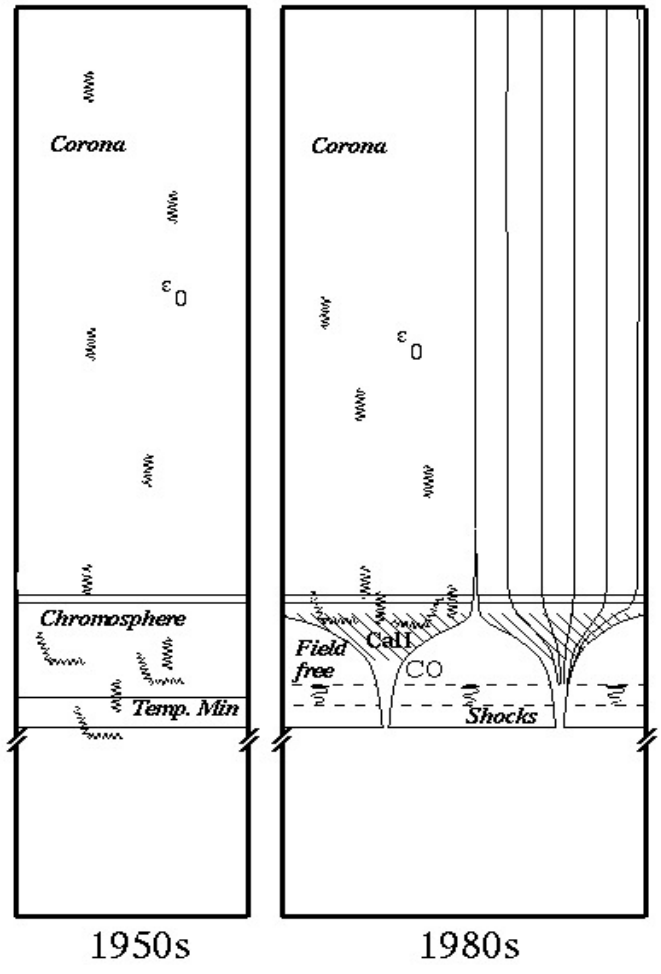
≈ 2400 km x 1400 km, ≈ 18 min

Atmospheric magnetic structure



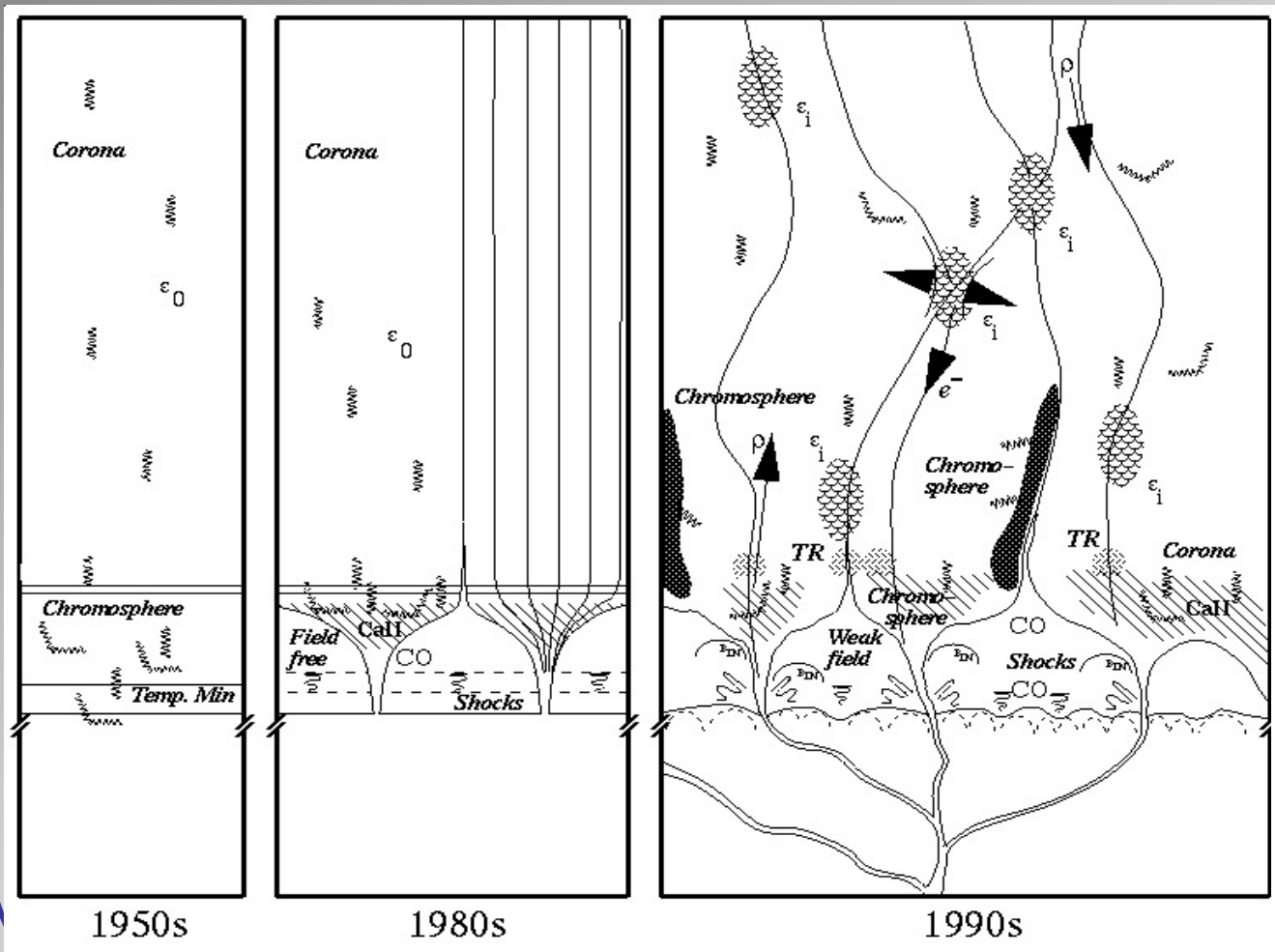
Images/interpretation: Karel Schrijver

Atmospheric magnetic structure



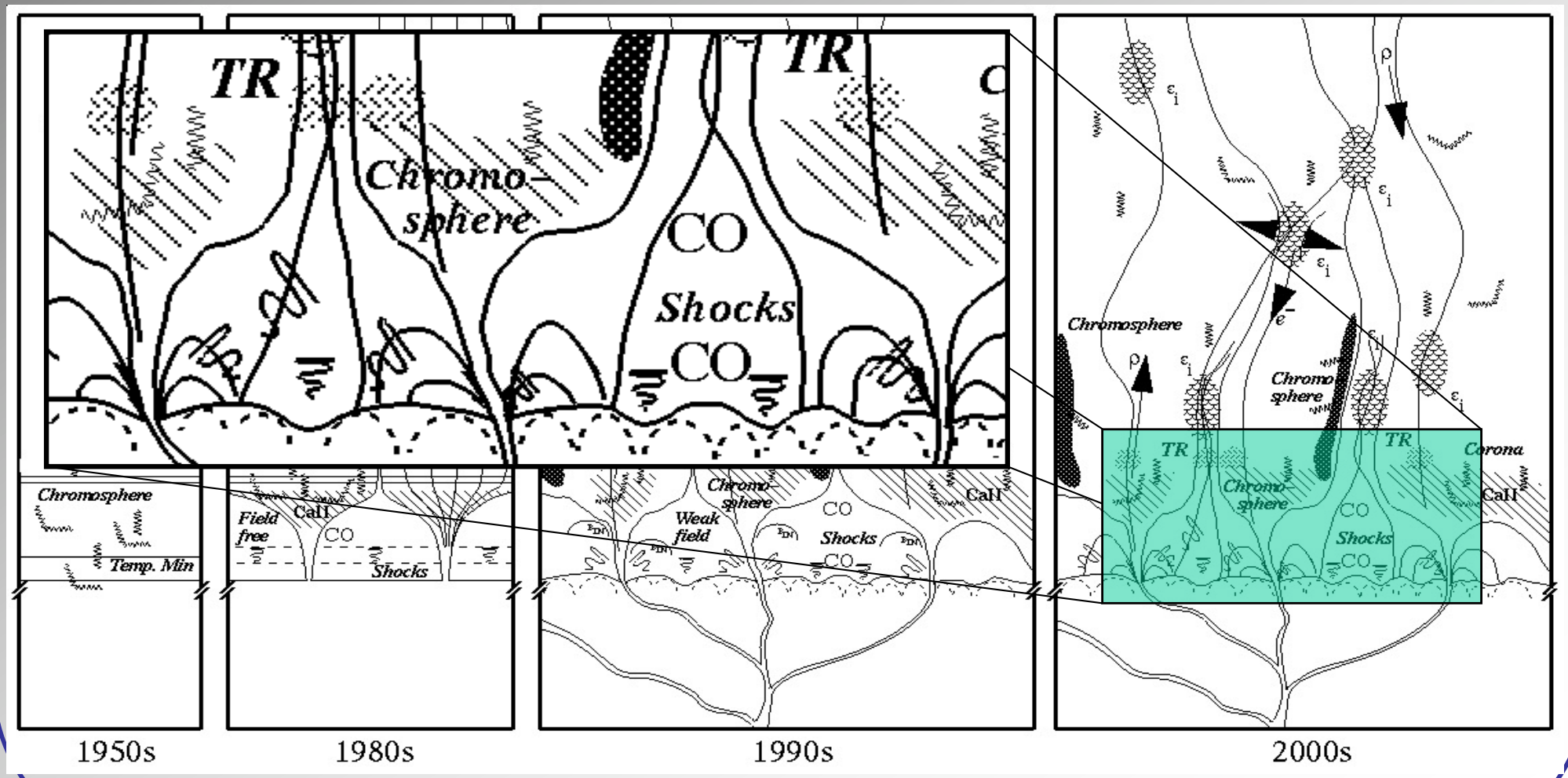
Images/interpretation: Karel Schrijver

Atmospheric magnetic structure



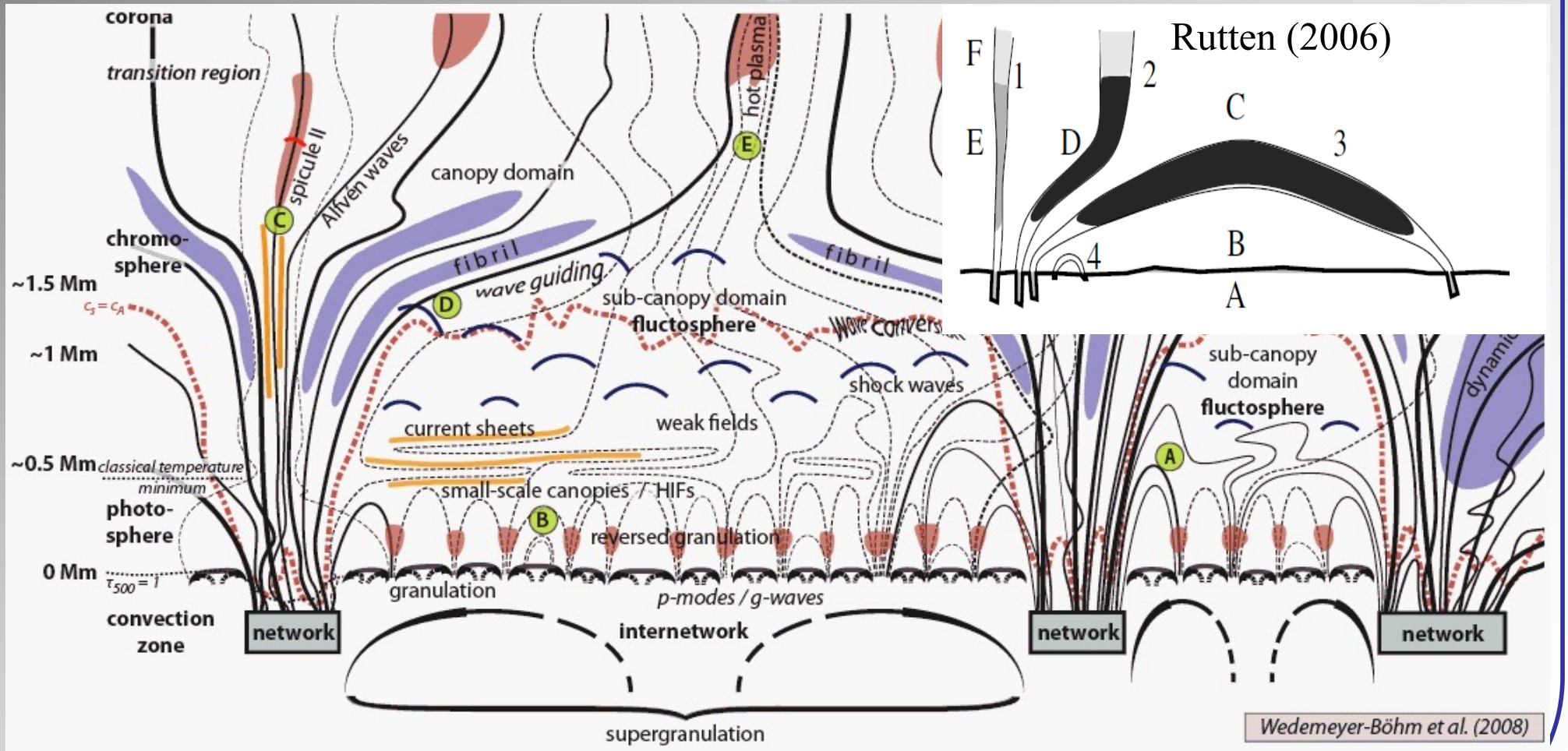
Images/interpretation: Karel Schrijver

Atmospheric magnetic structure

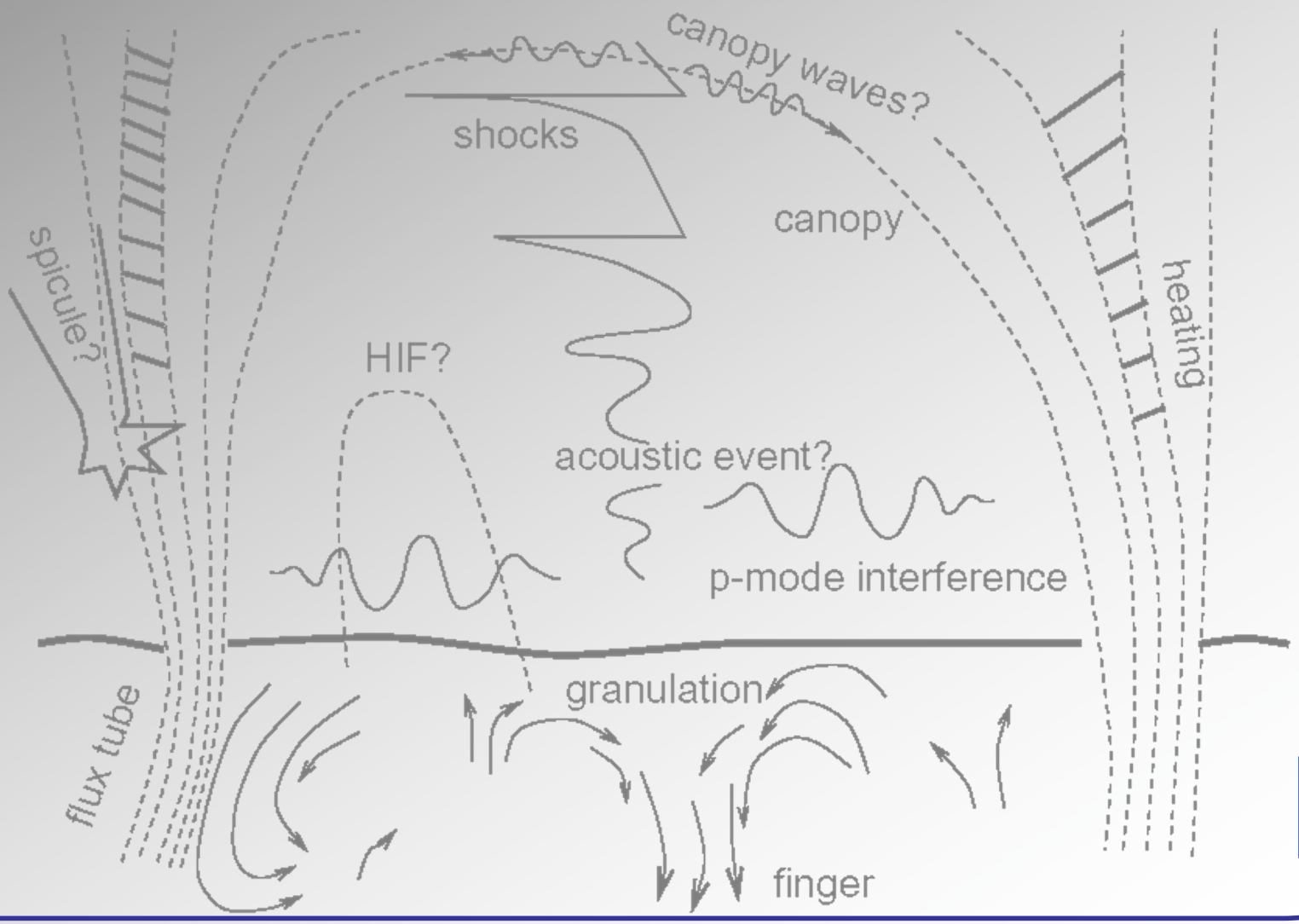


Images/interpretation: Karel Schrijver

