The Sun and the Solar Wind An Introduction

Valentina Alberti

Summary

- THE SUN
  - Sun’s facts
  - Solar spectrum
  - Solar structure
  - Solar activity
  - Flare
  - CME

- THE SOLAR WIND

SUN: data

G2 V, absolute magnitude = 4.8

$r_{Sun\text{-}Earth} = 1.5\times10^{11}$ m = 1 AU

Age = 4.5×10^{9} yr

$R_{\odot} = 6.96\times10^{8}$ m

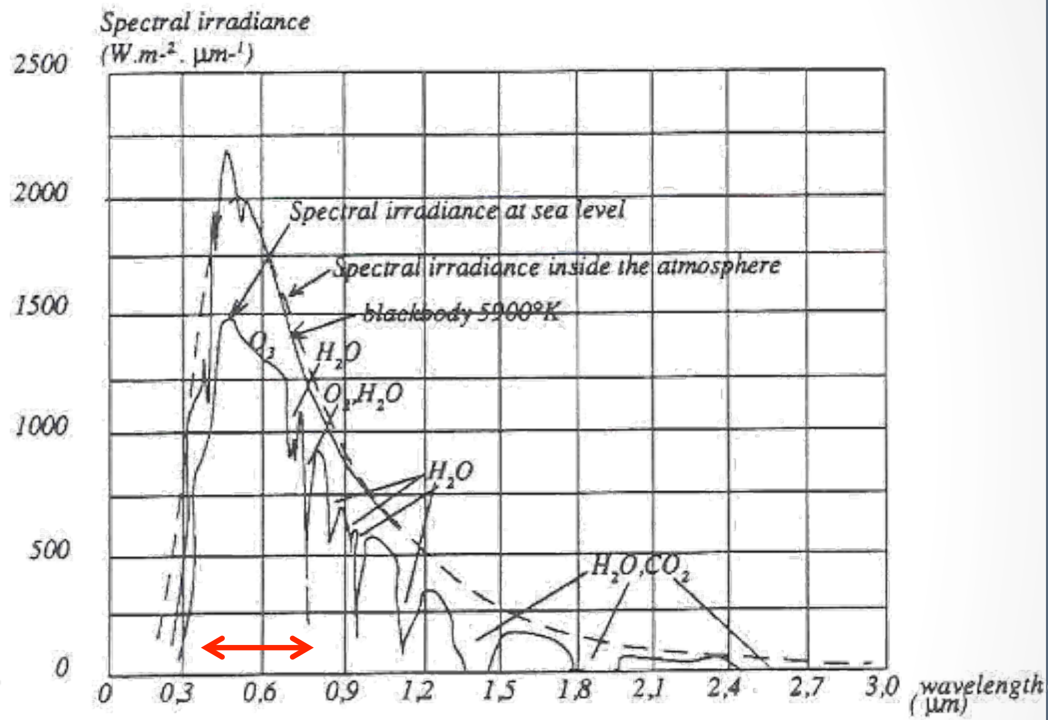
$M_{\odot} = 1.99\times10^{30}$ kg

$L_{\odot} = 3.86 \times 10^{26}$ W

	Temperature (K)	Density (kg m^{-3})	Chemical Composition
Core	1.56×10^{7}	1.5×10^{5}	35% H, 63% He, 2% C, N, O,..
Surface	5770	2.07×10^{-4}	70% H, 28% He, 2% C, N, O,..

SUN: spectrum

InfraRed	52 %
Visible	41%
NUV	<7%
EUV	0.1%
Radio	0.1%
X	<0.1%



Energy at Earth = 1380 Wm^{-2}

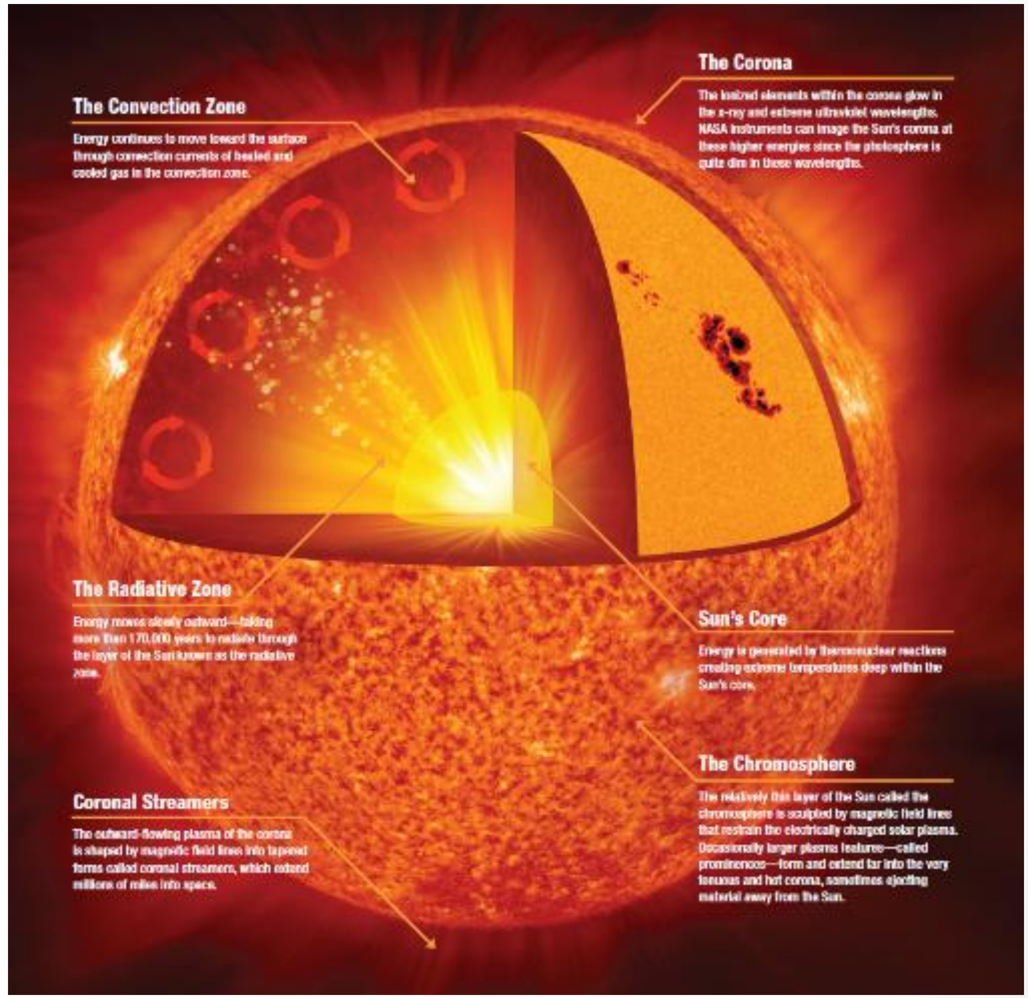
Variations ± 3% (1326 ÷ 1418 Wm^{-2}) → ΔT ~ 1%

Δ/year ~ 0.018%

SUN: structure

- Core
- Radiative zone
- Tachocline
- Convective zone
- Photosphere

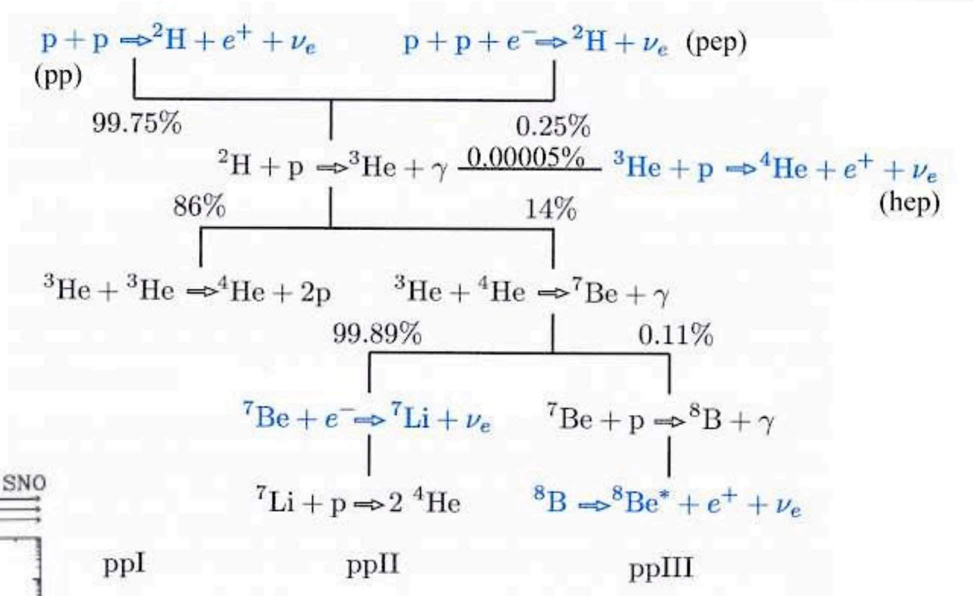
- Cromosphere
- Transition region
- Corona

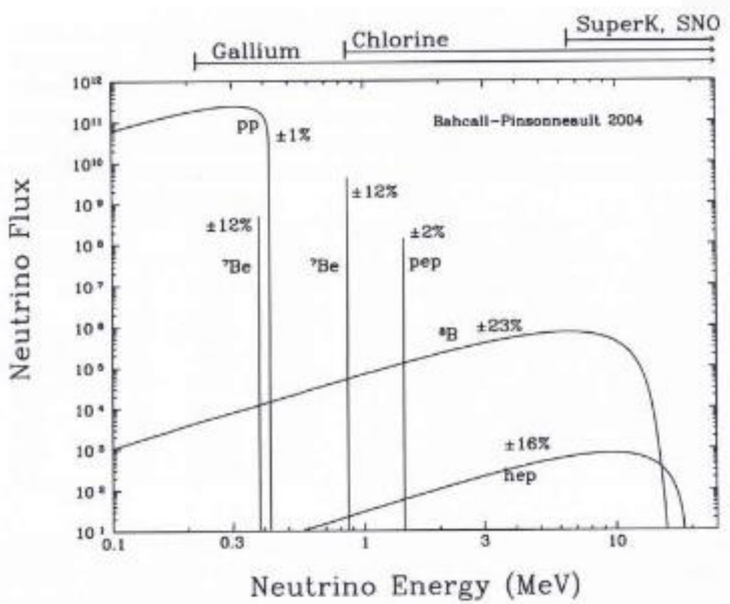


NASA Jenny Mottar

SUN: core

- $T \approx 1\times10^7$ K
- $R \approx R_\odot/4$
- $M \approx M_\odot/2$
- $\rho \approx 1.5 \times 10^5$ kg m^{-3}





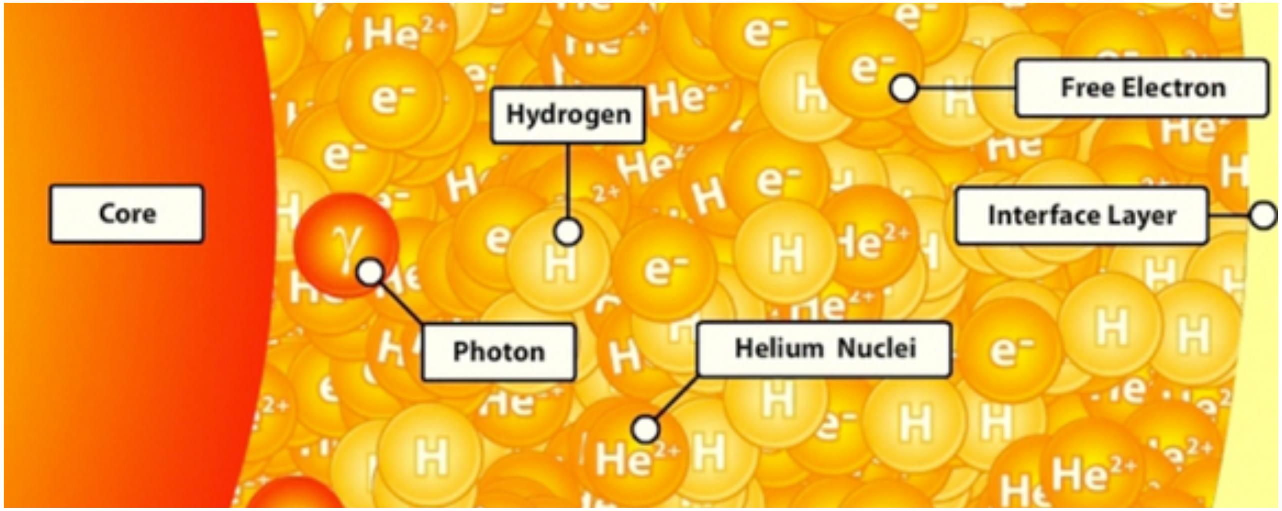
Photons: E of the order of MeV (gamma-rays) transport energy to the outer layers of the star.