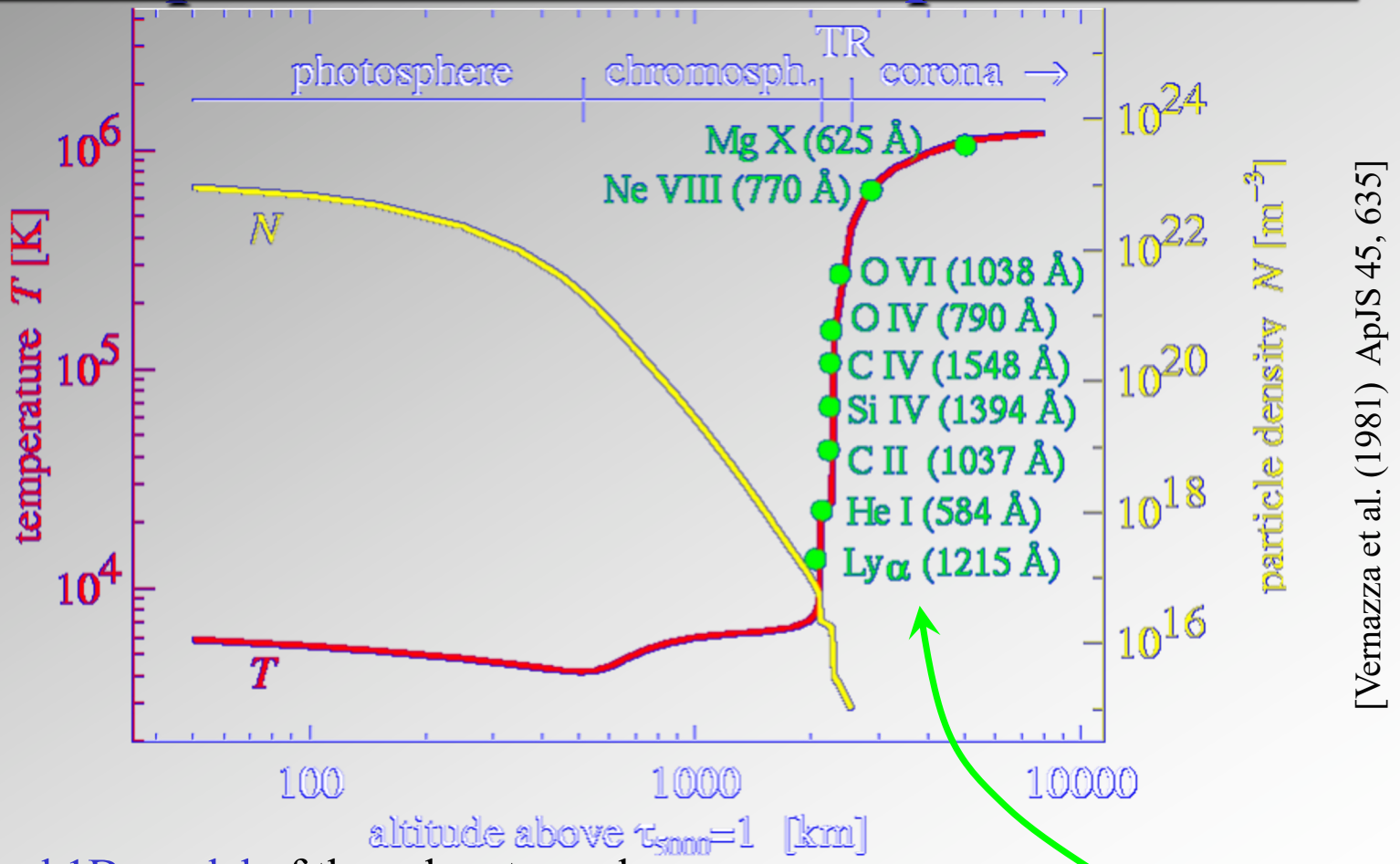
Model improvement



Atmoshperic structures: underlying driver (ch)



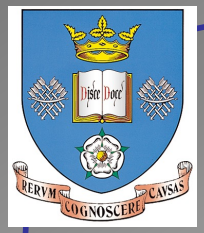
Photosphere ➔ corona: 1D point of view



[Vernazza et al. (1981) ApJS 45, 635]

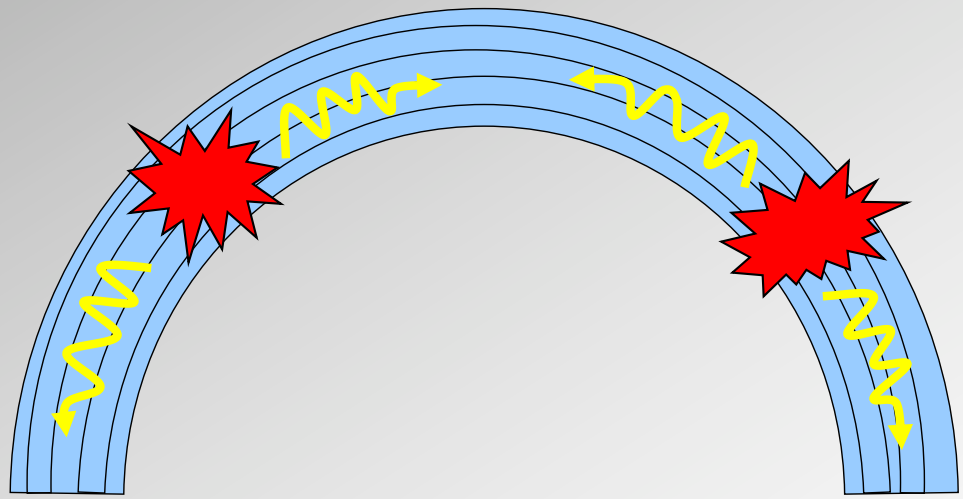
- Semi-empirical 1D-model of the solar atmosphere
- Steep increase of temperature in the transition region (TR) < 100 km thick

some lines observable with SUMER / SOHO

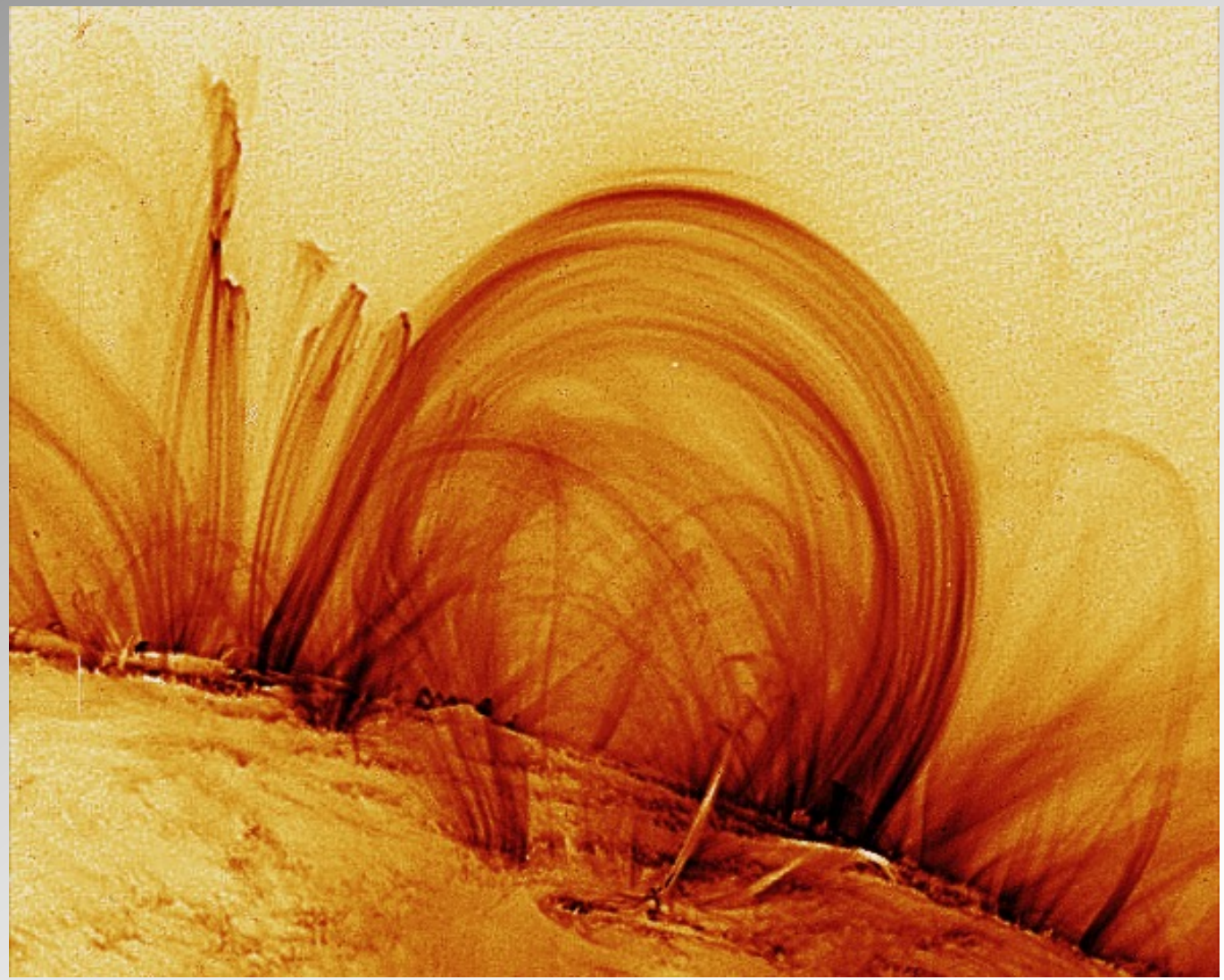


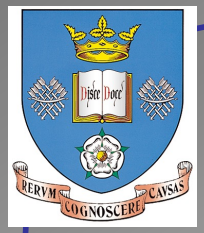
Is there magnetostatic equilibrium?

Magnetically closed structures



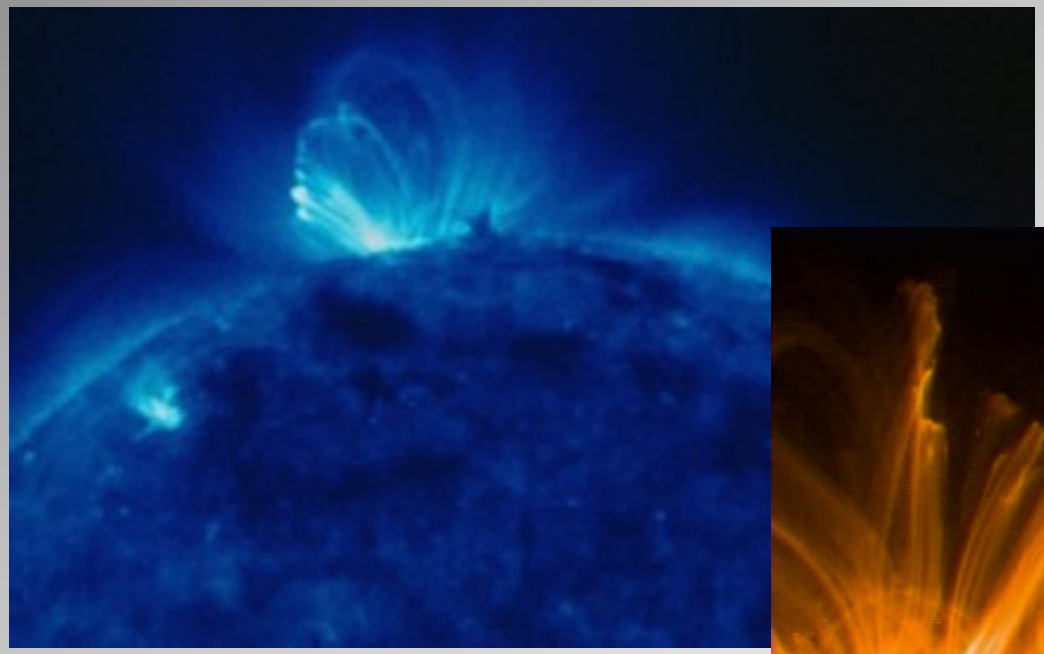
Coronal loops by TRACE





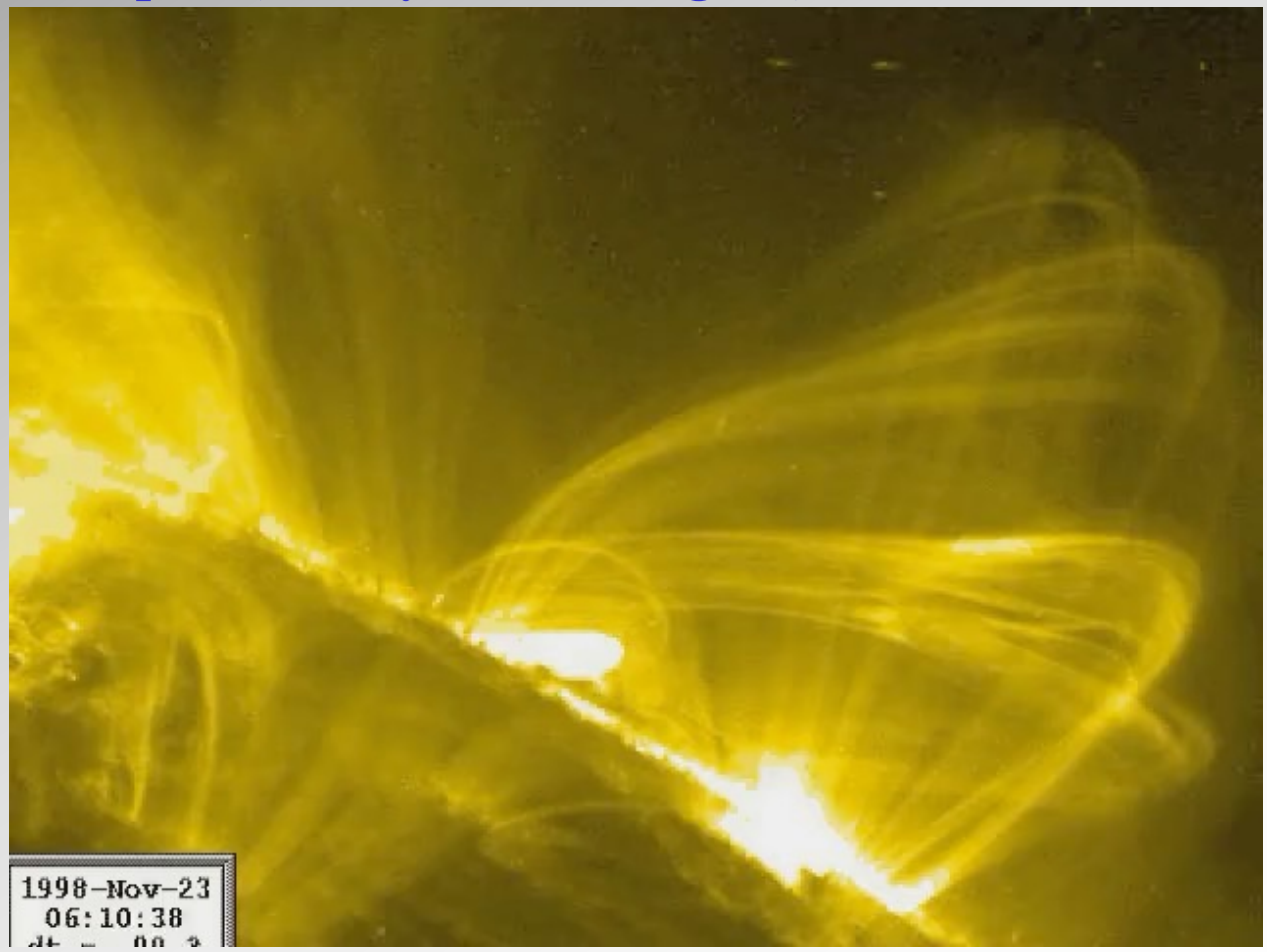
Solar Physics & Space Plasma Research Centre (SP²RC)

Coronal loops



Do loops move?

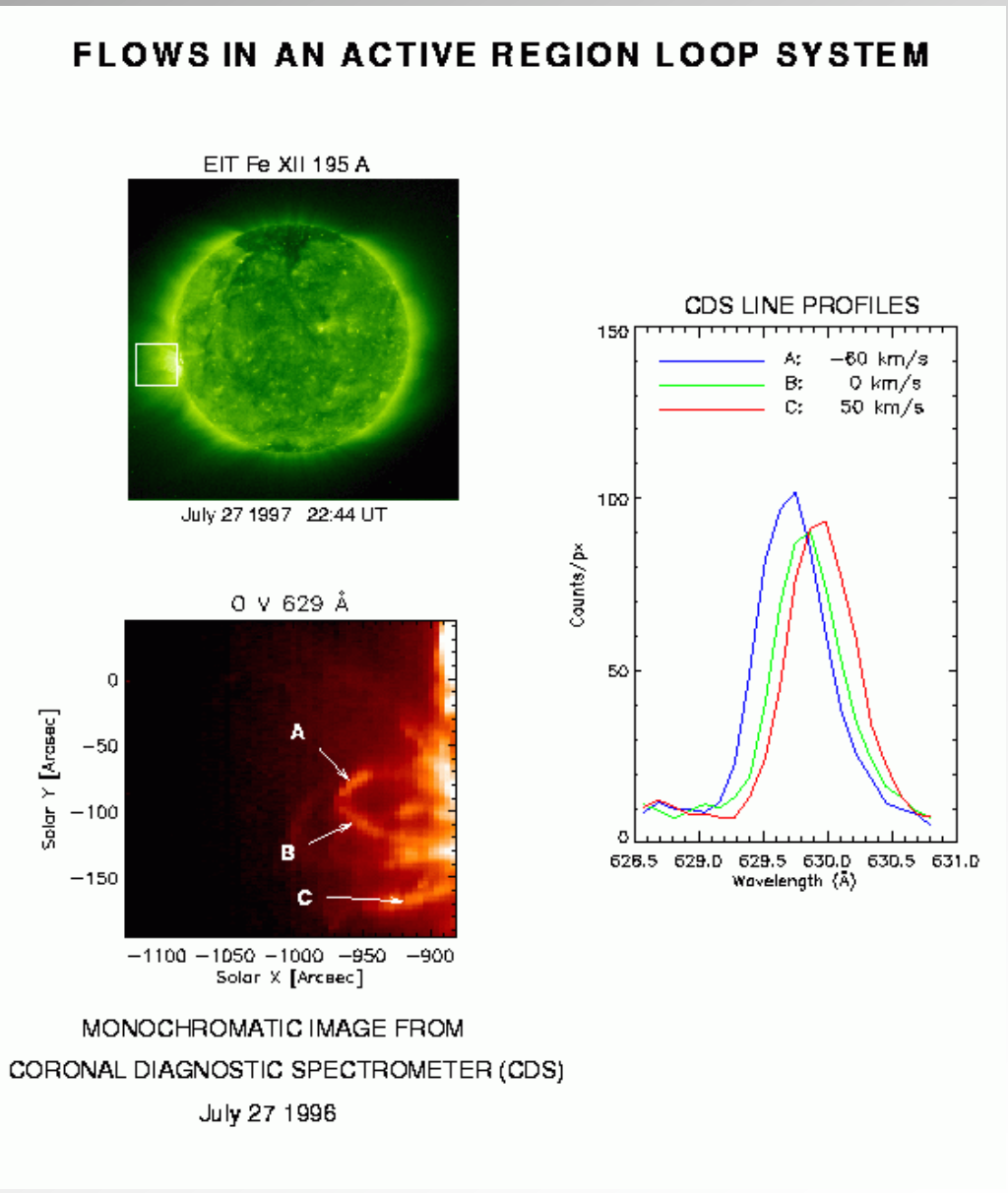
SOHO/TRACE examples (mainly TR and higher)



Do loops move?

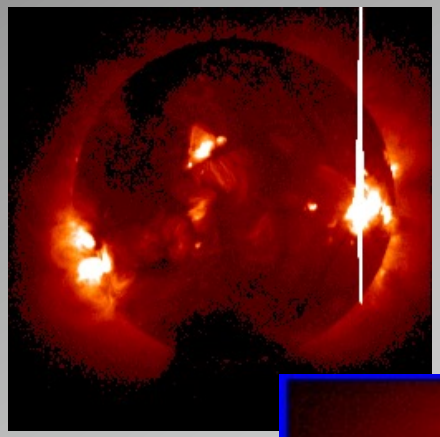
SOHO/TRACE examples (mainly TR and higher)