SUN: radiative zone

- ΔR: 0.25 $R_\odot$ ÷ 0.7 $R_\odot$
- ΔT: 1×10^7 K ÷ 2×10^6 K
- Δρ: 20×10^3 kg m^{-3} ÷ 2×10^2 kg m^{-3}

Mean free path: $\lambda_{ph} \approx 1$ mm

Diffusion timescale (radiative zone): $t_{ph} \approx 10^5$ yr

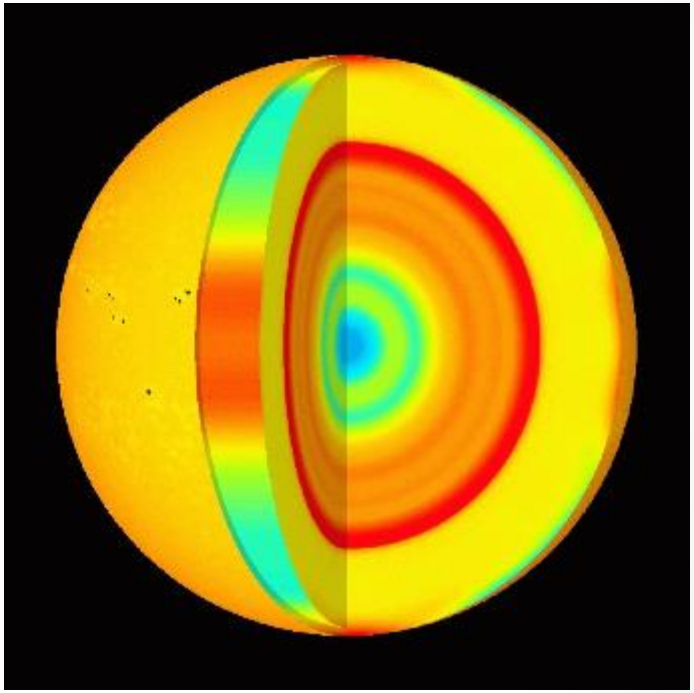


SUN: tachocline

Transition region between the radiative and the convective zone

- $R \approx 0.69 \div 0.71\ R_{\odot}$
- Thickness $< 0.05\ R_{\odot}$
- $R/R_{\odot}$ varies by 0.02 from 0° to 60° lat
- $\rho \approx 2 \times 10^{2}$ kg m^{-3}
- $T \approx 2 \times 10^{6}$ K

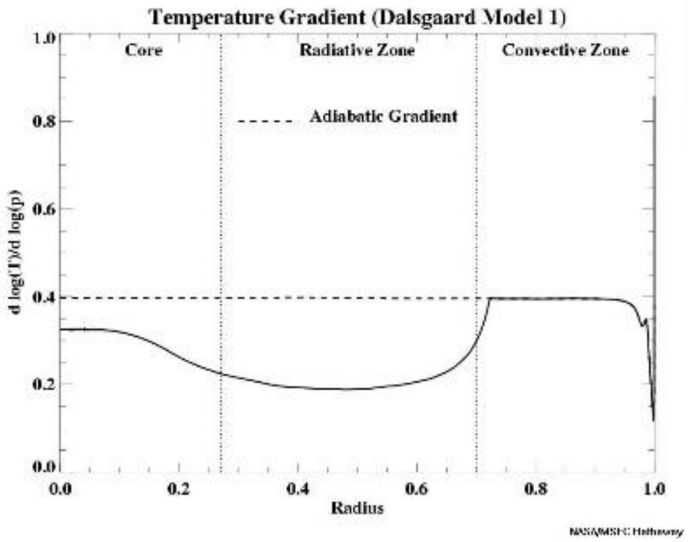
◆ Location of the SOLAR DYNAMO

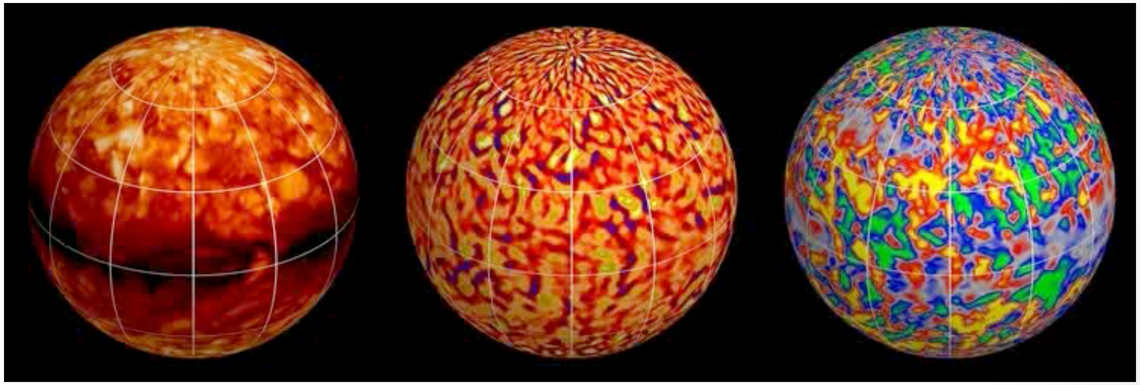


SOHO (ESA/NASA)

SUN: convective zone

- $T \approx 2\times10^6$ K
- $\Delta R \approx 200{,}000$ km





Fluid T vertical flow speed magnetic field

http://www.astro.umontreal.ca/~paulchar/grps/mhd_a.html#sec1

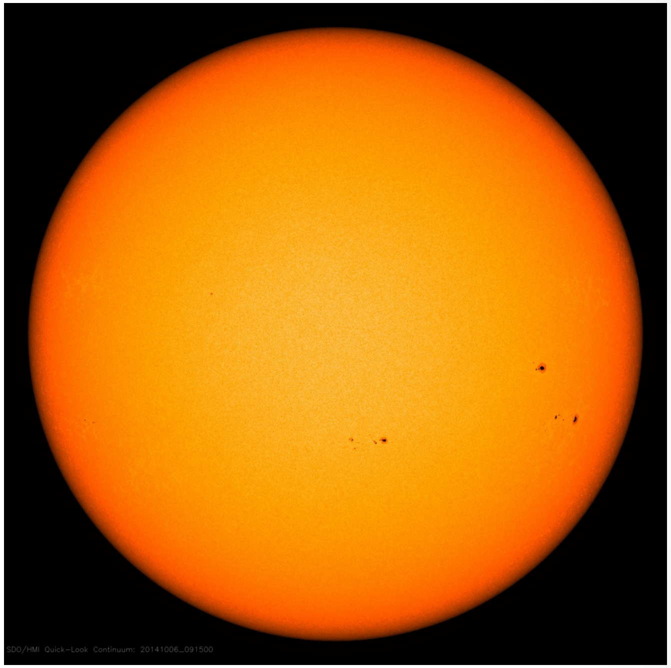
SUN: photosphere

Solar surface visible in the optical band.

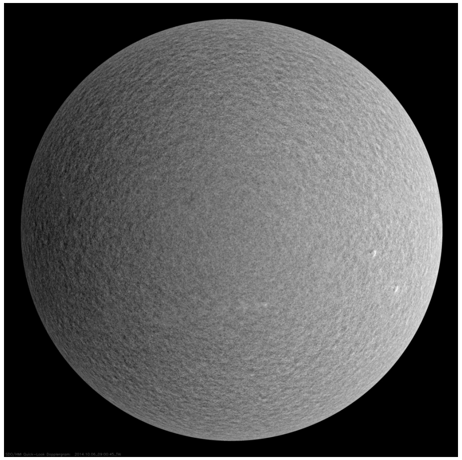
- $\Delta R \sim 600$ km
- $T \sim 7500 \div 4200$ K (r >)
- $\rho \sim 10^{-4}$ kg m^{-3}
- $n \sim 10^{23} \div 10^{21}$ m^{-3} (r >)

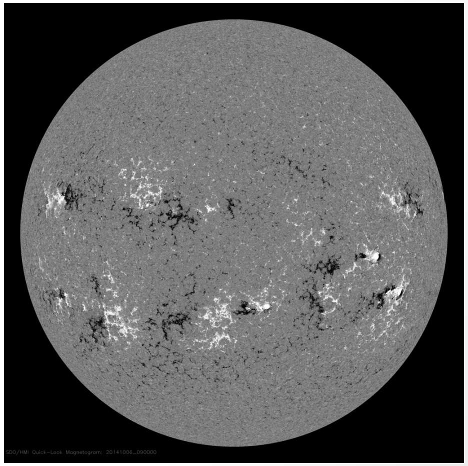
Solar Activity Manifestations

Sunspots
Faculae
Granules
Supergranules



SDO Oct 6, 2014

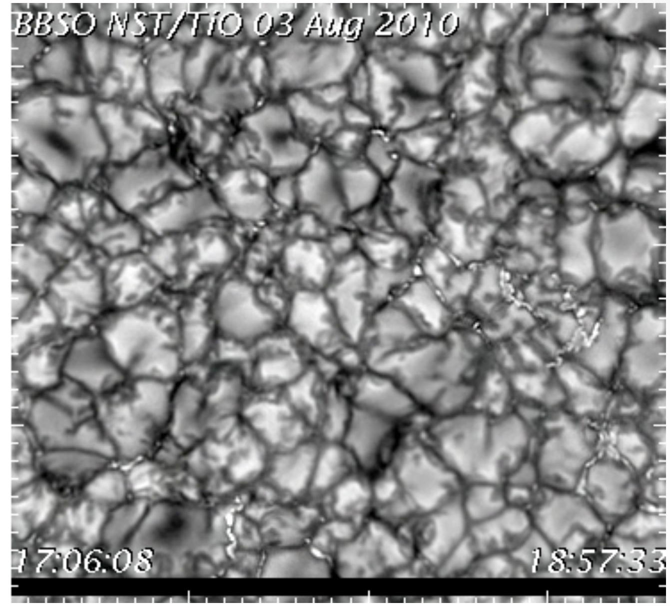




SUN: photosphere

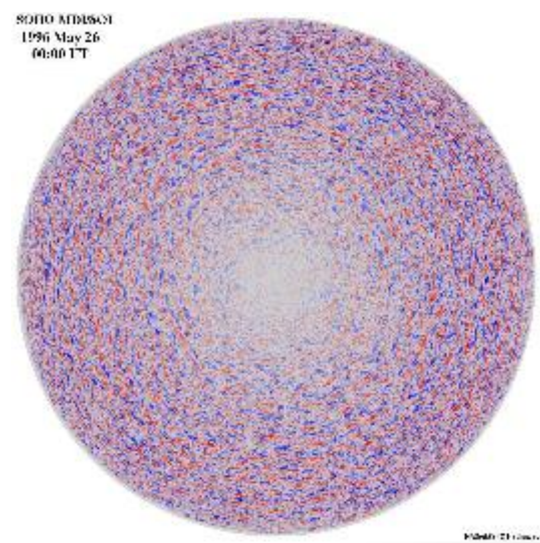
◆ GRANULES

- size: $10^4 \div 10^6$ m
- plasma velocity: 7 km s^{-1}
- mean lifetime: 10 min



◆ SUPERGRANULES

- size: 10^7 m
- plasma velocity: 0.5 km s^{-1}
- mean lifetime: $12 \div 24$ h

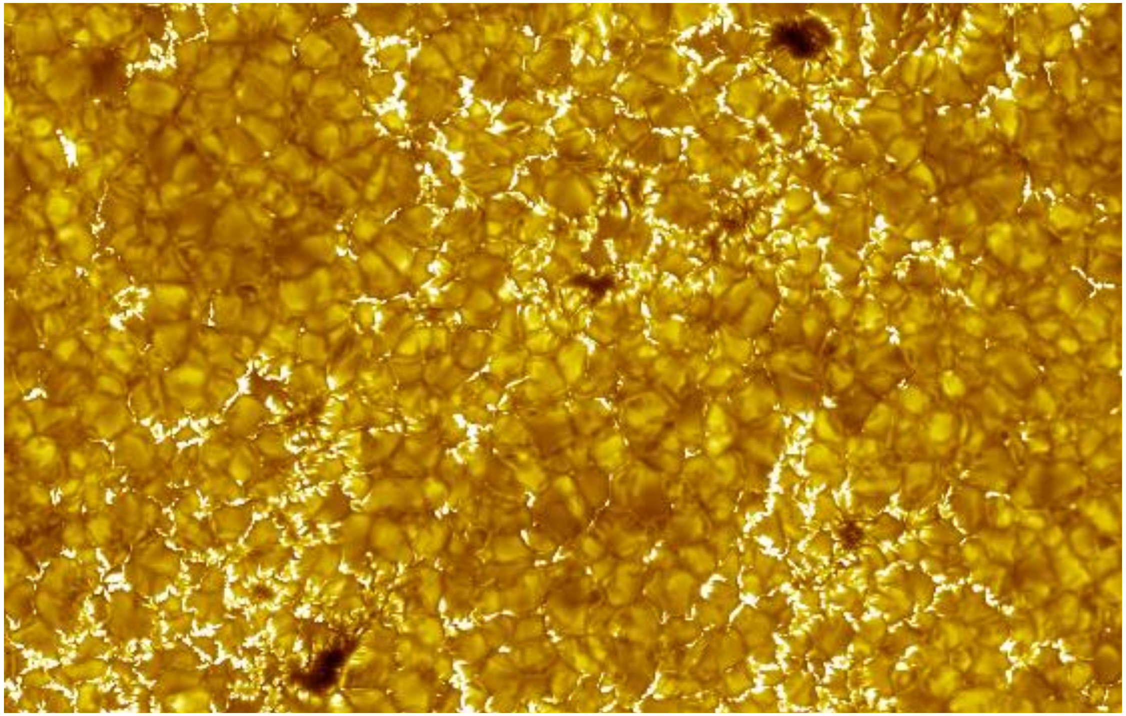


October 9, 2017

SUN: photosphere

◆ FACULAE

- Very intense B concentrated in small regions
- Solar irradiance augmentation ~ 1%



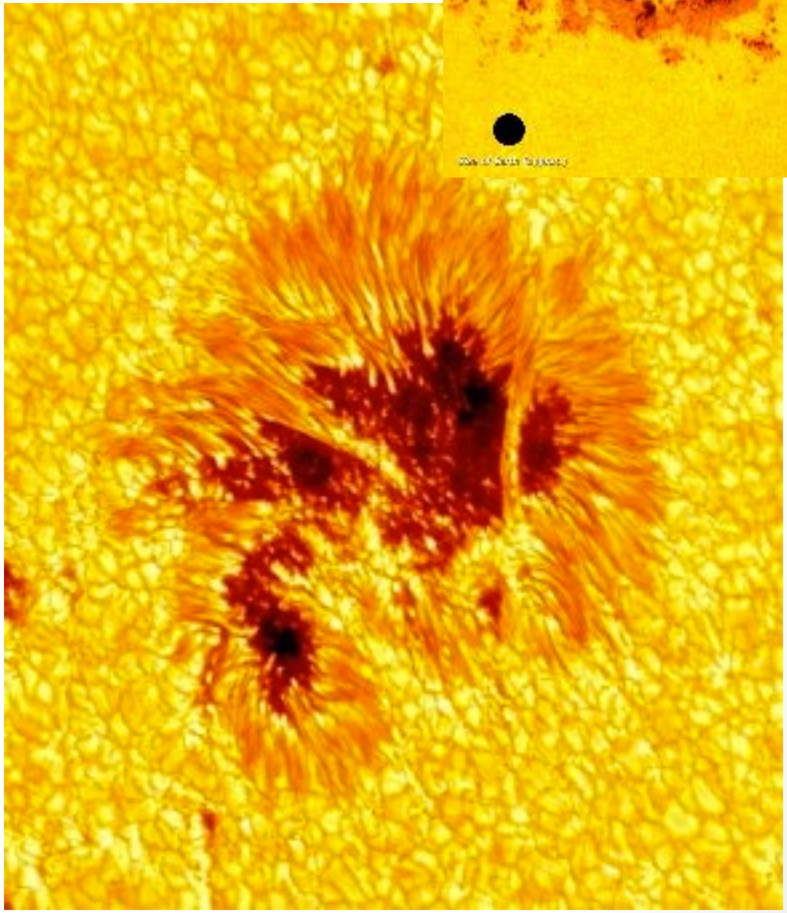
SST La Palma

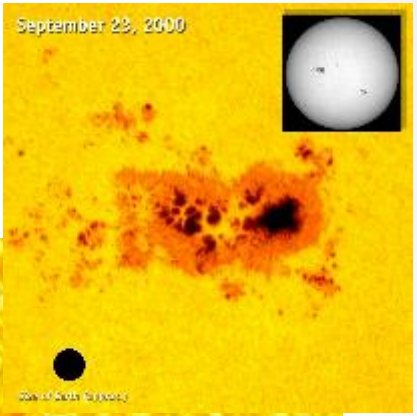
Intense B lowers opacity and makes visible deeper and hotter parts of granules

SUN: photosphere

◆ Sunspots

- Umbra:
  - B ~ 0.2 ÷ 0.4 T, vertical
  - T ~ 3700 K
  - L ~ 3-5% $L_{\odot}$ (@500 nm)
- Penumbra:
  - B ~ 0.1 ÷ 0.2 T, horizontal
  - L ~ 80% $L_{\odot}$ (@500 nm)