Equilibrium of coronal loops

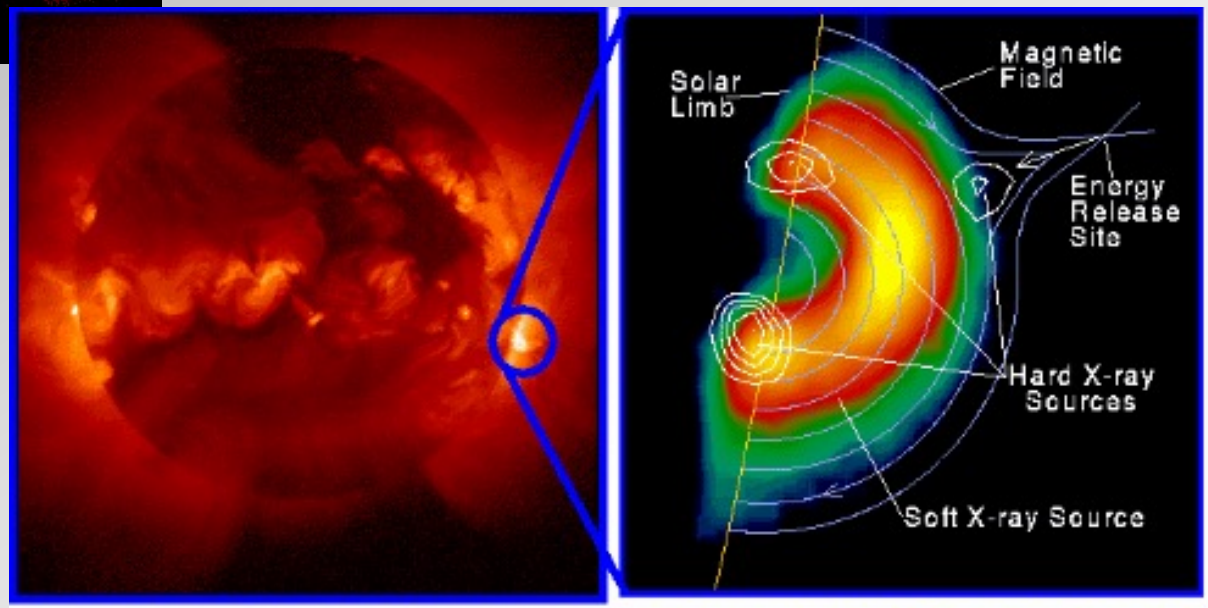


- Background flows

Solar flares

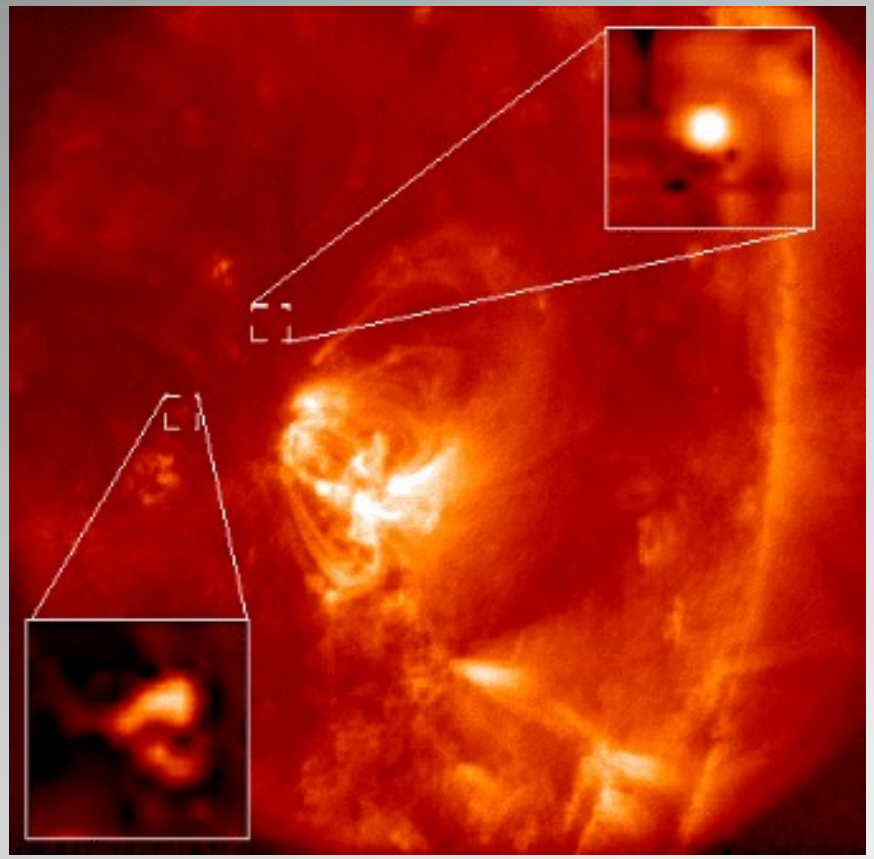


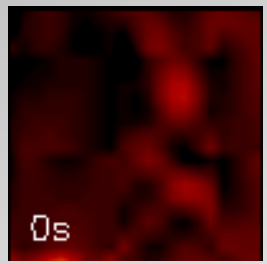
- Most violent explosions in the solar system
- 10^{32} ergs = 5000 atom bombs!



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.

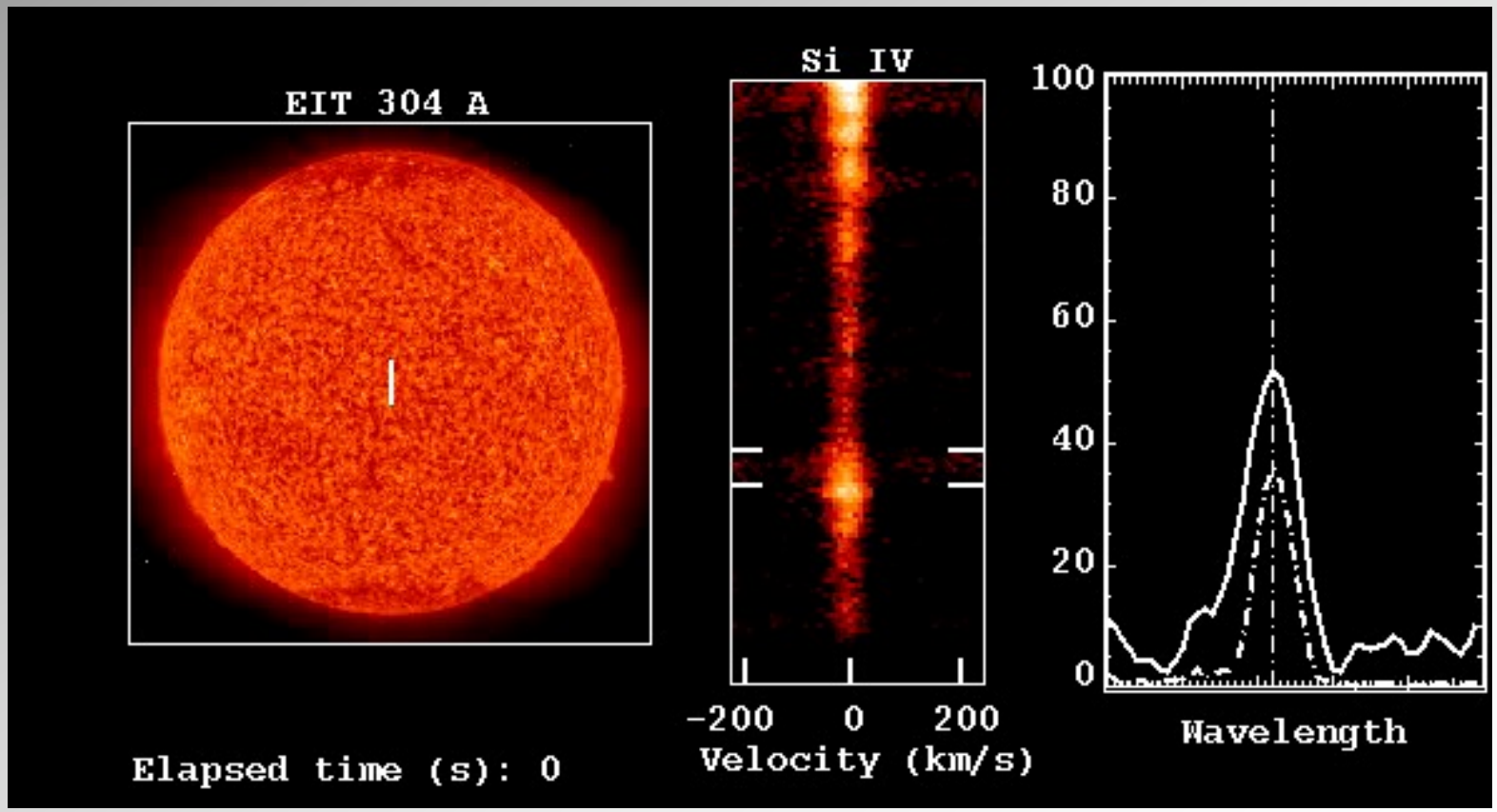
Nanoflares



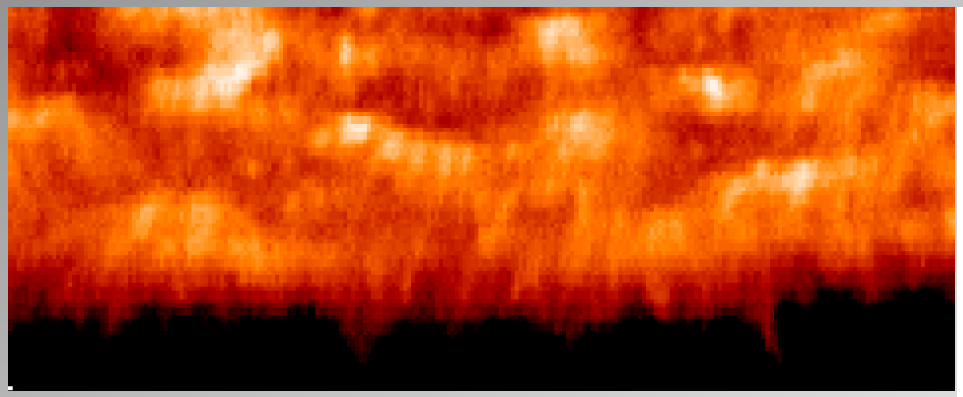


- Much smaller energy release
- At detection limit
- Cumulative effect to heat corona

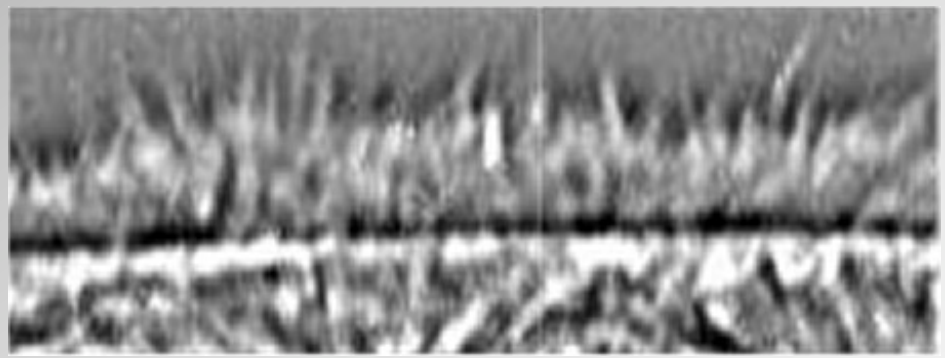
Explosive events



Solar spicules (tornadoes)



SOHO Image of the Solar limb taken March '96



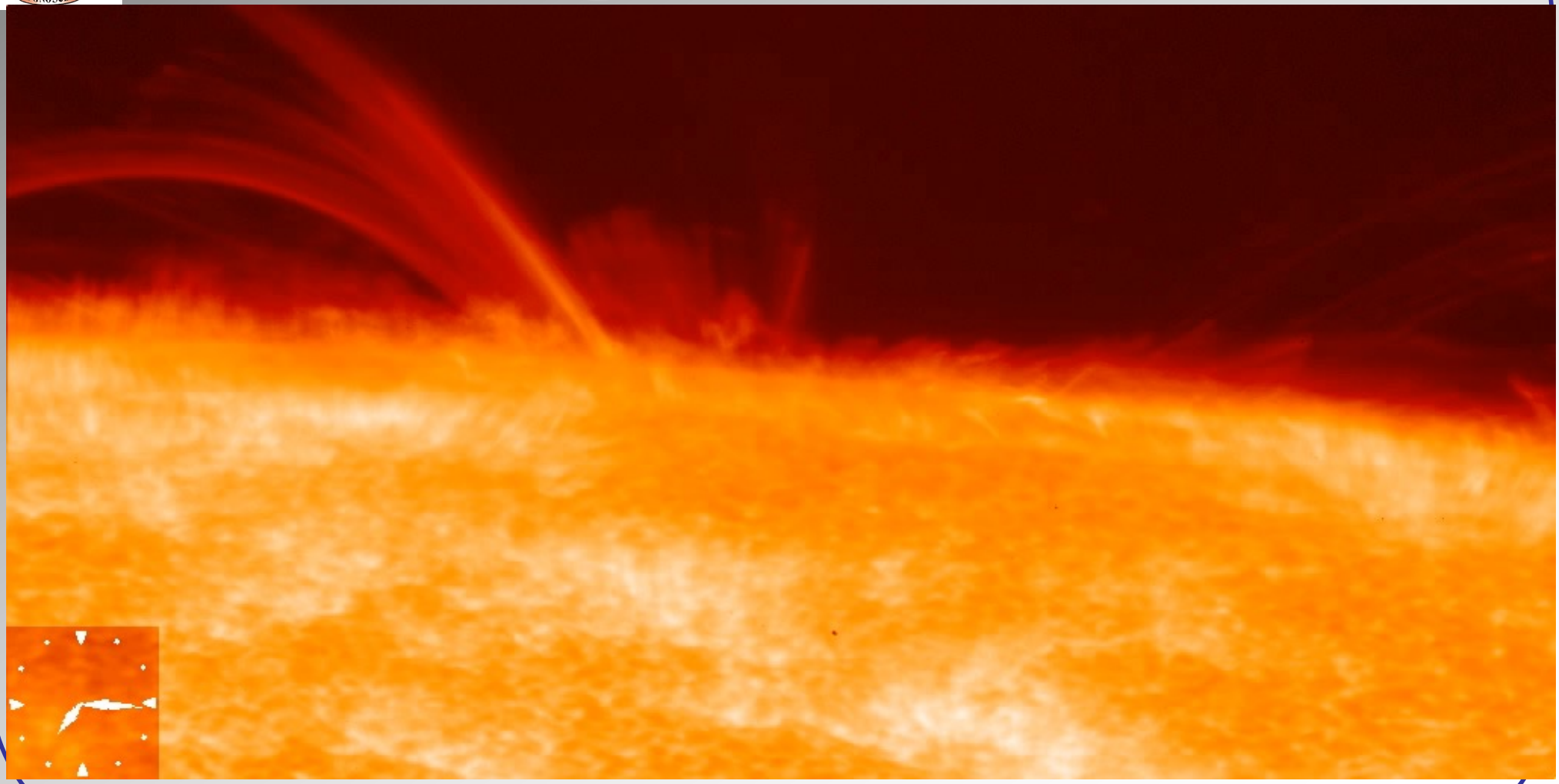
Hα Image from the Big Bear Solar Observatory, California

- 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:

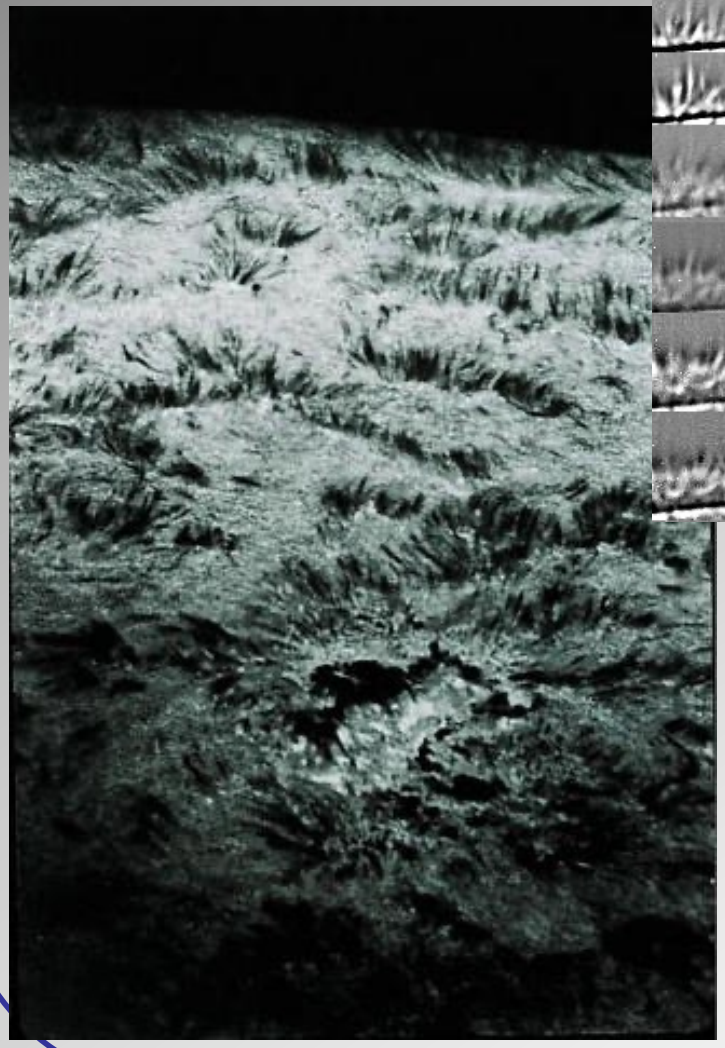
Width	200-1000km
Height	5000-10000km
Lifetime	5-15mins
Axial Velocity	20kms^{-1}
Temperature	5000-15000K
Density	0.5-2.5kgm^{-3}

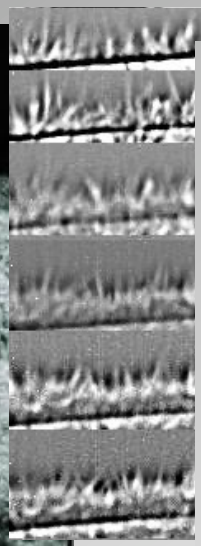
- Some spicules display rapid rotation about their axis, typically of the order of 25km s^{-1}
- The spicule rise is probably not ballistic, although the evidence for this is not conclusive

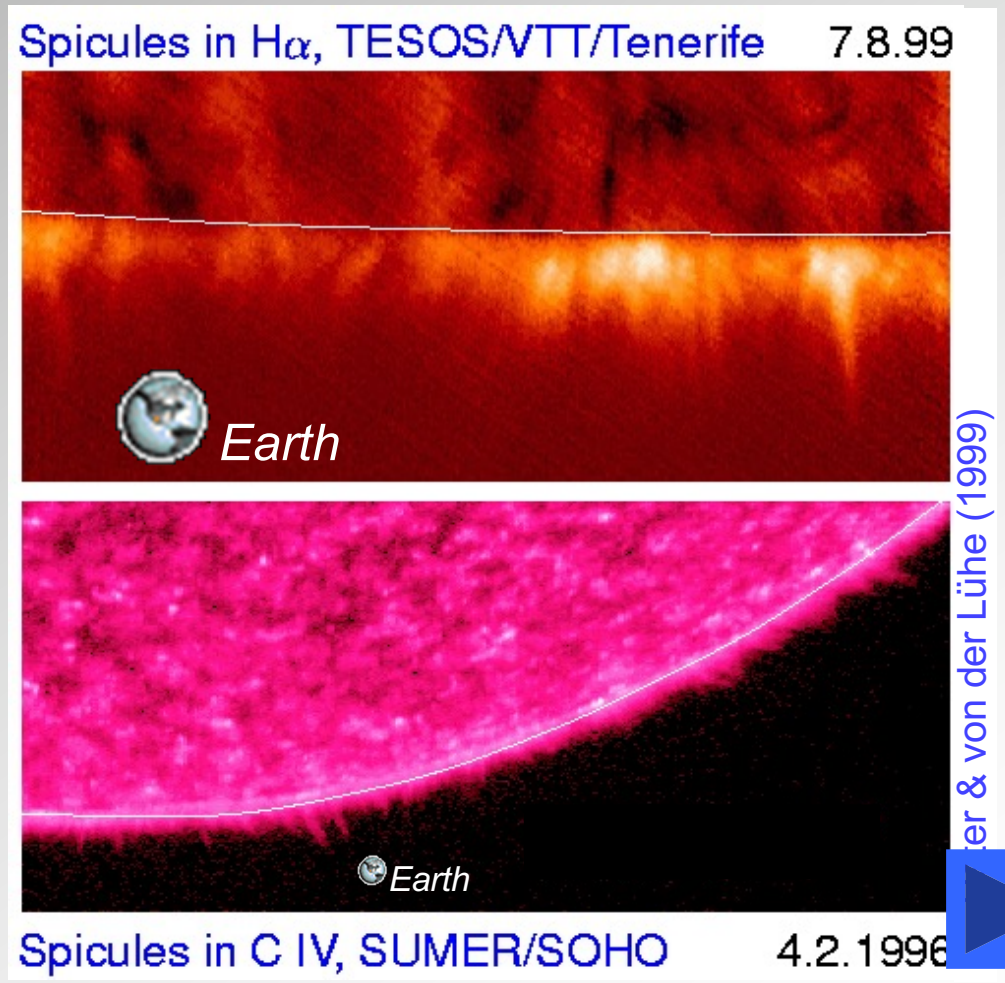
Solar spicules (tornadoes)



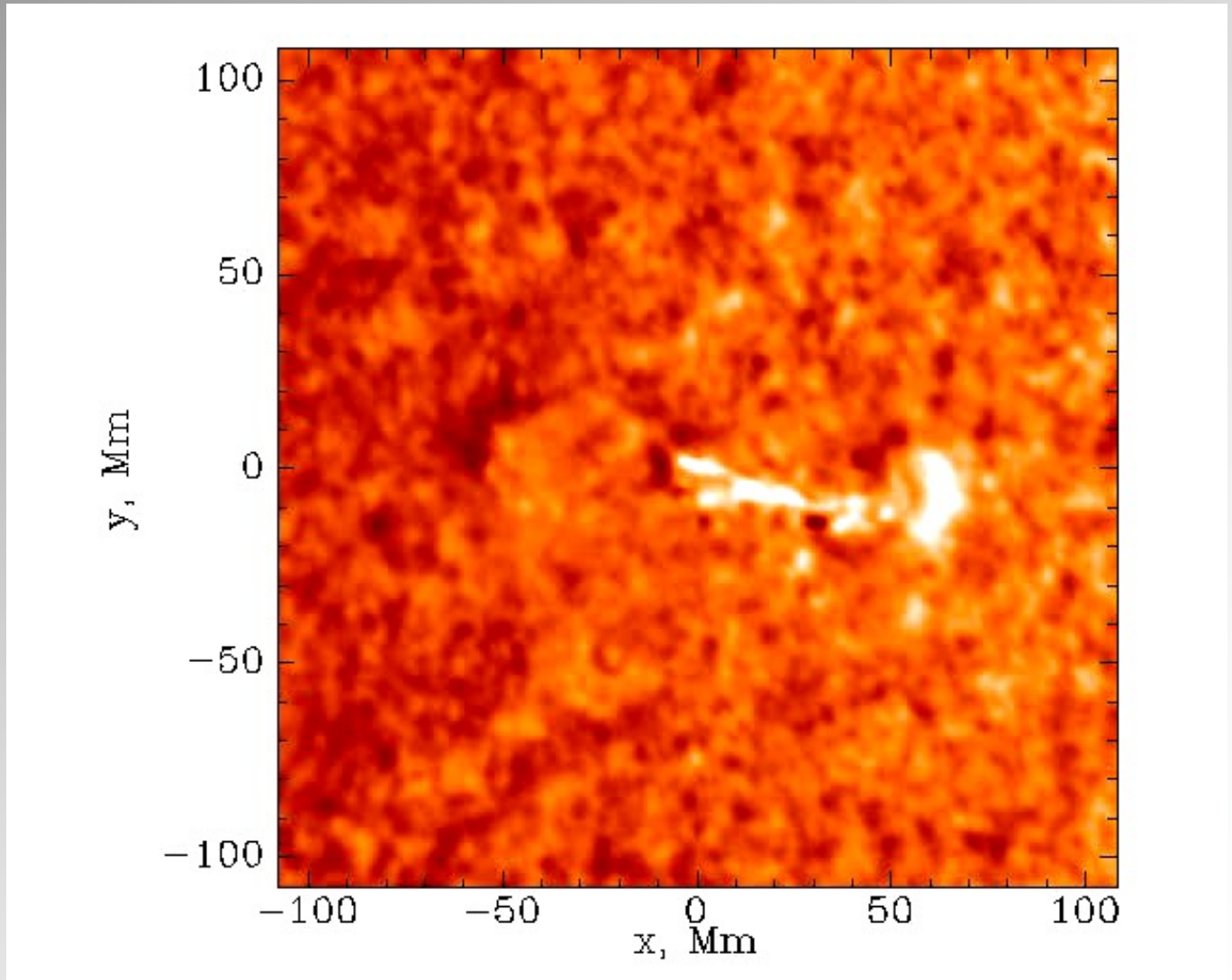
Solar spicules (tornadoes)



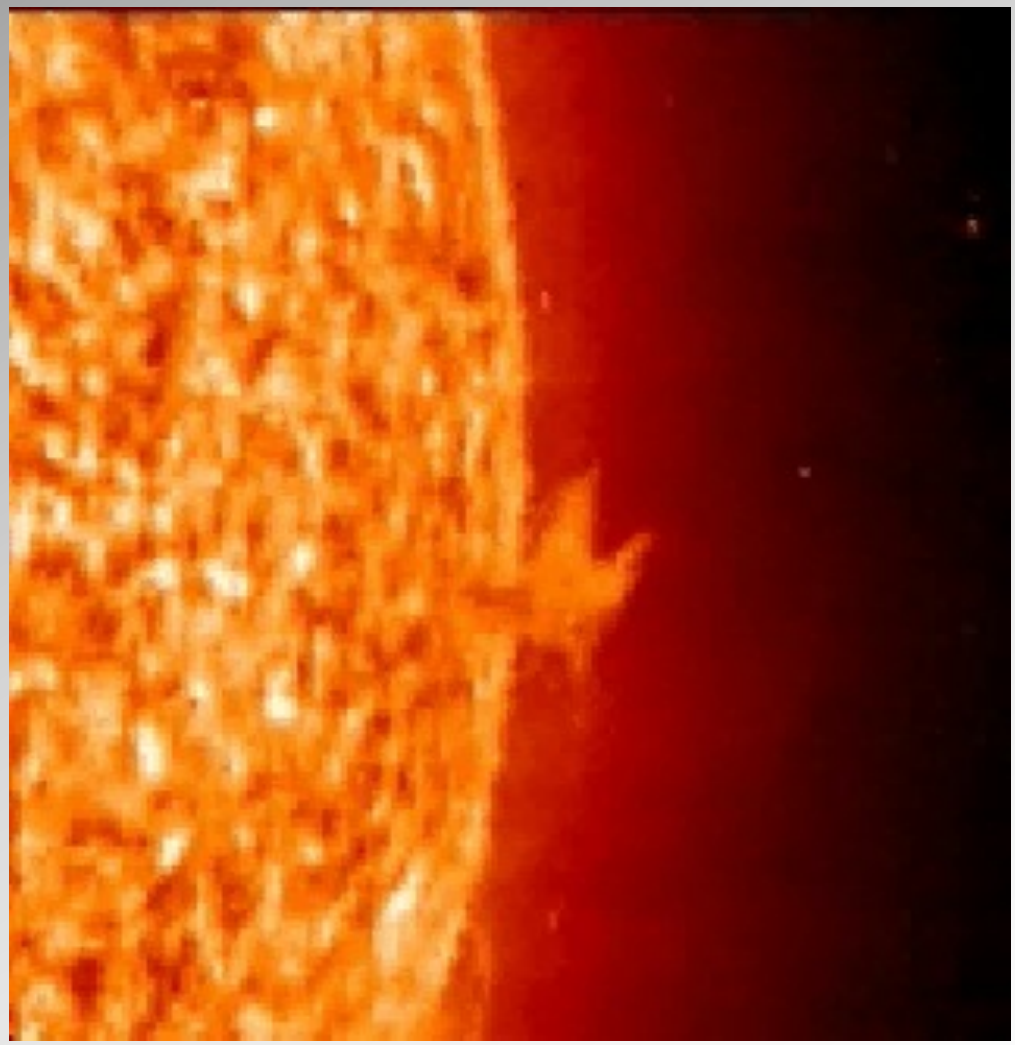




Tansition Region Quakes (TRQs)