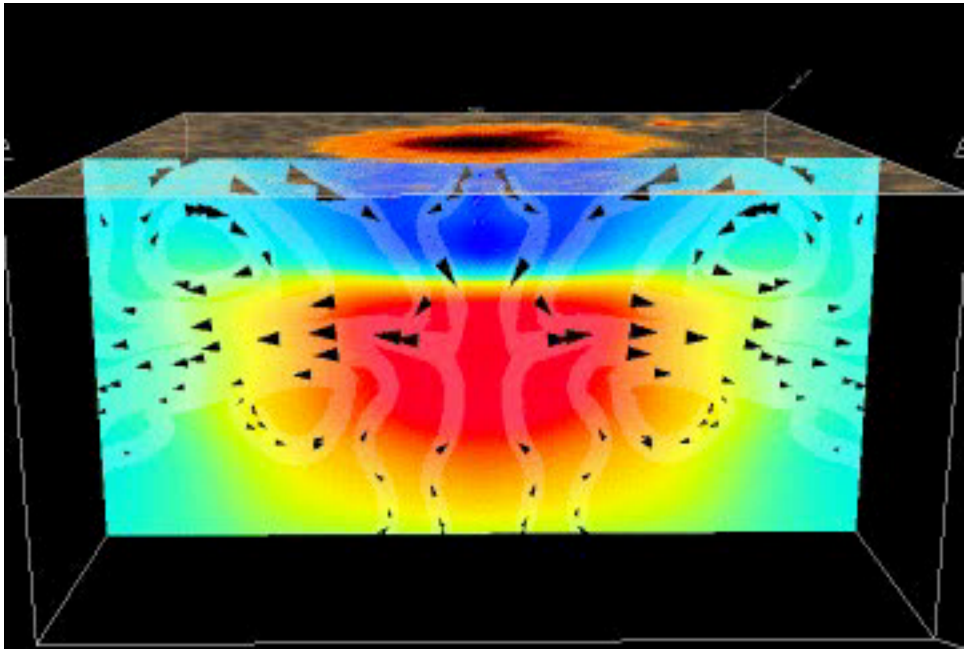


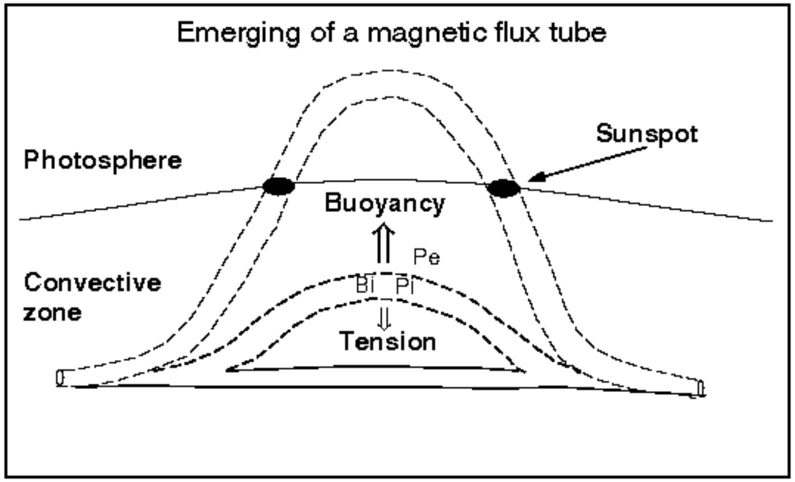


BBSO/NJIT

SUN: photosphere

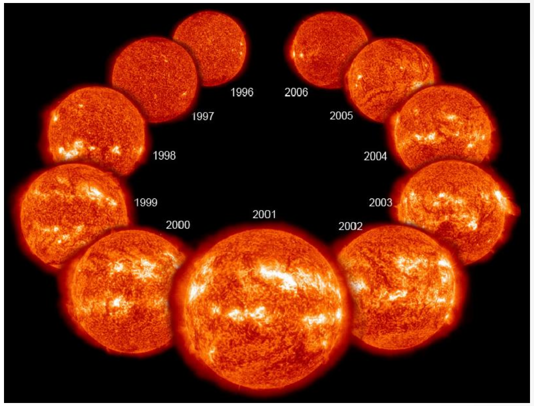
- Sunspots
  - Are originated by the presence of very intense magnetic fields that inhibit upwards motion of hotter plasma from regions at higher depths
  - A flux tube is less dense than the surroundings and rises up

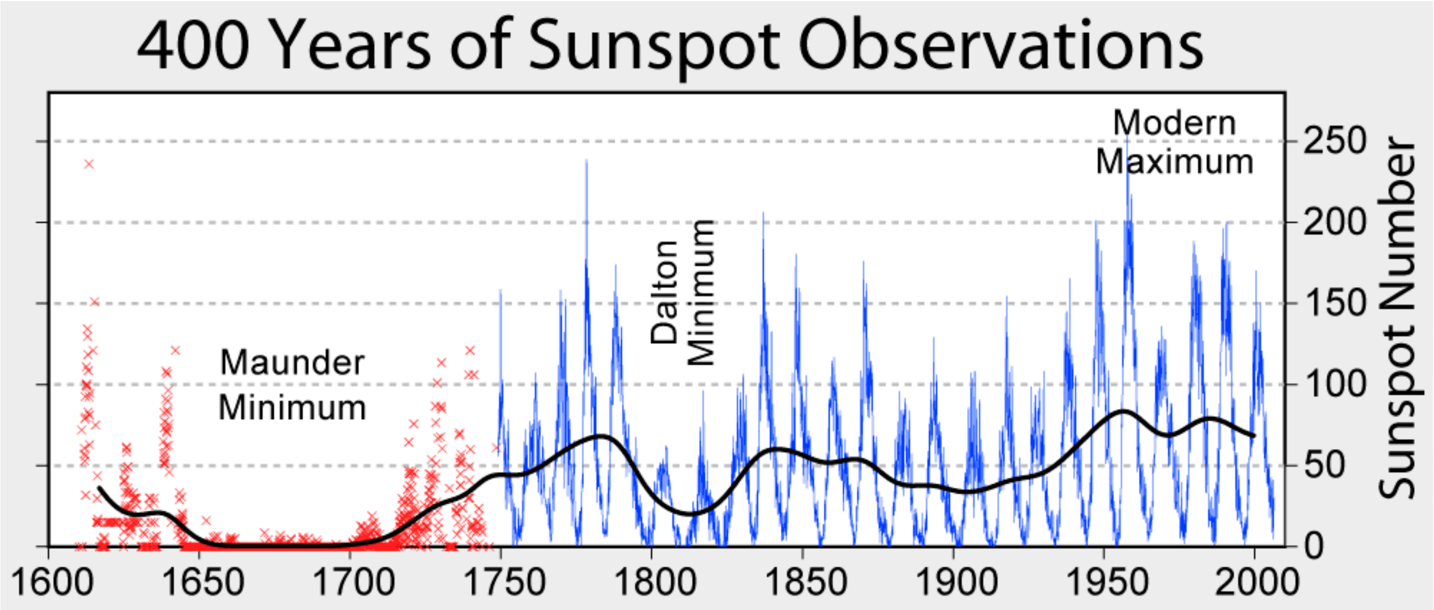




SUN: solar activity

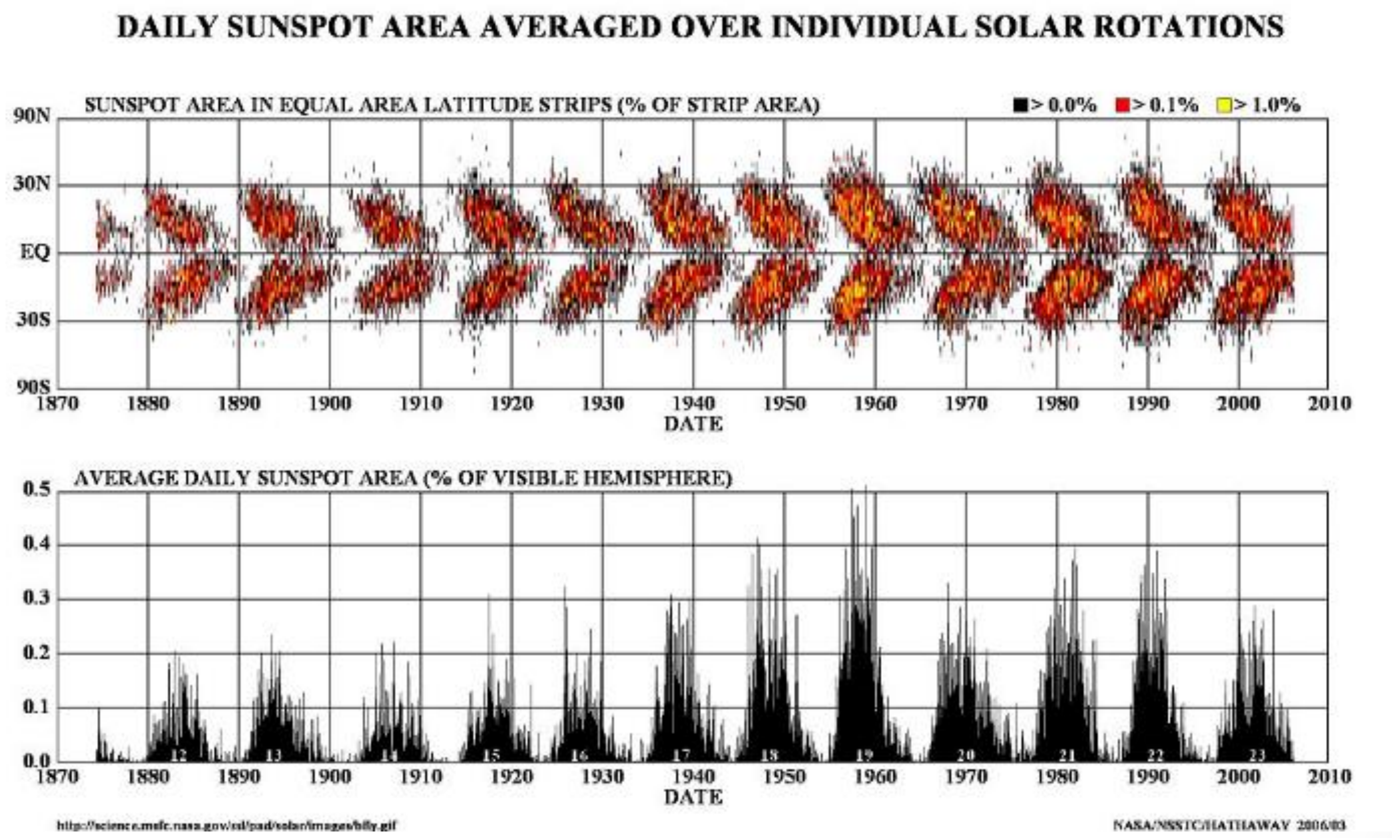
- **Sunspot cycle**: periodicity ~ 11 years
- Equatorward drift of activity latitude (butterfly diagram)
- Hale's law for sunspot polarity, **magnetic cycle** of 22 years
- Sunspot groups tilt (Joy's law)
- Polarity inversion at maximum of solar cycle





SUN: solar activity

- Equatorward drift of activity latitude during the cycle

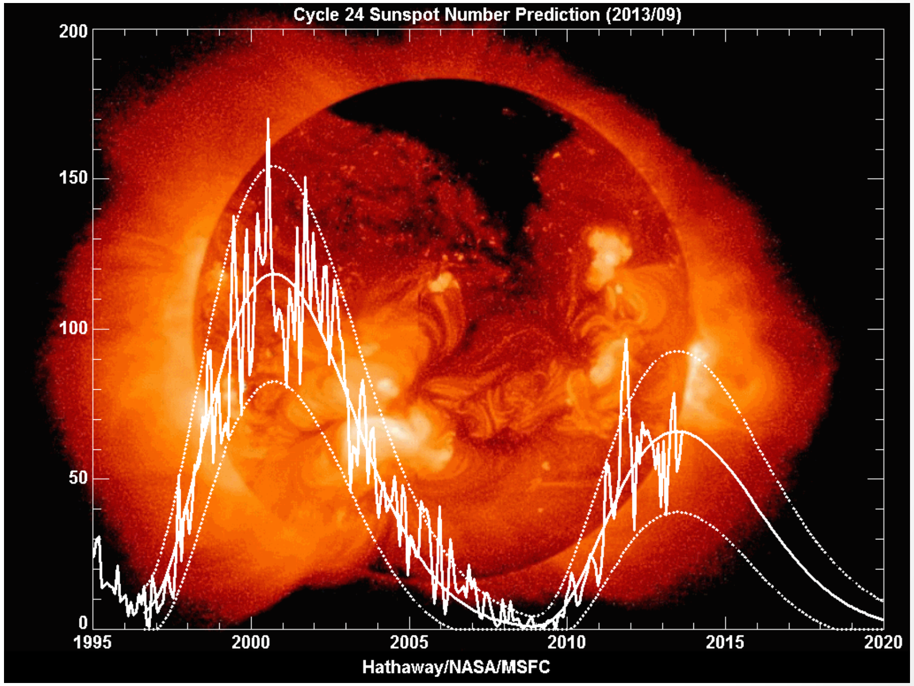


SUN: solar activity

◆ ACTIVITY CYCLE Period range: 7÷13 years

- Shapes the coronal structure and modulates the solar wind
- Modulates the occurrence of eruptive phenomena (flares, CMEs, etc.)
- Modulates solar irradiance
- Modulates UV, X radiation
- CME ➔ Space Weather
- Modulates GCR flux

The present solar cycle is the weakest (smoothed sunspot number for Cycle 24 = 70) since 1906 (smoothed sunspot number for Cycle 14 = 64,2)



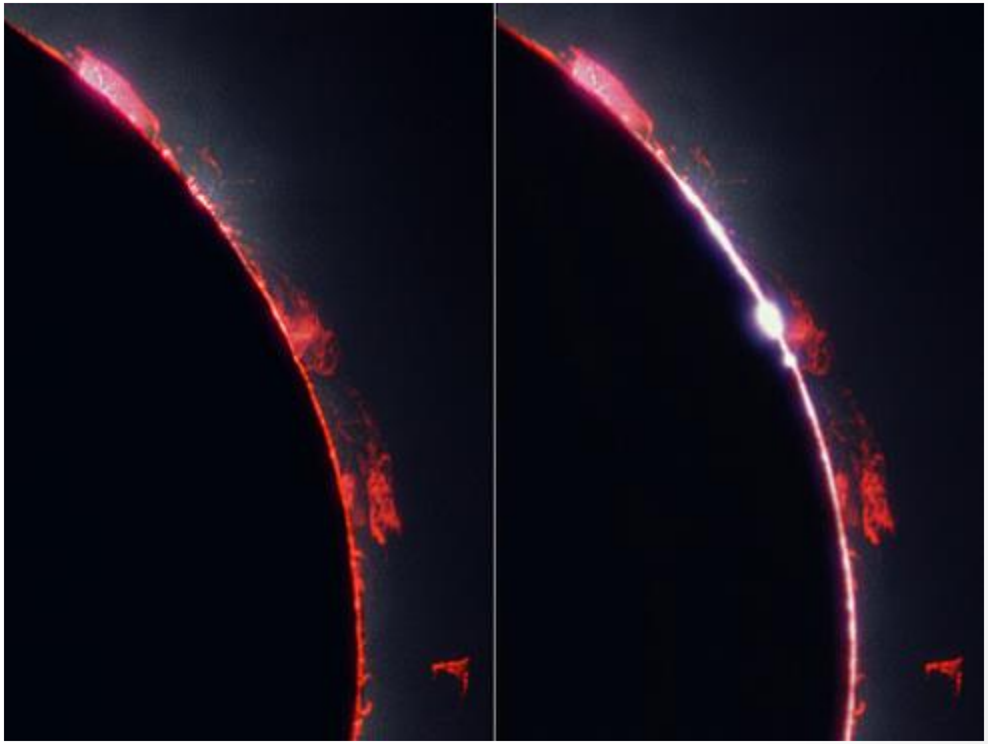
http://solarscience.msfc.nasa.gov/predict.shtml