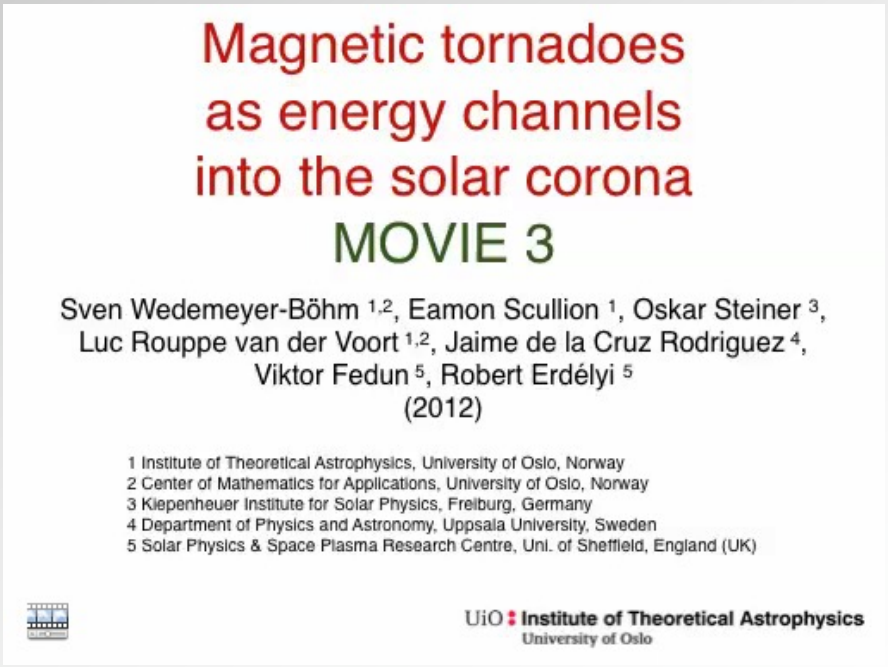


Solar spicules (tornadoes)



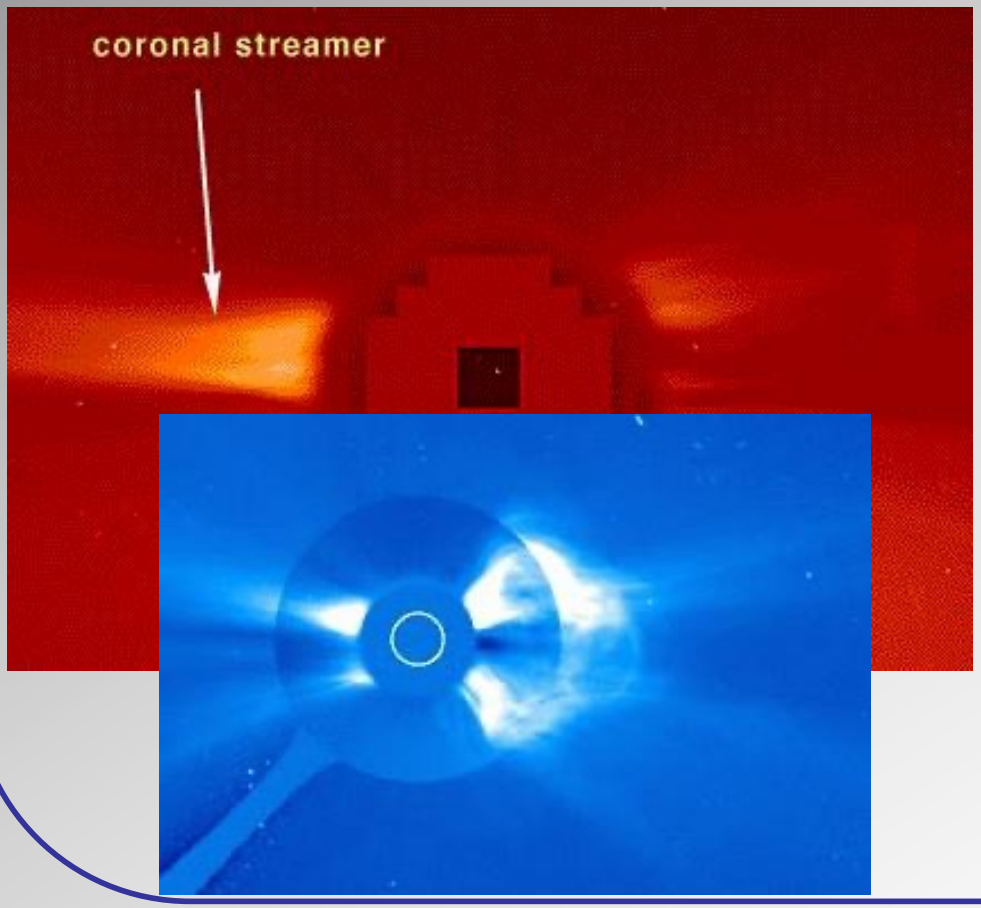
Detection of signature of direct energy channelling to corona!

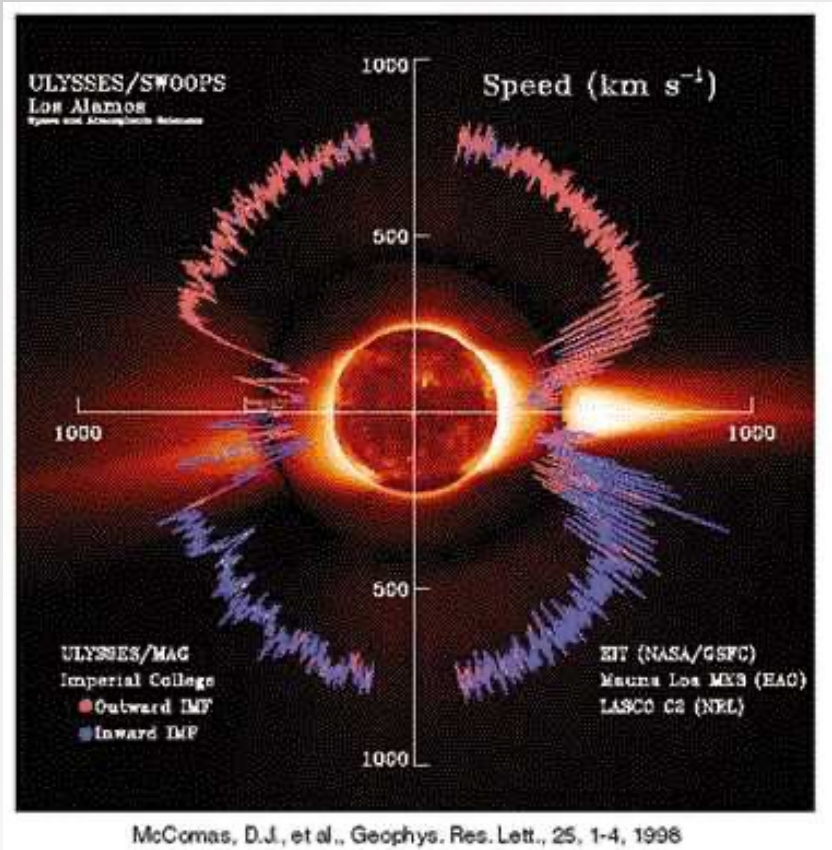
Wedemeyer-Bhom, Scullion, Steiner, Rouppe van der Voort, de la Cruz Rodriguez, Fedun & Erdélyi Nature (2012)