SUN: chromosphere

Red light emitted by neutral H atoms, visible during solar eclipses

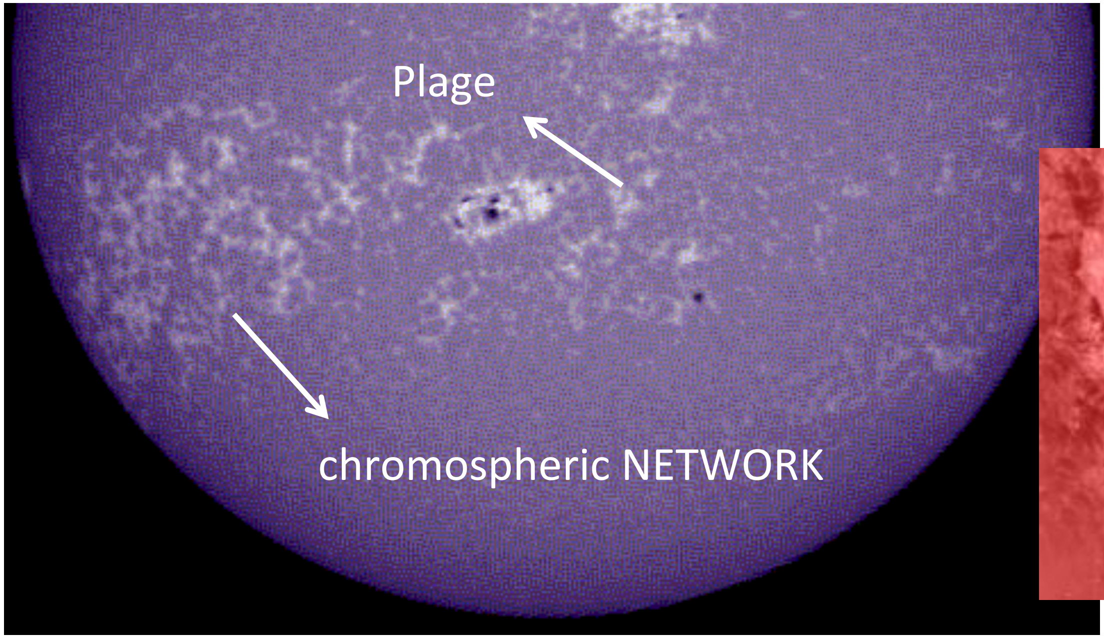
- $\Delta R \sim 10 \div 15 \times 10^3$ km
- $T \sim 10^4 \div 10^5$ K

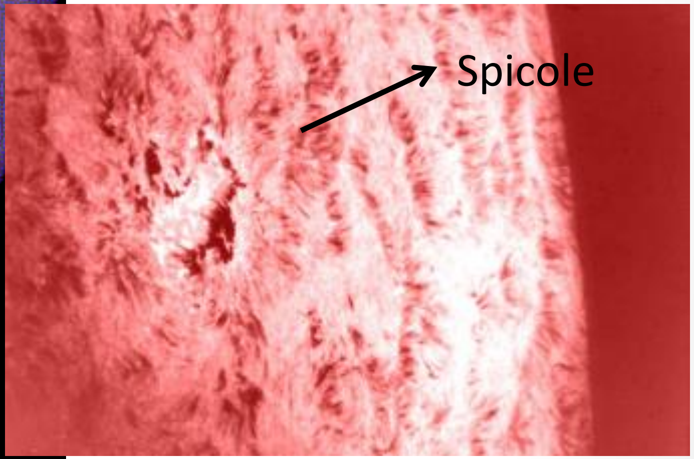
Chromospheric Network
Filaments
Plages
Prominences
Spicules



SUN: chromosphere

- Chromospheric Network, plages and spicules





CaII (393.4 nm, UV)

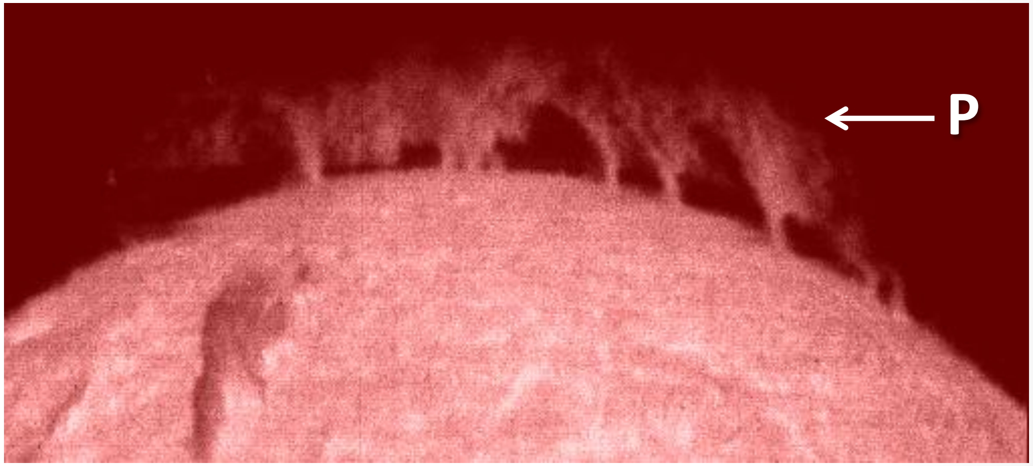
BBSO

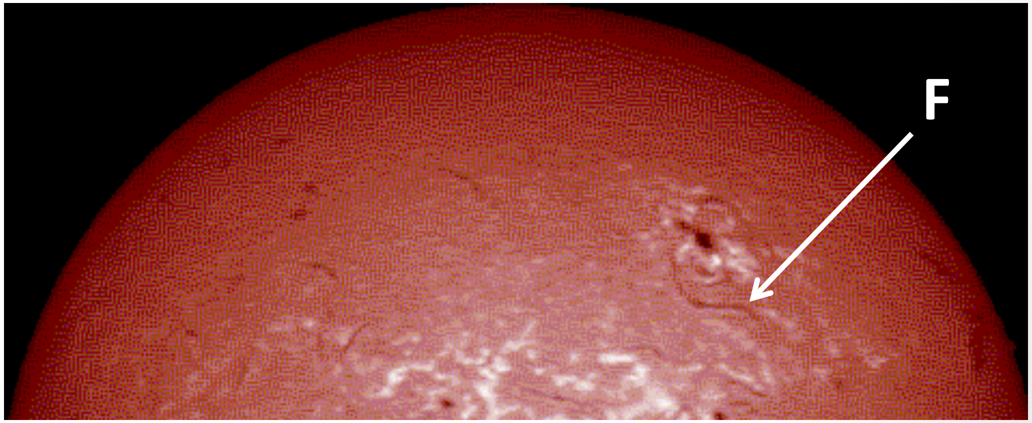
SUN: chromosphere

- Prominences (P) and filaments (F)

Quiescent:
$\tau \sim 200$ days
$T \sim 5 \times 10^3$ K ÷ 10^4 K
$n \sim 10^{16} \div 10^{17}\ m^{-3}$
Length = 2×10^8 m
Width = 6×10^6 m
Height = 5×10^7m

Near active regions:
$n > 10^{17}\ m^{-3}$
smaller by a factor of 3

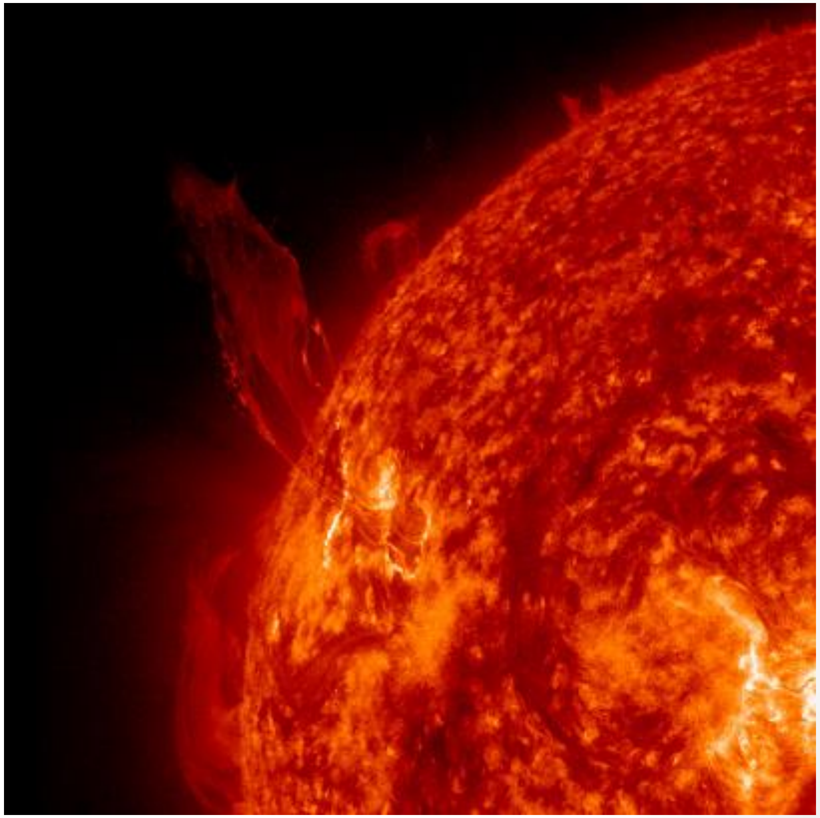




SUN: chromosphere

- Globally filaments and prominences are in equilibrium but they can erupt upon instability set in

The number of prominences varies with the activity level

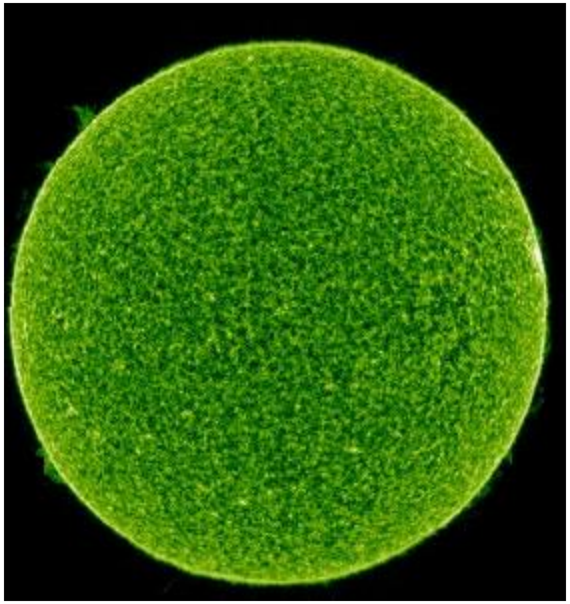


SDO, Sept 24, 2013

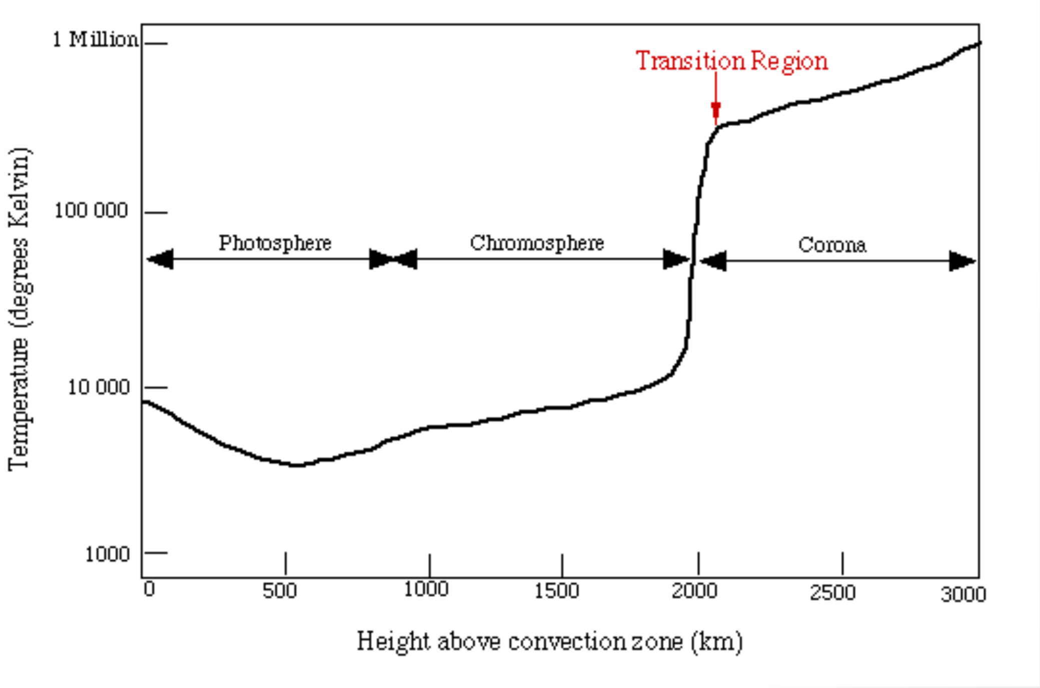
SUN: transition region

- It separates the chromosphere from the corona and it extends by a few tens of km

ΔT: 2 x 10^4 ⟶ 1-2 x10^6 K ⇒ Ionised atoms



SUMER/SOHO
CIV, 10^5 K

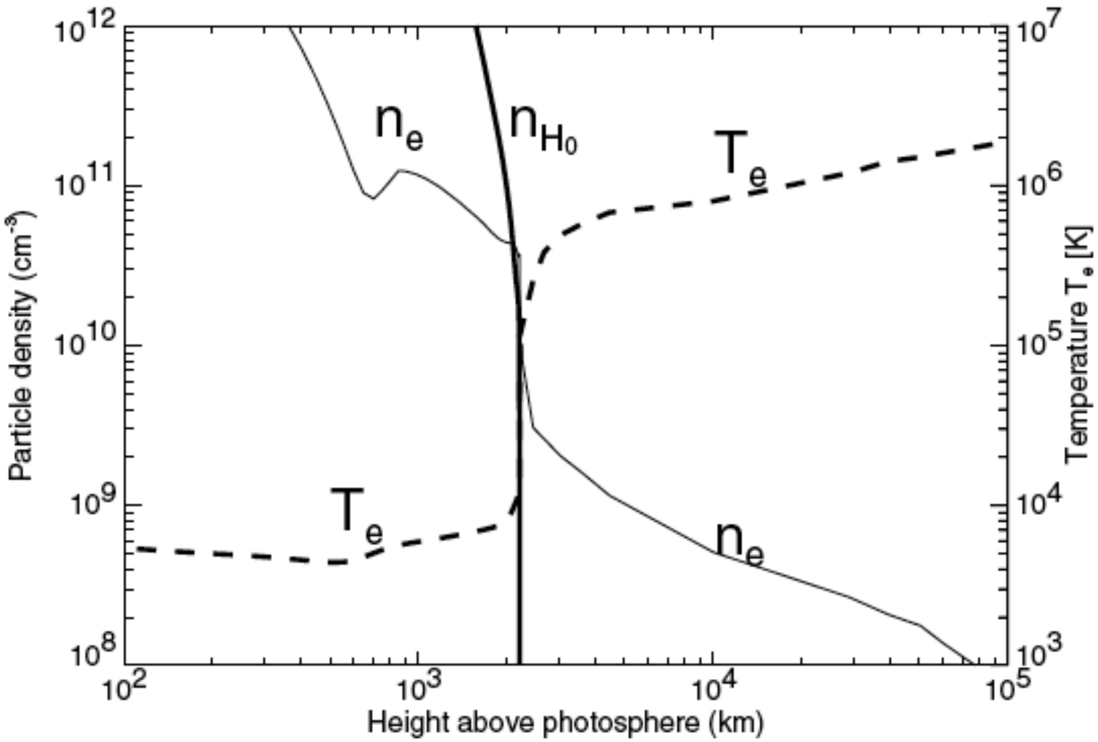


SUN: corona

$T \sim 2 \times 10^6$ K → X, EUV, UV

$n \sim 10^{15} \div 10^{16}$ m^{-3}

Helmet Streamers
Polar Plumes
Coronal Loops
Coronal Holes



Fontela et al.1990

SUN: corona

- In white light it can be observed only during total eclipses.
- Its structure varies with solar activity

CORONA AT SOLAR ACTIVITY **MAXIMUM**

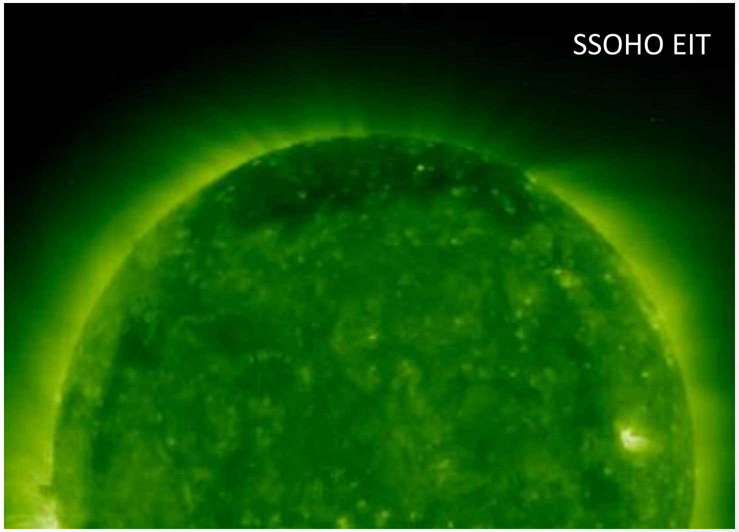
CORONA AT SOLAR ACTIVITY **MINIMUM**

SUN: corona

- **Helmet Streamers**
  - Formed by magnetic arches that connect two sunspots
  - The elongated structure is due to the solar wind

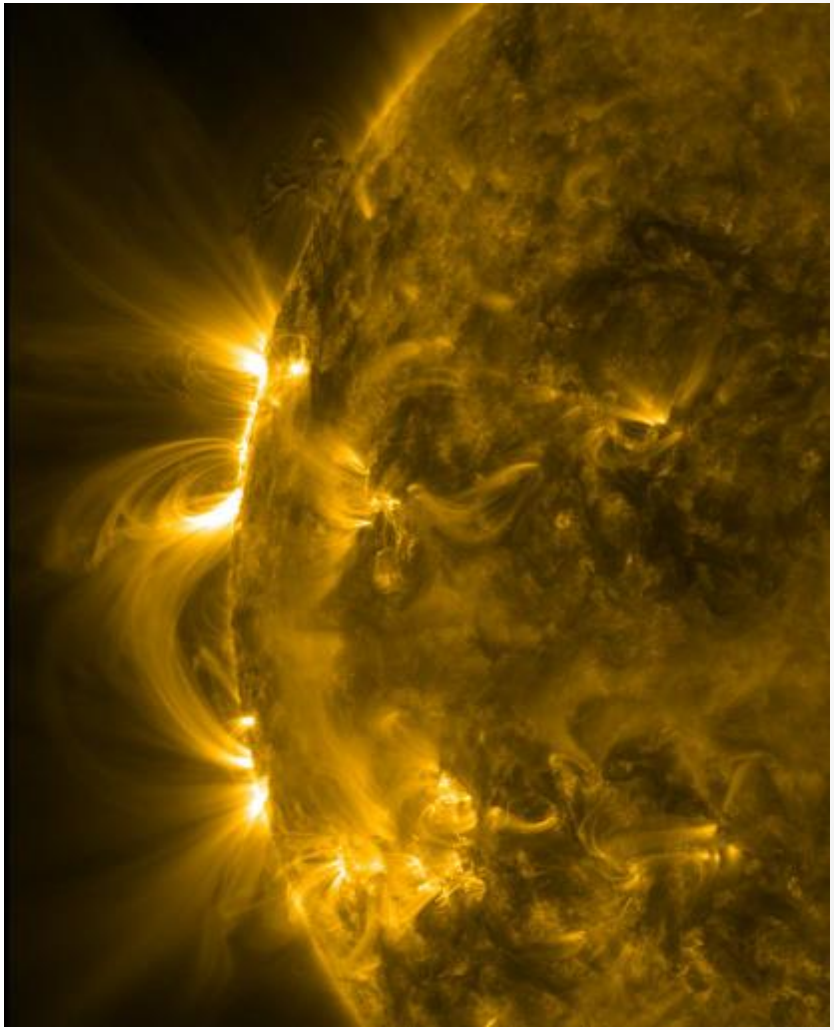
Often prominences are visible at the base of such structures

- **Polar Plumes**
  - Visible at the poles
  - Associated with open magnetic field lines
  - Their structure is due to the solar wind



SUN: corona

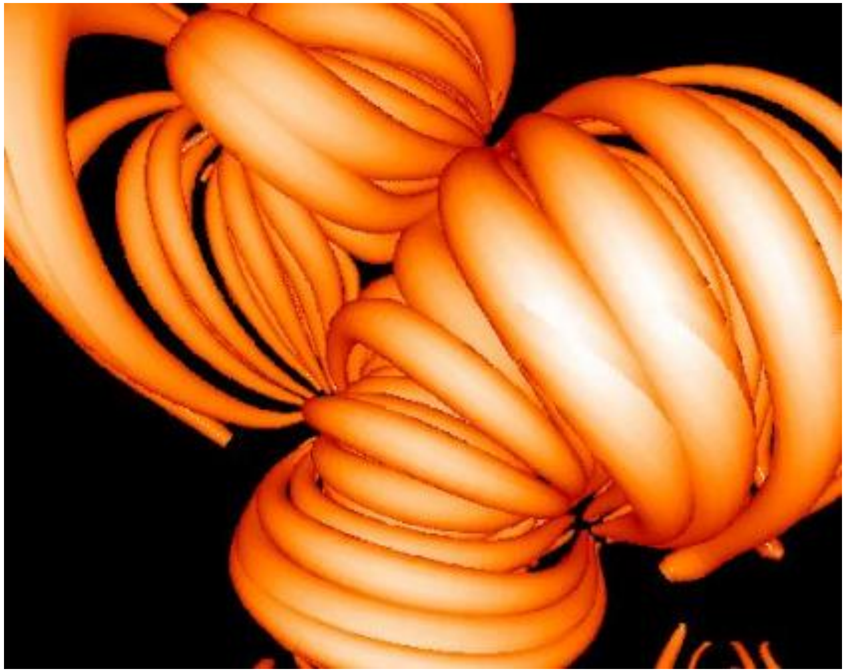
- Coronal Loops
  - Associated with closed magnetic field lines
  - Plasma is injected into the corona from underlying layers
  - Can persist for days even if the structure is changeable
  - Are associated with solar flares
  - Exhibit a 3D structure