Expanding corona

Parker's solar wind



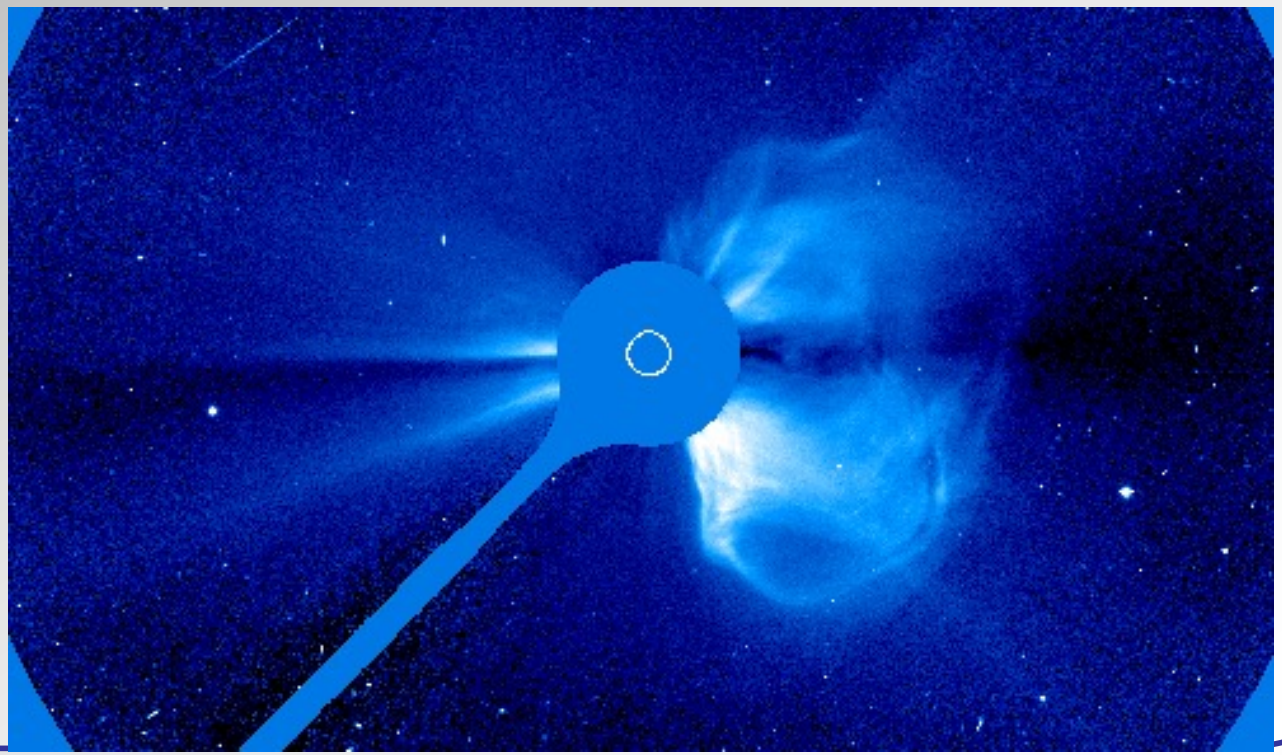


McComas, D.J., et al., Geophys. Res. Lett., 25, 1-4, 1998

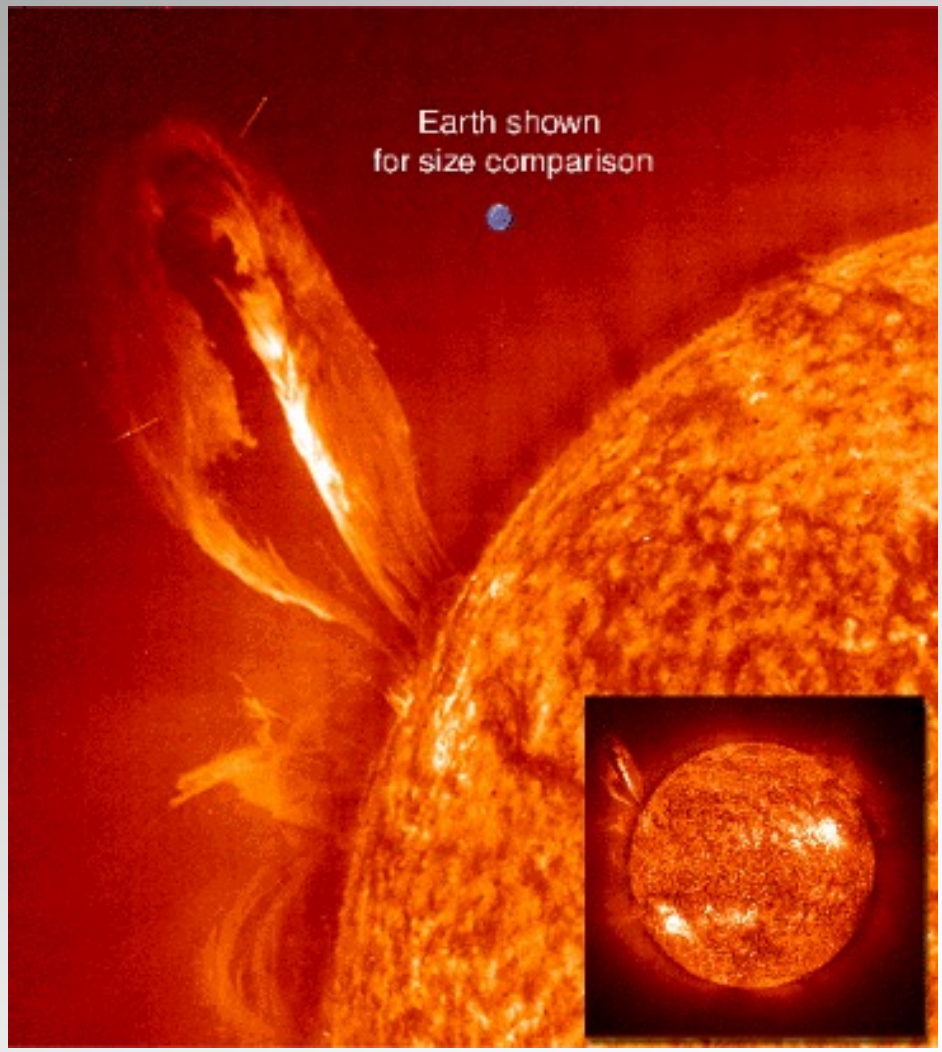
Expanding corona: solar storms

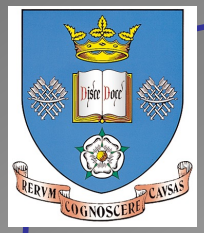
Coronal mass Ejections

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



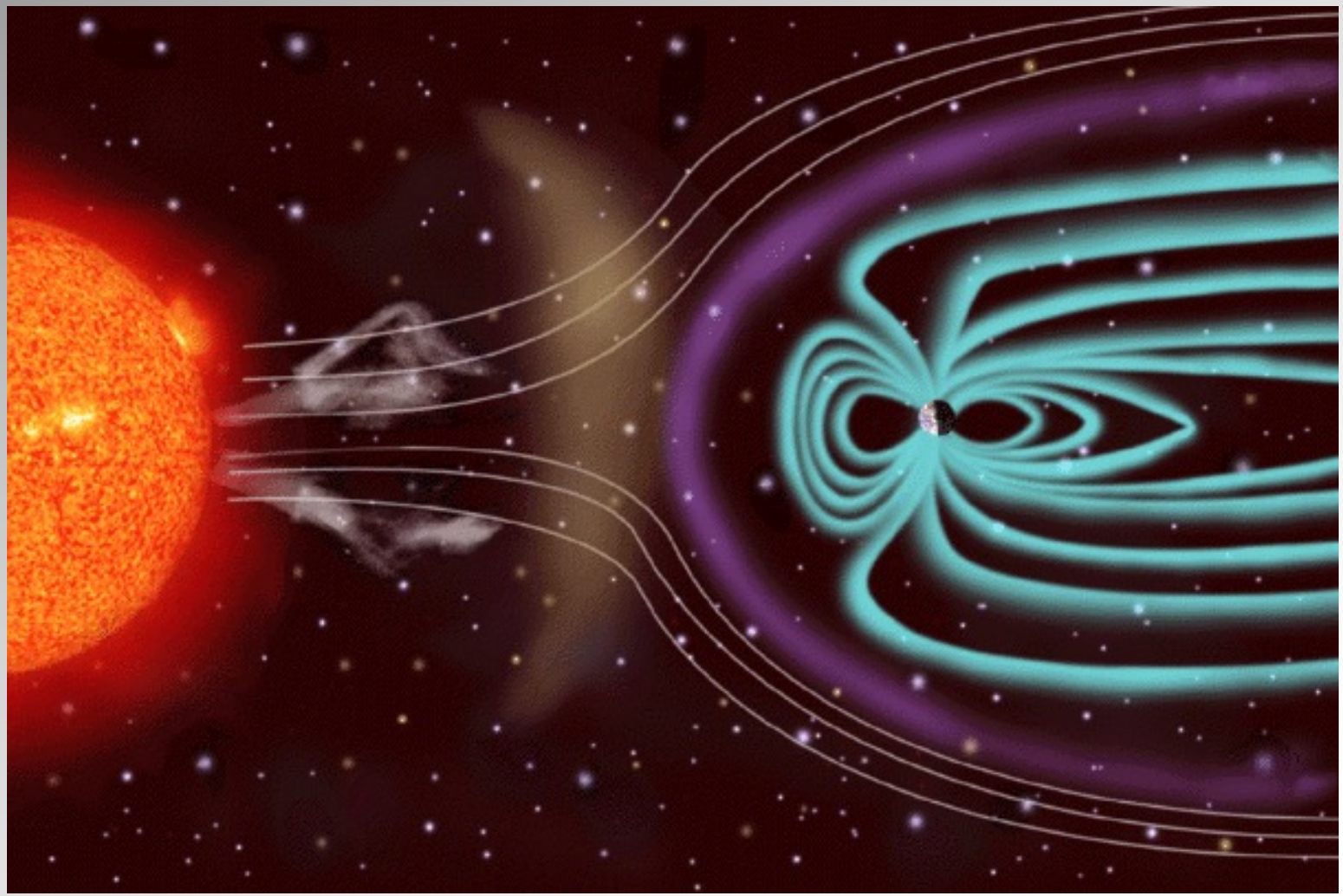
Expanding corona: solar storms (ctd)





Solar Physics & Space Plasma Research Centre (SP²RC)

Space Weather



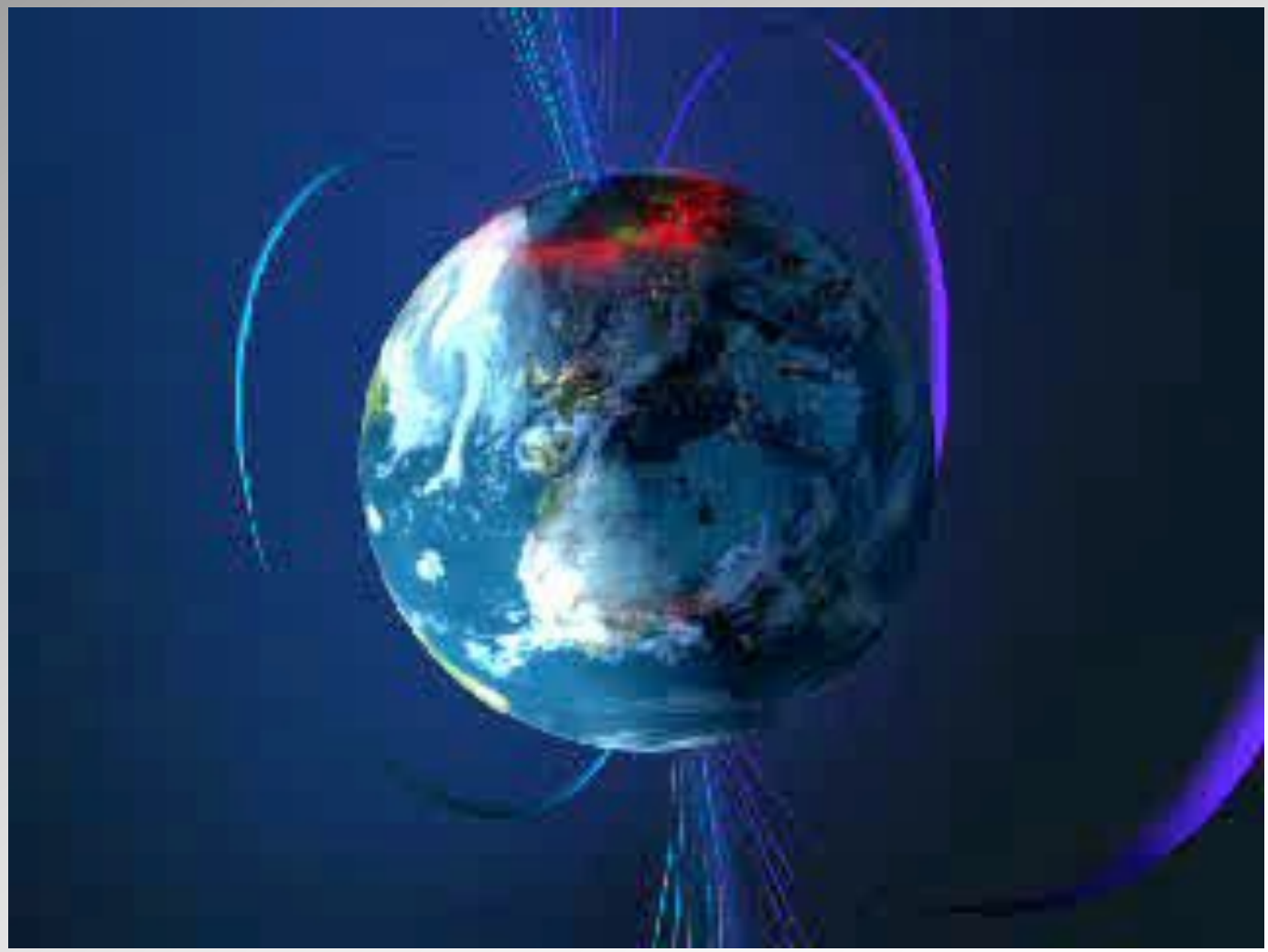
STFC I4STP
01-06 Sep 2024, Sheffield

University of Sheffield

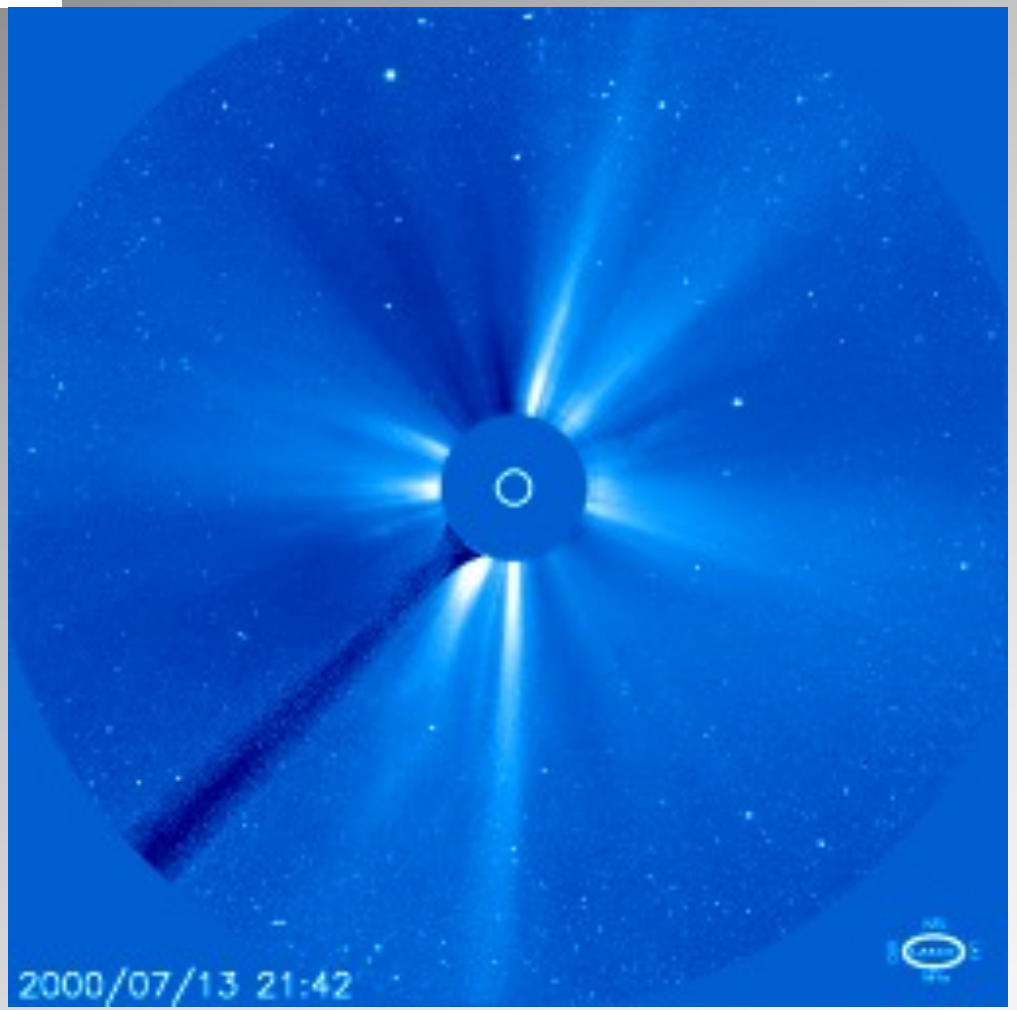
http://robertus.staff.shef.ac.uk

Solar Physics & Space Plasma Research Centre (SP²RC)