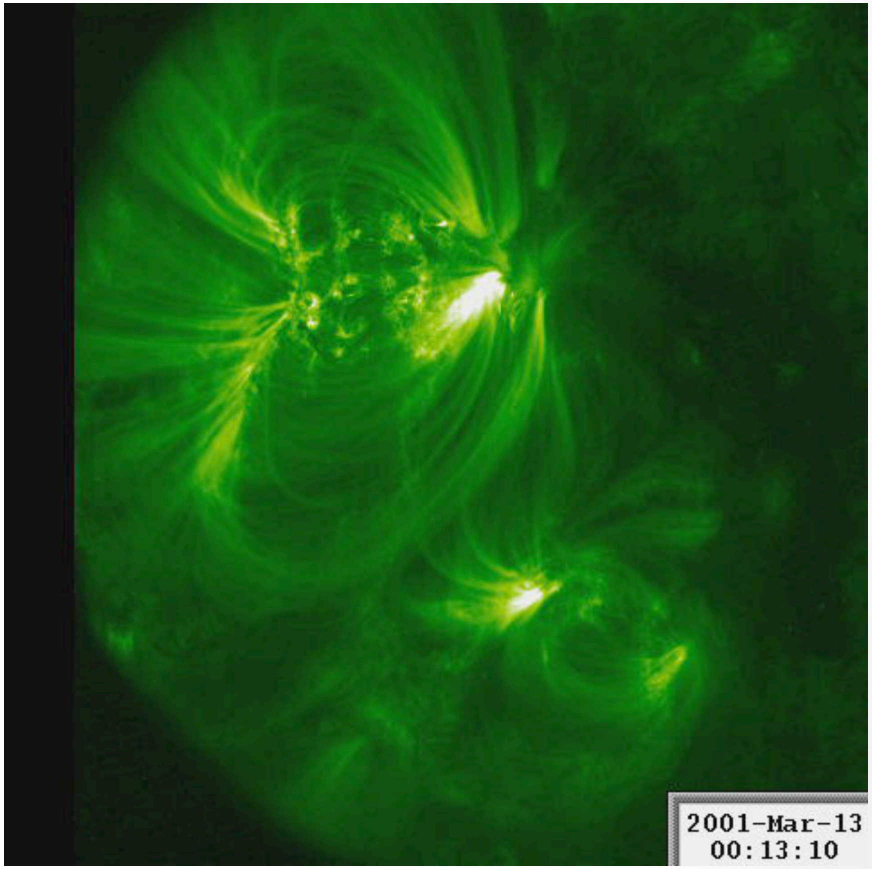
Solar Dynamics Observatory/NASA

SUN: corona

- Coronal Loops



Dr. Allen Gray

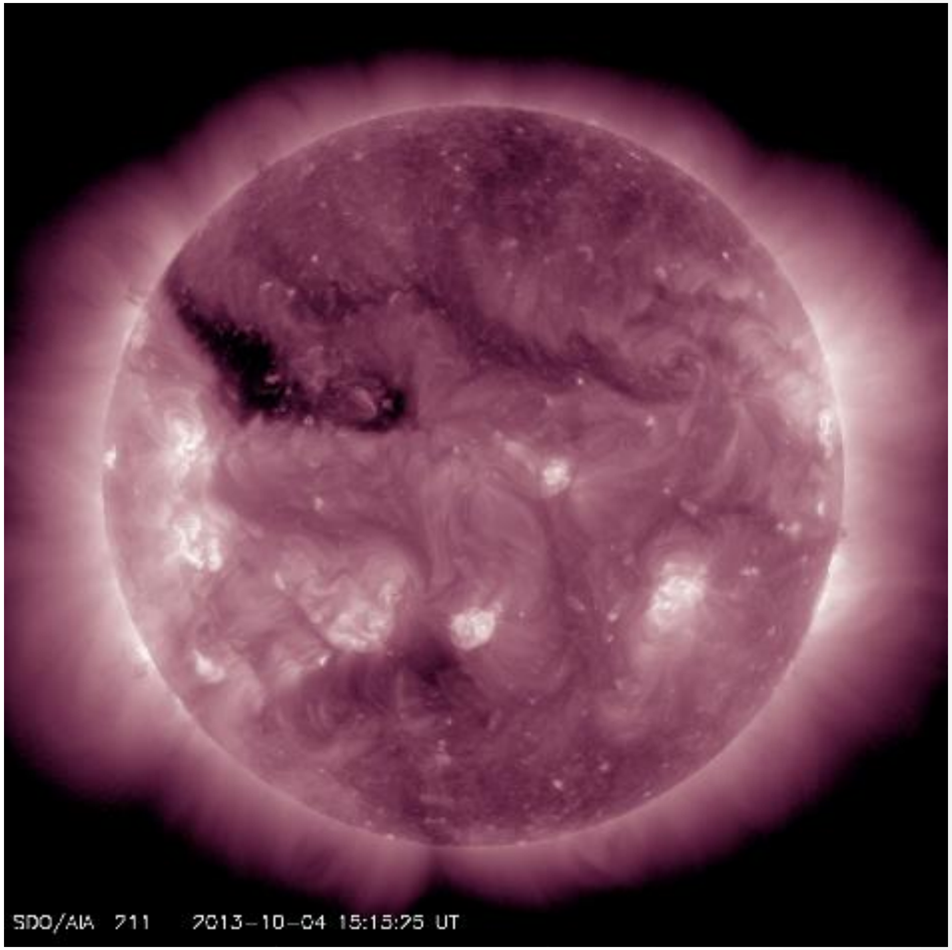


TRACE

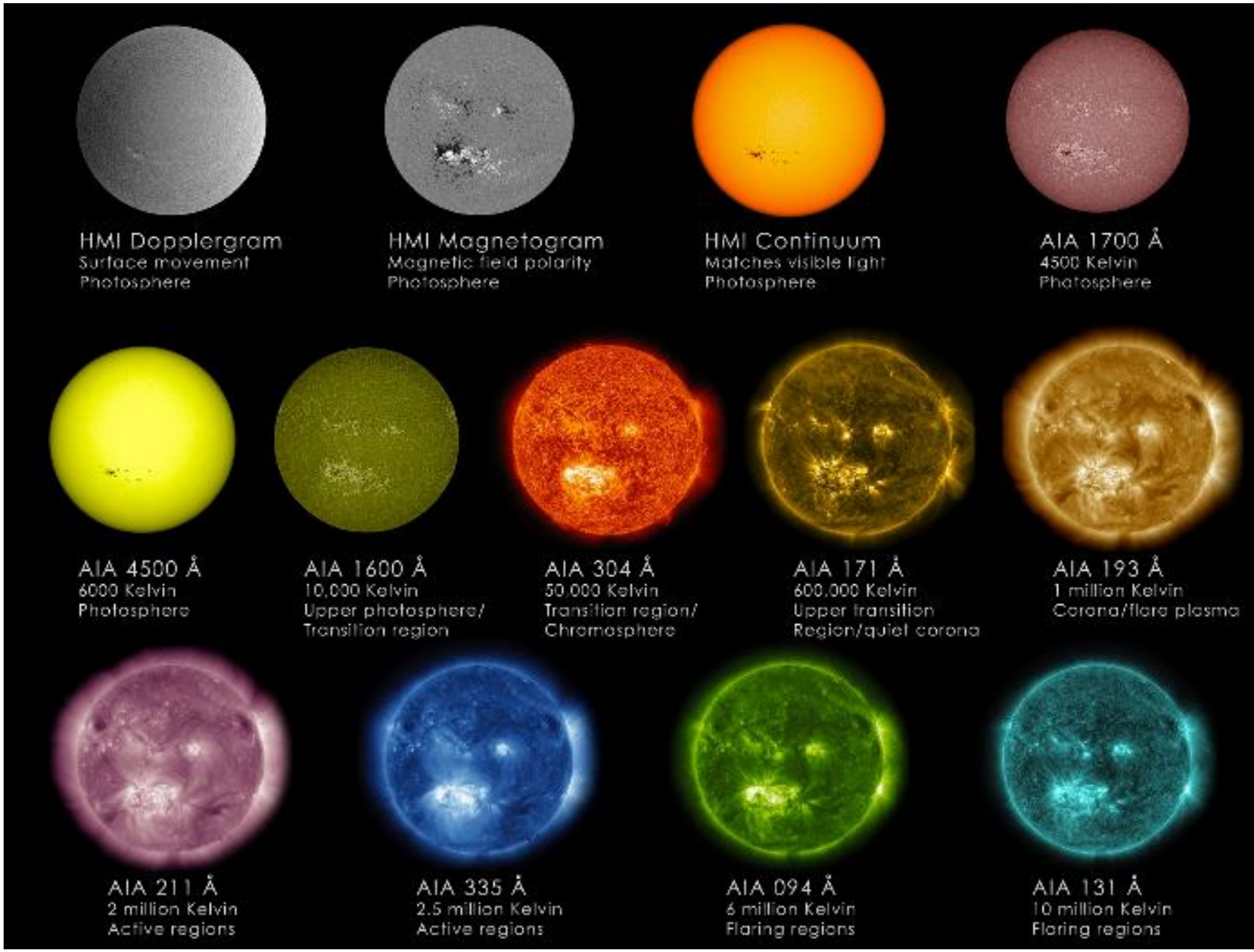
SUN: corona

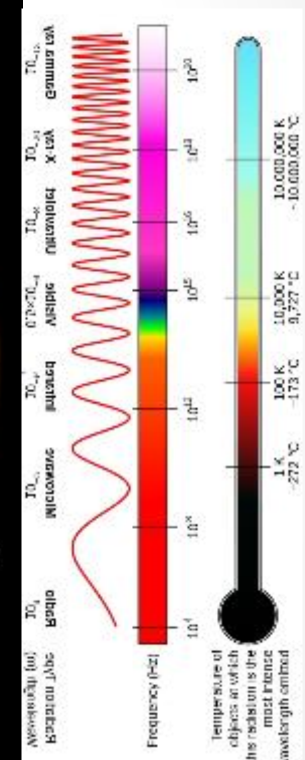
- Coronal Holes
  - Low-emissivity regions in the solar corona
  - Associated with open magnetic field lines

    → high speed solar wind
  - Polar regions



SUN: Sun Wavelength Chart





NASA SDO Goddard Space Flight Center

SUN: flare

- A solar flare is a rapid energy release in solar corona triggered by an instability in the magnetic configuration. (Magnetic reconnection)
- Flares release $10^{16} \div 10^{25}$ J ($10^{23} – 10^{32}$ erg) energy in tens of minutes (Note: one H-bomb: 10 million TNT = 5.0×10^{23} erg)
- Emission almost at all wavelength + energetic particles

	Peak in 0.1 to 0.8 nm band
Class	[$W \cdot m^{-2}$]
B	$I < 10^{-6}$
C	$10^{-6} \leq I < 10^{-5}$
M	$10^{-5} \leq I < 10^{-4}$
X	$I \geq 10^{-4}$

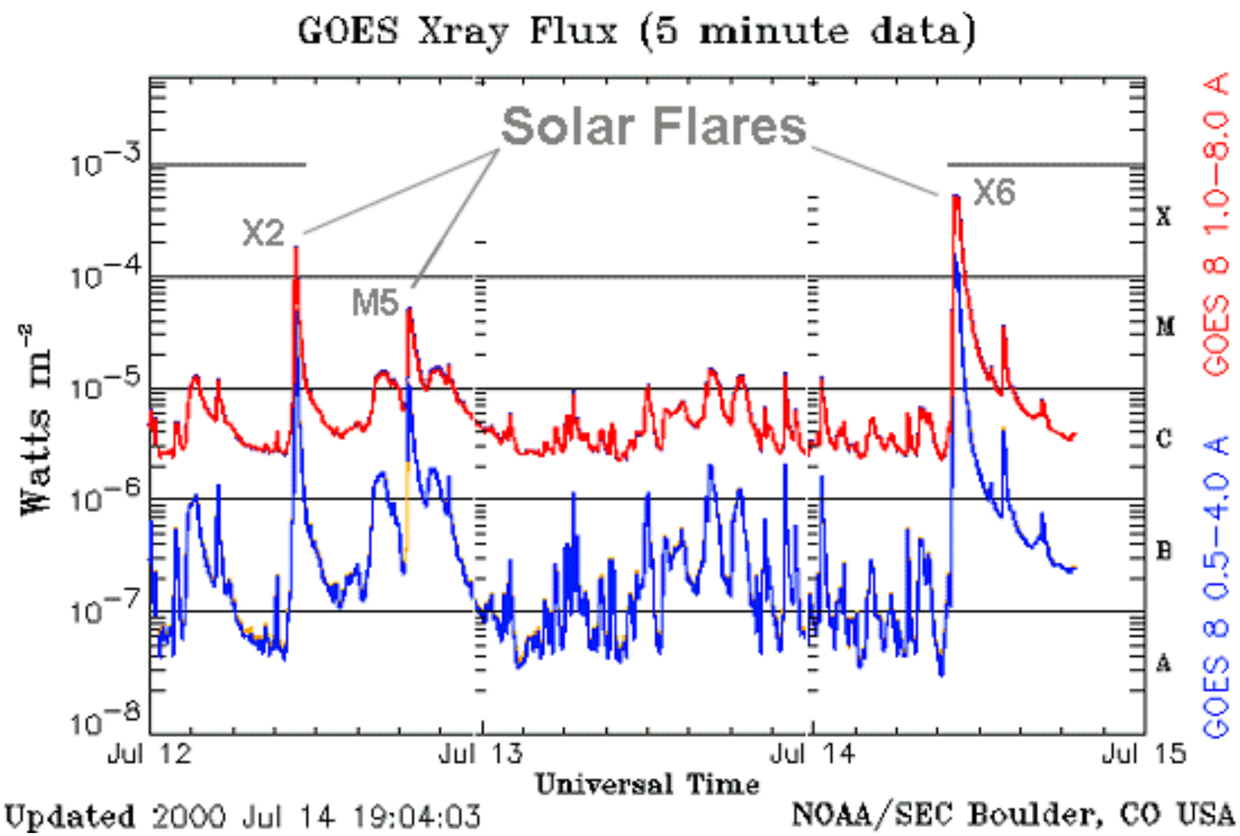
Each category for x-ray flares has nine subdivisions ranging from, *e.g.*, C1 to C9

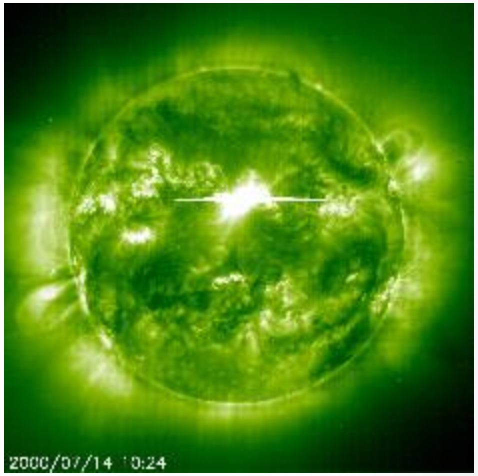
A multiplier is used to indicate the level within each class. For example:
M6 = 6×10^{-5} $W \cdot m^{-2}$

I = burst peak intensity

SUN: flare

- The X6 flare triggered a radiation storm around Earth nicknamed the Bastille Day event.





SUN: flare

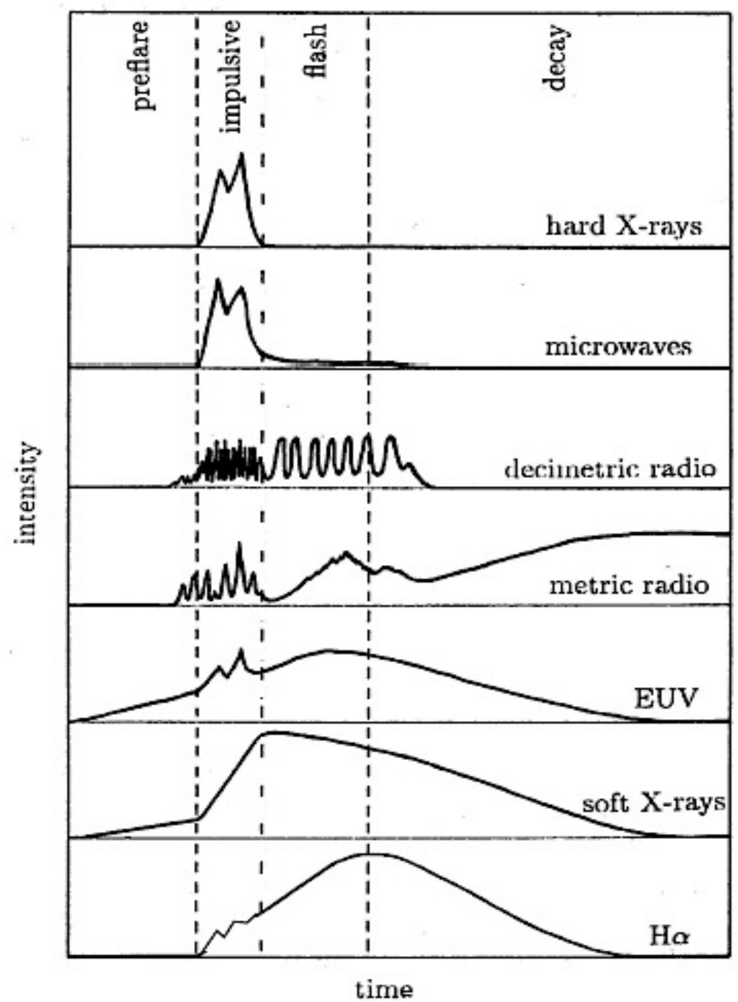
- The temporal evolution of a flare may consist of *three phases*:

Preflare phase: lasts a few minutes, coronal plasma heats up, soft x-rays and H_α brightening

Impulsive phase: ~ 3 ÷ 10 min, energetic particles acceleration, hard x-rays emission

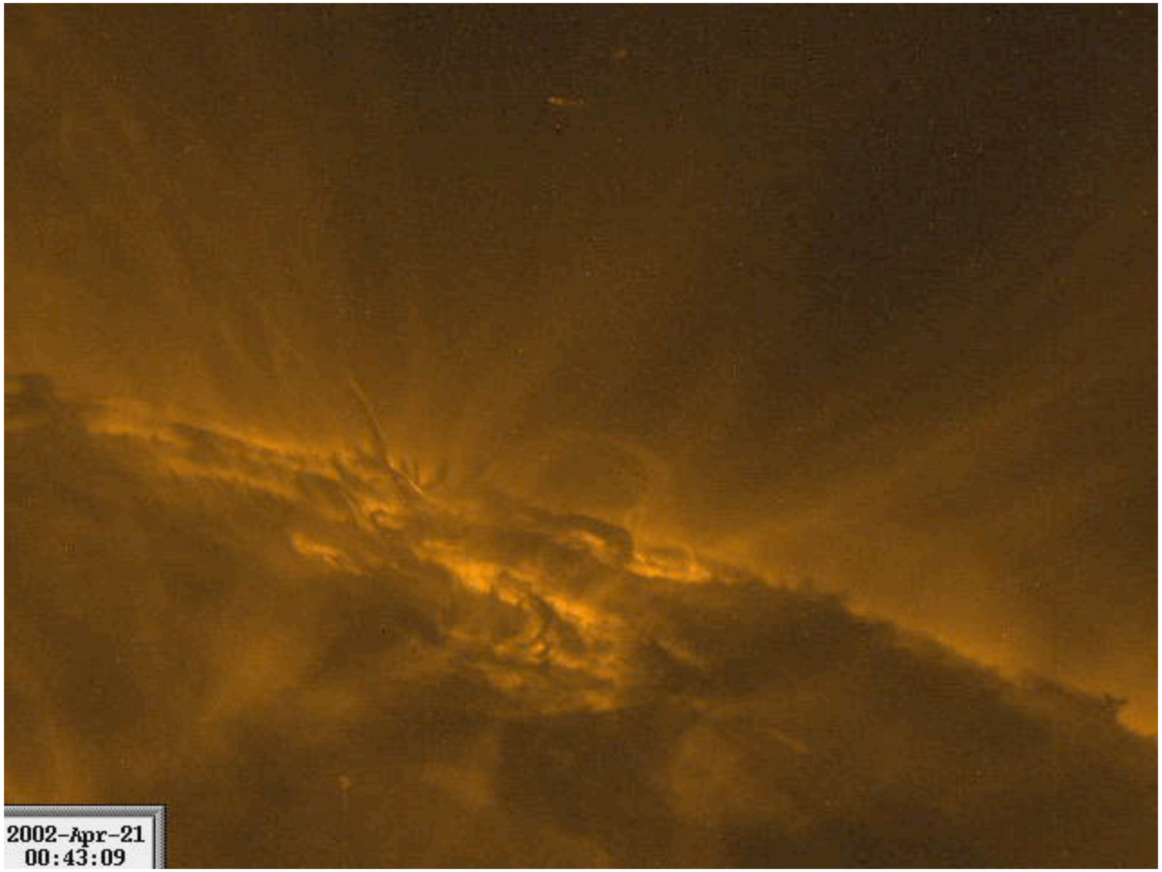
(flash phase: rapid increase in H_α, 5 ÷ 10 min)

Gradual phase: coronal plasma gradually returns to its original state



SUN: flare

Flare evolution by TRACE (19.5 nm)



SUN: coronal mass ejection

- A CME is a huge cloud of magnetized plasma ejected from the Sun’s corona into space at high speeds
  - Sometimes, but not always associated with flare and prominence eruption

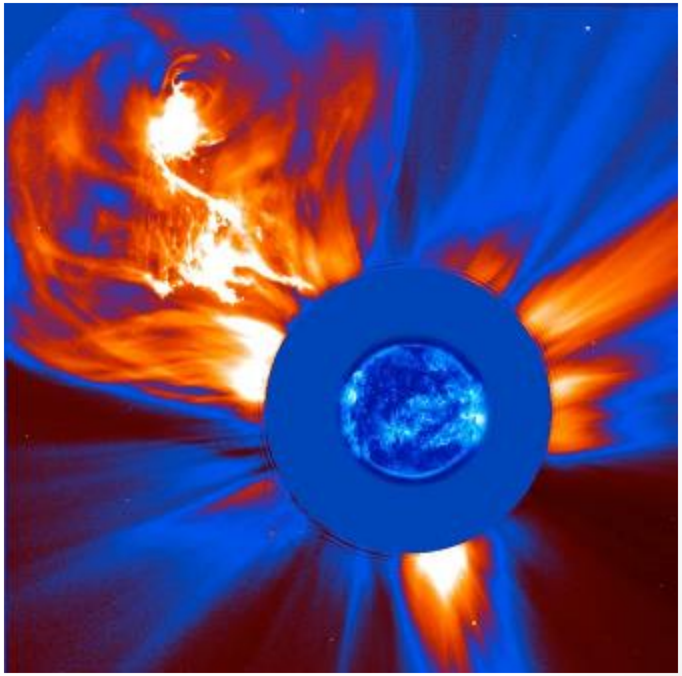
Apparent angular width:

few ÷ 120° (normal CME)

120° ÷ 360° (partial halo CME)

Front (Earth) or back side directed

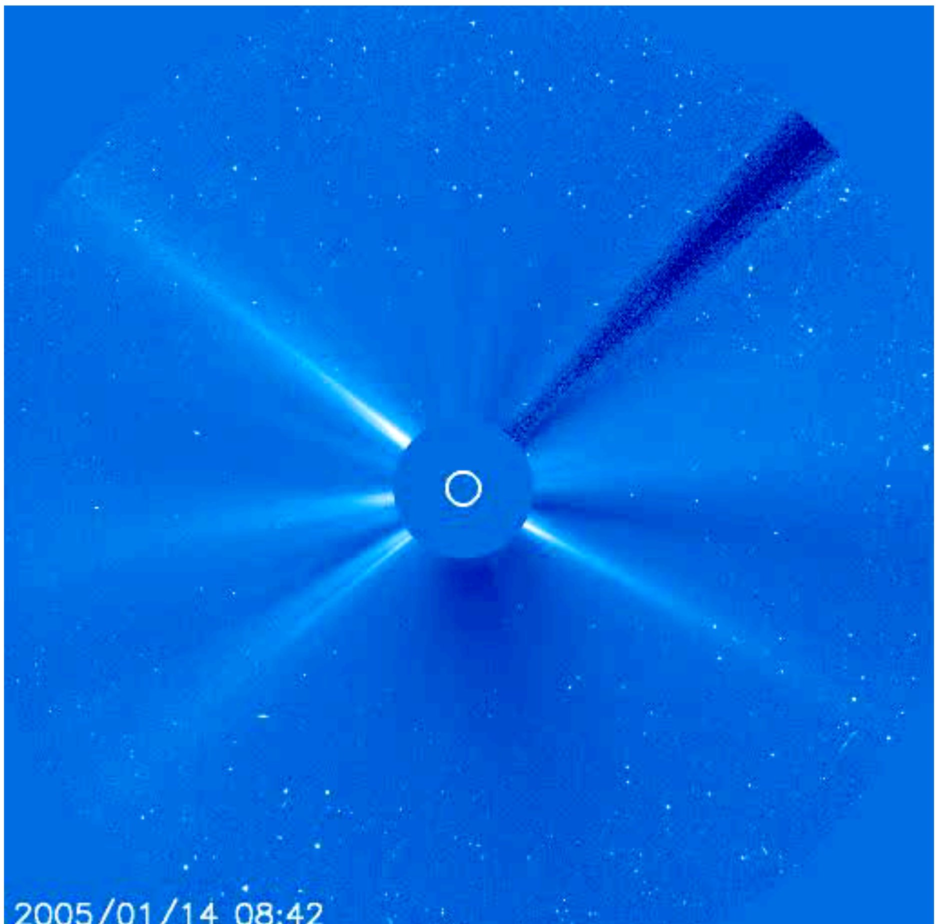
CMEs are referred to as halo CMEs

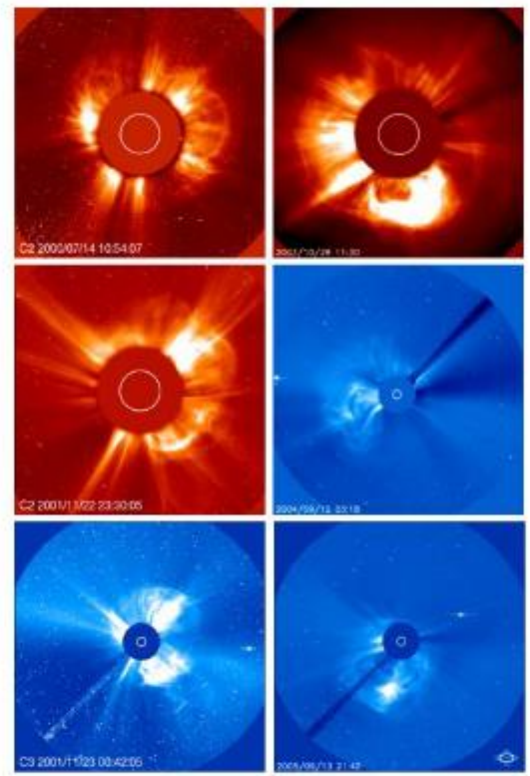


SOHO/LASCO

SUN: coronal mass ejection

- Halo CME are Earth-directed CMEs





SOHO/LASCO

SUN: coronal mass ejection

- $M_{ej} = 10^{10} \div 10^{13}$ kg
- $E_{tot} = E_{cin} + E_{potential} = 10^{20} \div 10^{26}$ J
- $V = 300 \div 2000$ kms^{-1}

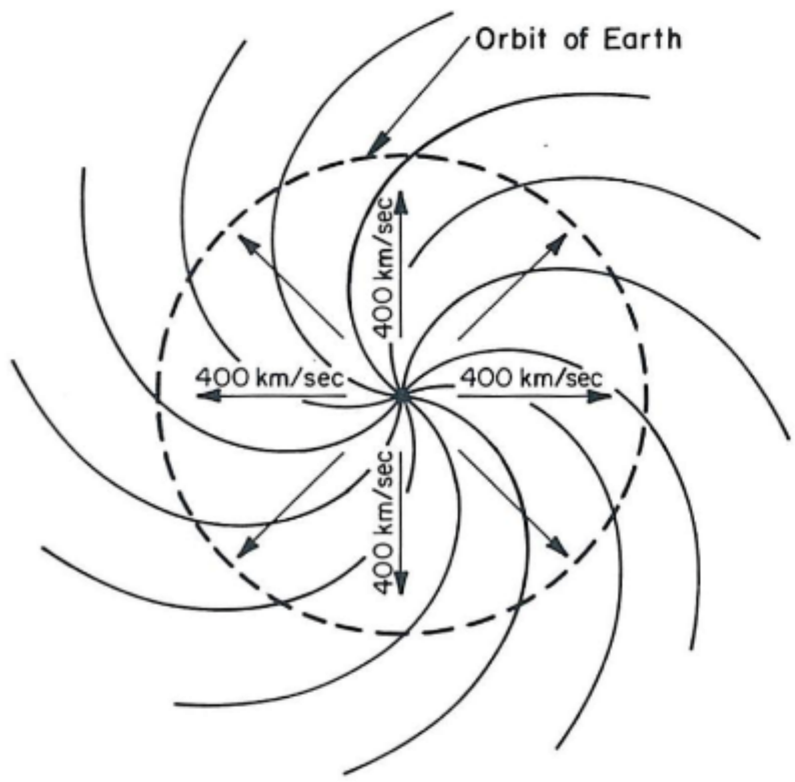
- Interfere with solar wind for example by the creation of a shock wave that moves ahead the CME, accelerating solar wind particles to high energies

SOLAR WIND

- It is a stream of charged particles (mostly e^- and p) released from the Sun's corona in radial direction

The solar magnetic field is frozen in to the radial outflowing solar wind. Thus, due to the Sun's rotation, the magnetic field lines exhibit an Archimedean spiral configuration.

The angle to the radial direction of the magnetic field depends on distance, latitude and the local solar wind velocity.



SOLAR WIND

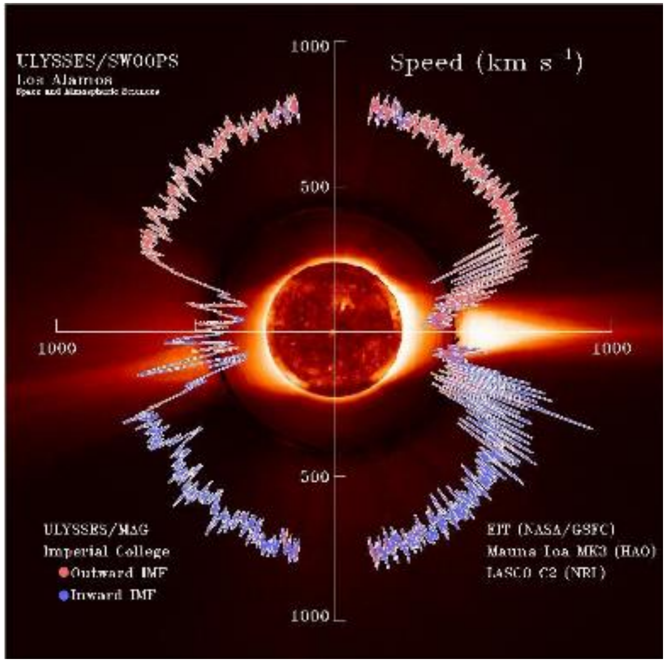
- Typical values of several solar wind parameters as measured by Helios 2 at 1AU

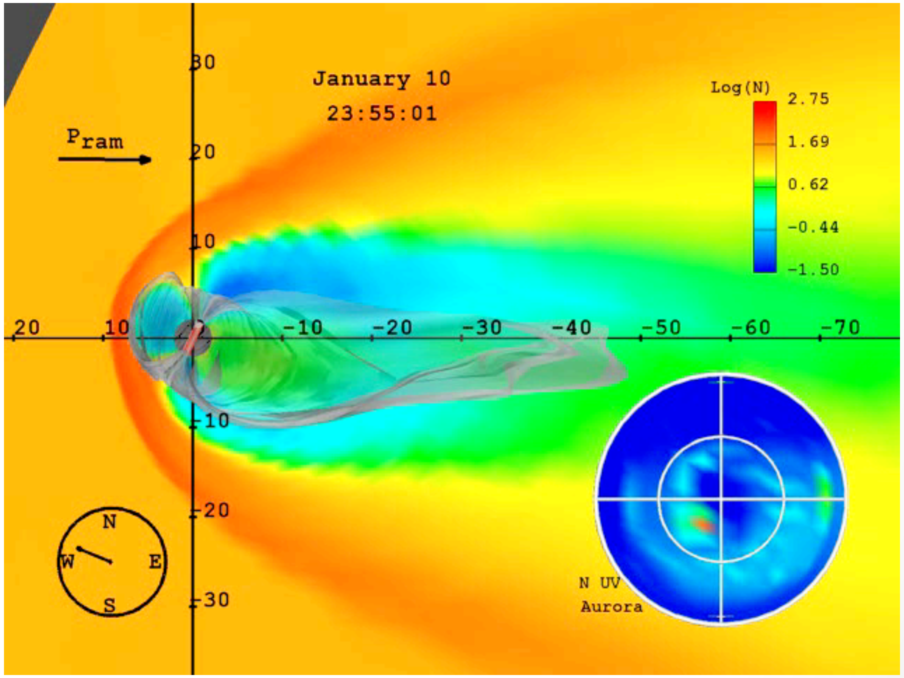
Wind Parameter	Slow wind	Fast wind
number density	~ 15 cm^{-3}	~ 4 cm^{-3}
bulk velocity	~ 350 km s^{-1}	~ 600 km s^{-1}
proton temperature	~ 5 x 10^4 K	~ 2 x 10^5 K
electron temperature	~ 2 x 10^5 K	~ 1x 10^5 K
α-particles temperature	~ 2 x 10^5 K	~ 8 x 10^5 K
magnetic field	~ 6 nT	~ 6 nT

http://solarphysics.livingreviews.org/open?pubNo=lrsp-2005-4&page=articlese12.html

SOLAR WIND

- Solar wind velocity and interaction with the magnetosphere





SUN: state of the matter

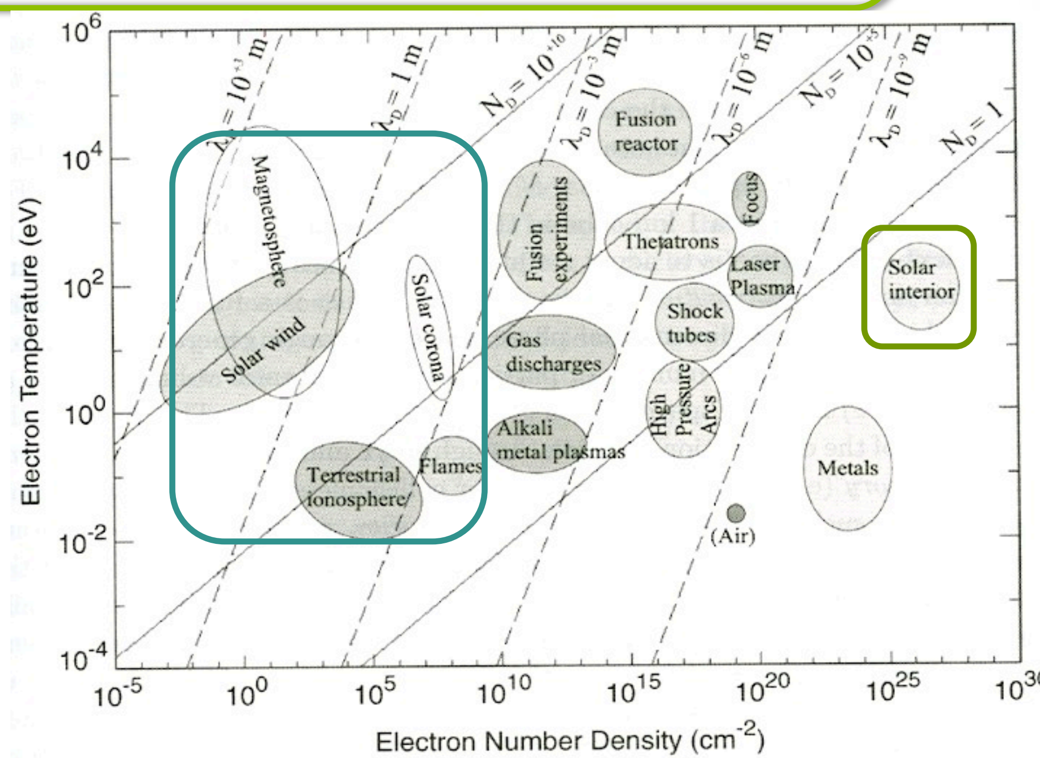
The matter that constitutes the Sun is in the state of PLASMA