Space Weather



X-flare : 14th July 2000

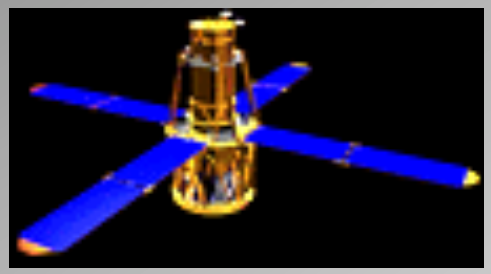


Bastille day flare

- 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

Current/future space observatories

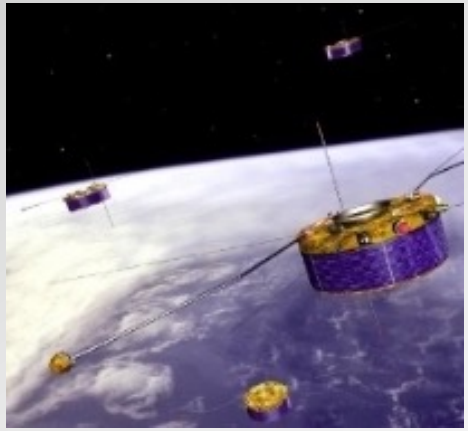


RHESSI

- Solar flare X-ray mission
- March 2001

CLUSTER II

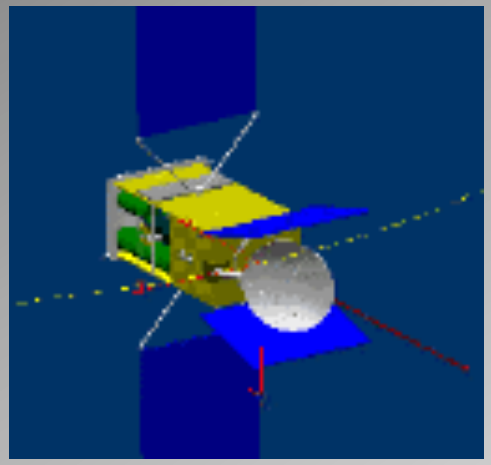
- Four satellite
- 3D magnetosphere
- July & August 2000



Solar-B/Hinode

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

Current/Future space observatories

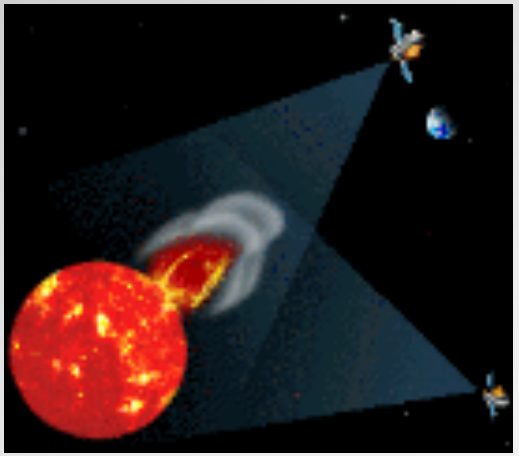


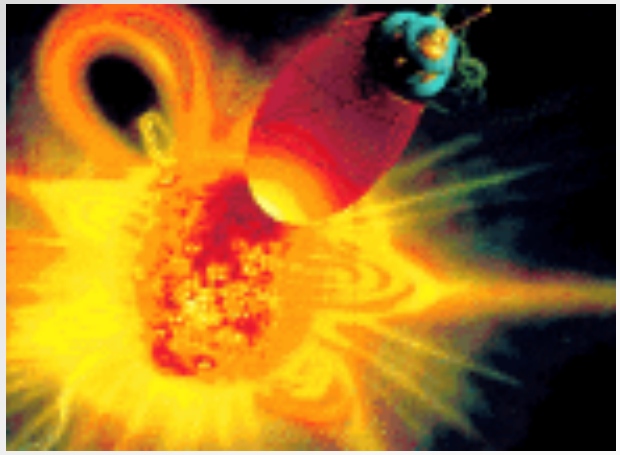
Solar Orbiter

- ESA mission
- 20 million km (3 times closer than Mercury)
- Stays over one position
- 2015 – 2017 - 2020

STEREO

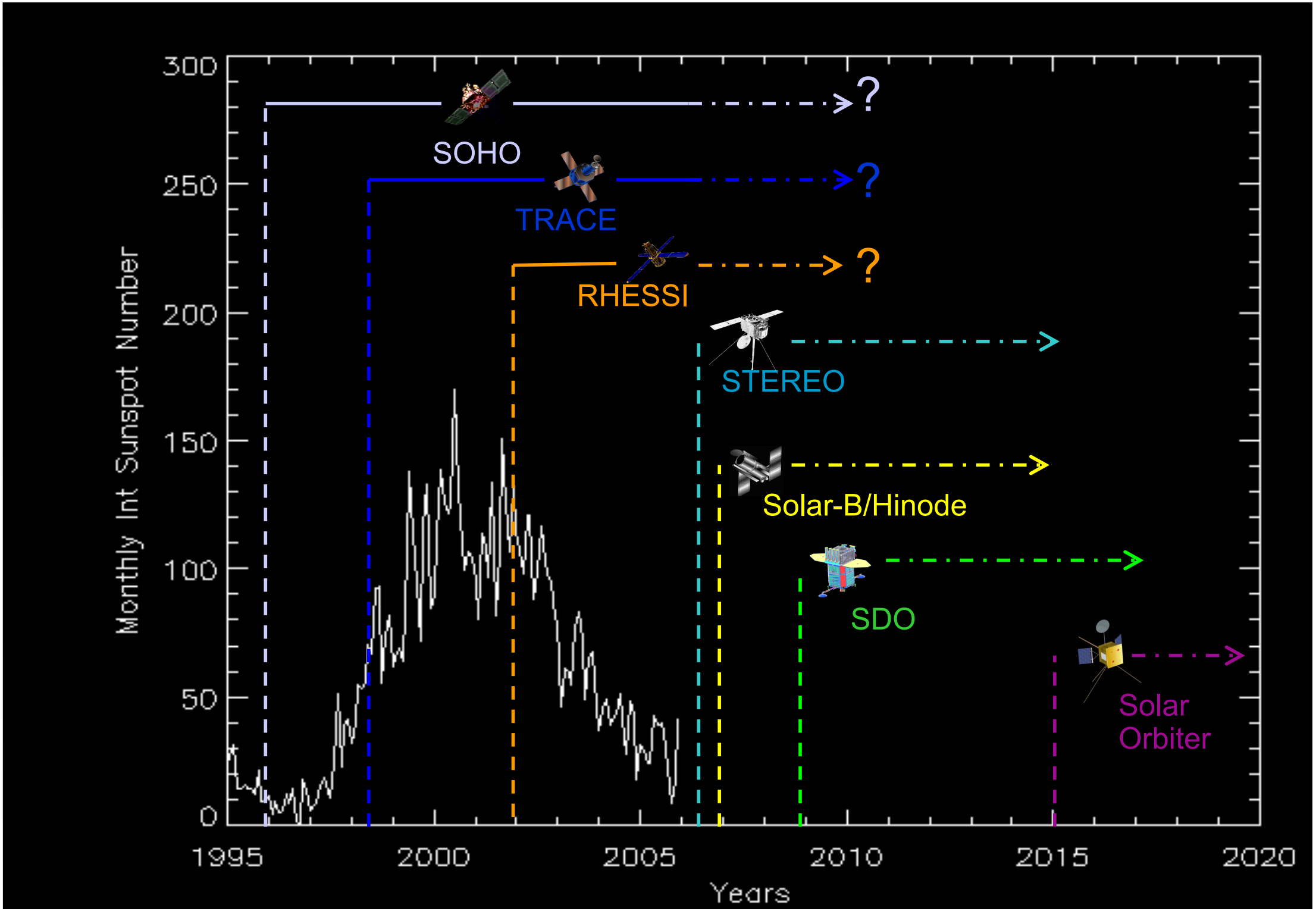
- NASA Mission
- Two satellites
- Stereoscopic images of the corona

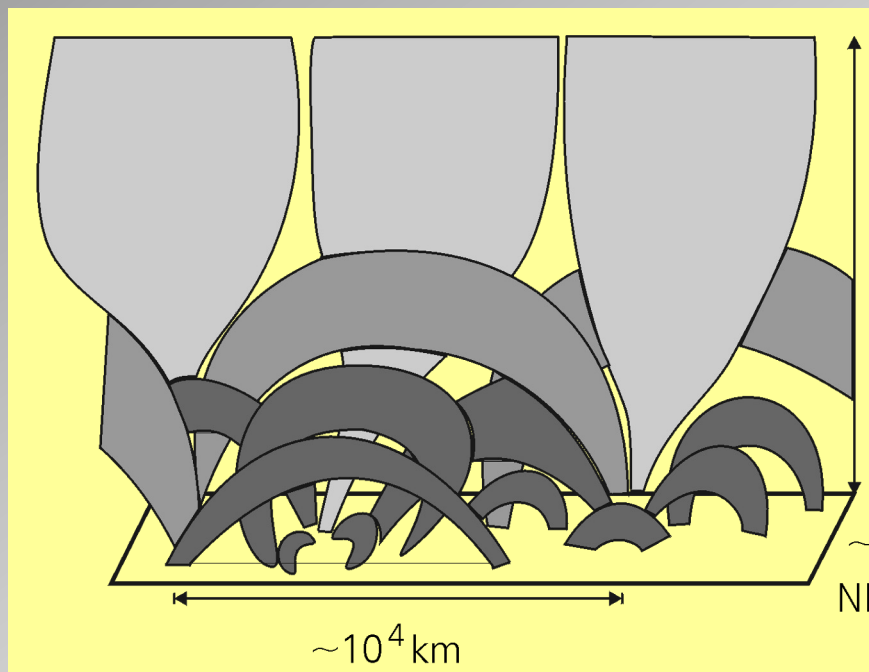




Solar Probe

- NASA Mission
- Fly through the corona at 2 million km at 2000 K
- Lasts only 24 hours
- 202?


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



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

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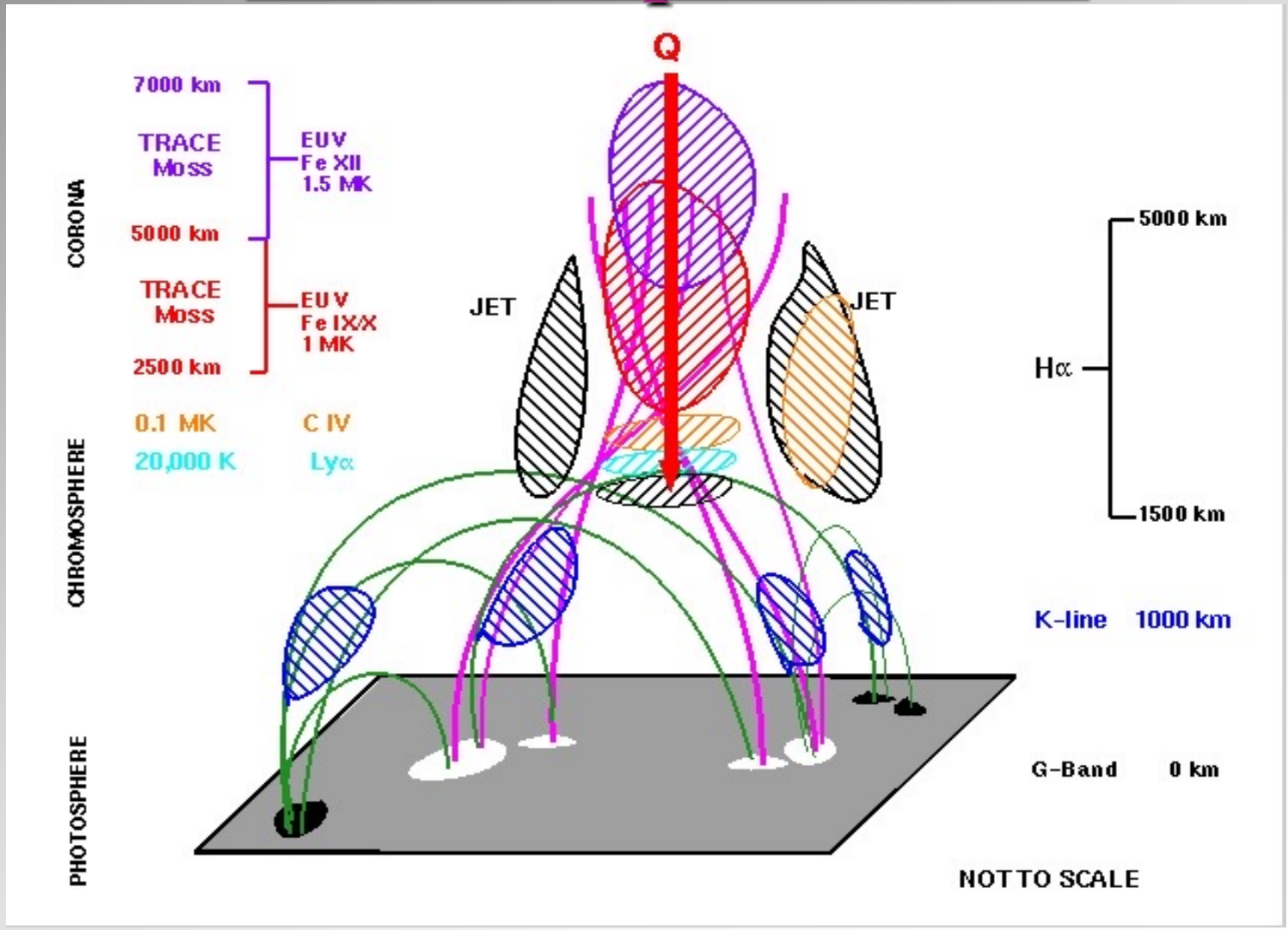
➢ press

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

Model improvement



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

The end