PLASMA: quasi-NEUTRAL gas of CHARGED particles that exhibit a COLLECTIVE BEHAVIOUR

Sun-Earth Plasma:

T: 6 orders of magnitude

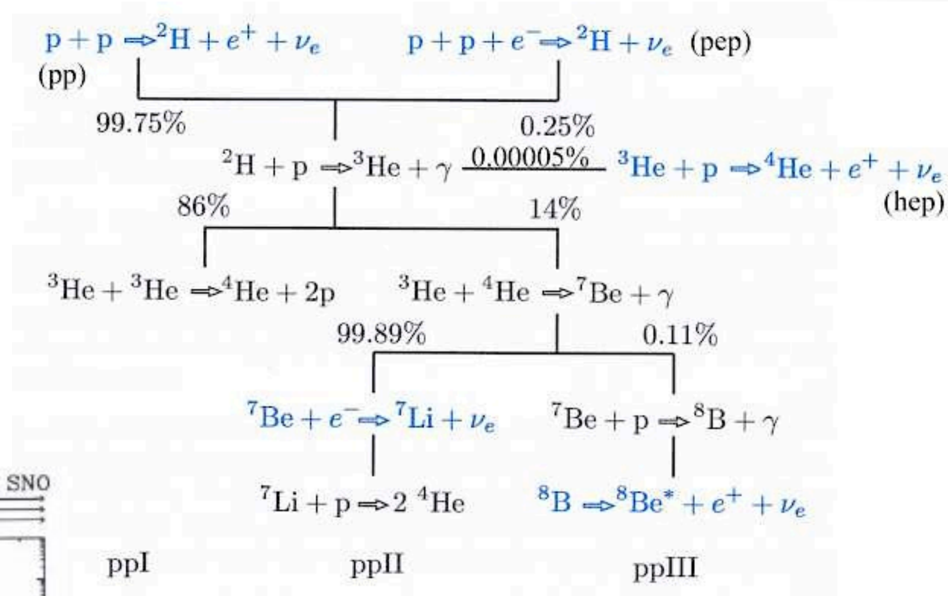
n: 10 orders of magnitude

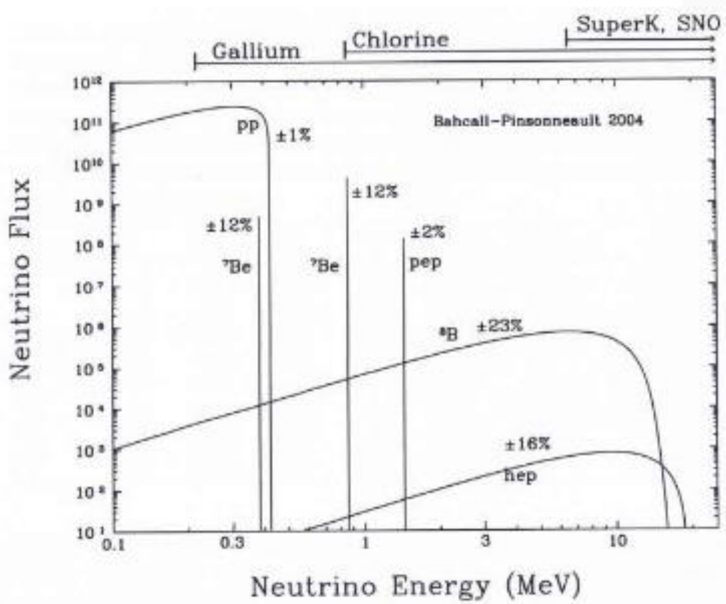


1eV = 11,604.5 K

SUN: core

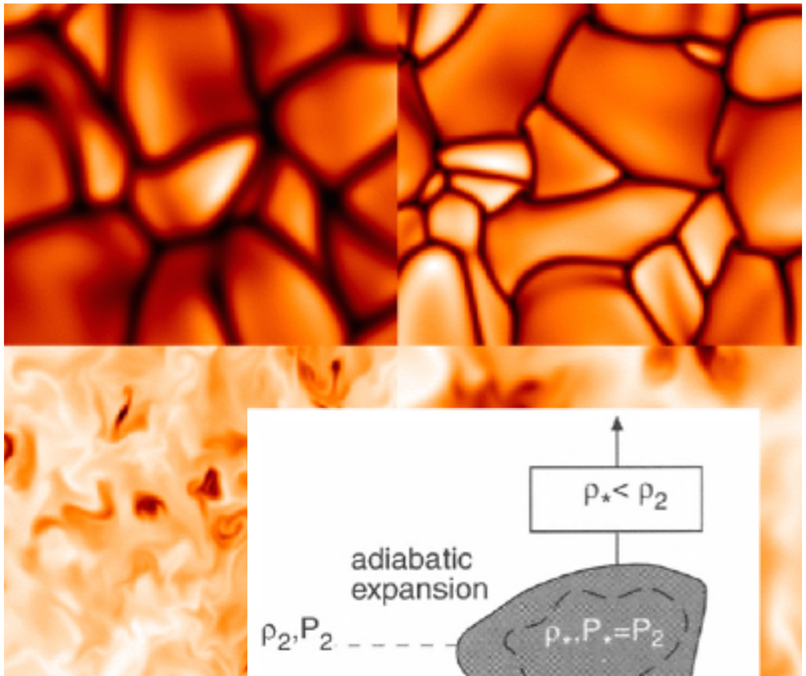
- T ≈ 1×10^7 K
- R ≈ R$_\odot$/4
- M ≈ M$_\odot$/2
- ρ ≈ 1.5 x 10^5 kg m^{-3}

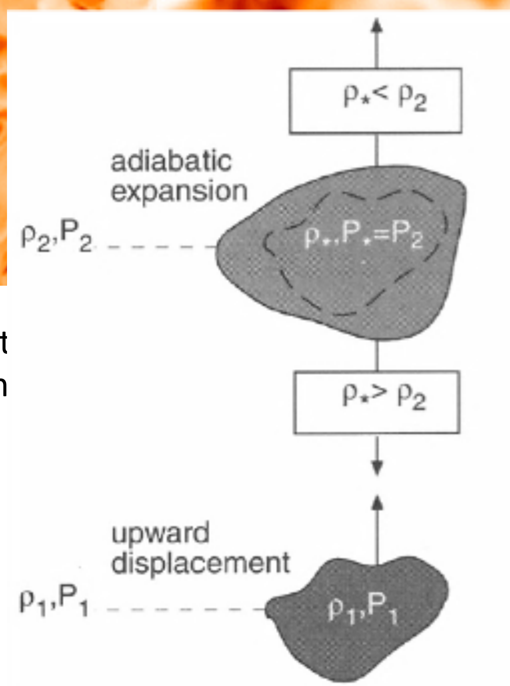




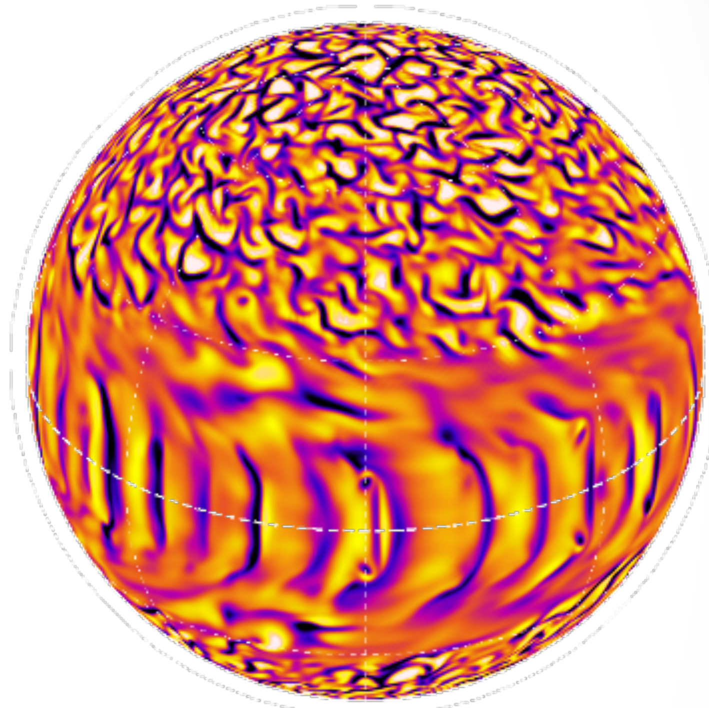
Photons: E of the order of MeV (gamma-rays) transport energy to the outer layers of the star.

SUN: convective zone





3D MHD simulat) different treatm l. 2004).



Convection in a star rotating five times the current solar rate. Shown here is the radial velocity near the upper boundary of the simulation box, with upflows in bright tones and downflows in dark tones . lcd-www.colorado.edu/bpbrown/Research/index.html

SUN: photosphere

- Sunspots
  - A flux tube is less dense than the surroundings and rises up

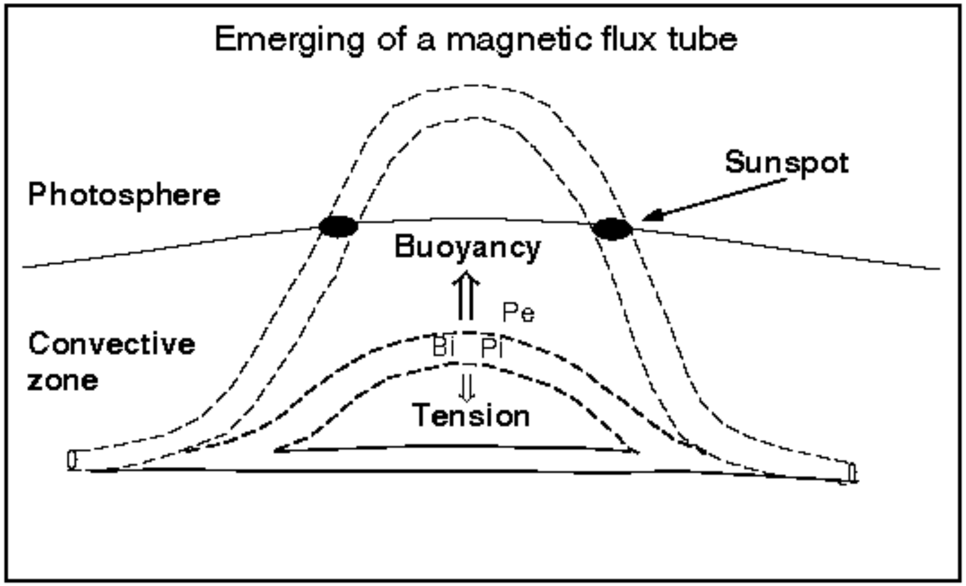
$$P_g^i + P_m^i = P_g^e \rightarrow \frac{k_b}{m}\rho_i T_i + \frac{B^2}{2\mu} = \frac{k_b}{m}\rho_e T_e$$

$$\rho_e = \rho_i + \frac{\frac{B^2}{2m}}{\frac{k_b}{m}T} > \rho_i$$

$$(\rho_e - \rho_i)\, gV > \frac{B^2 S}{\mu}$$

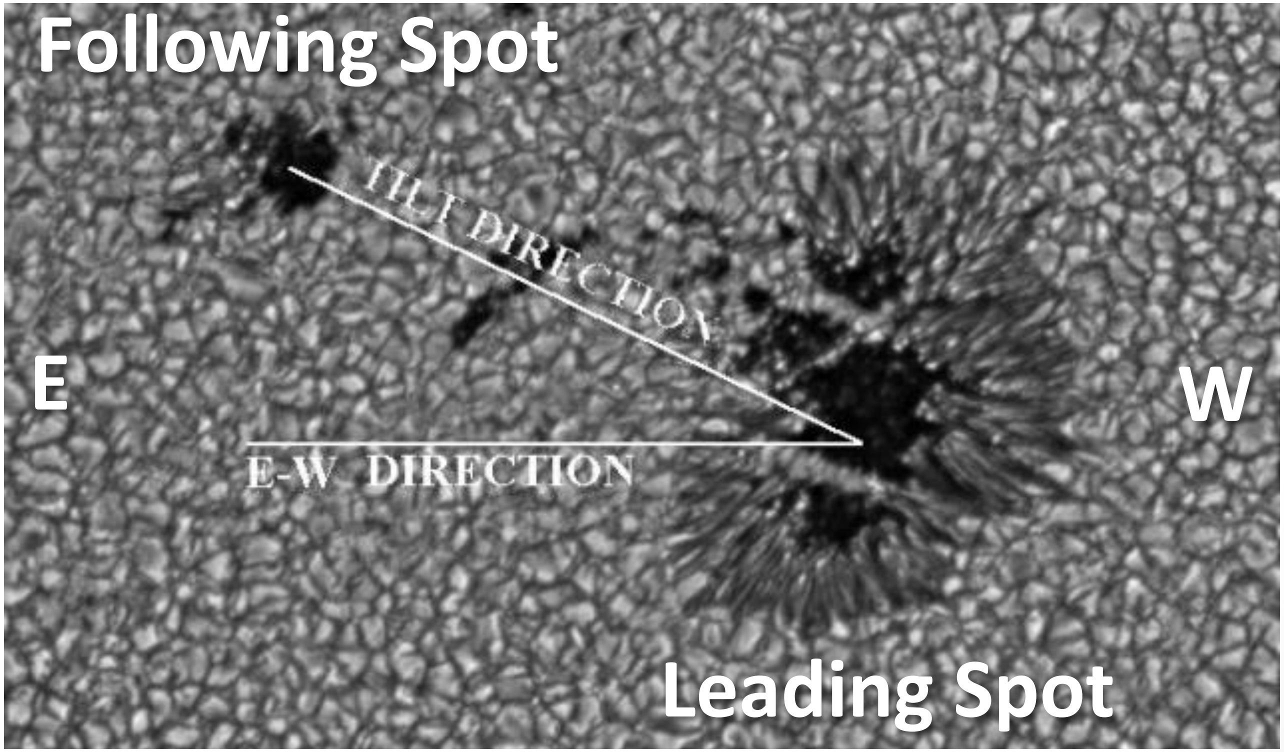
Archimedean Force

Magnetic Tension



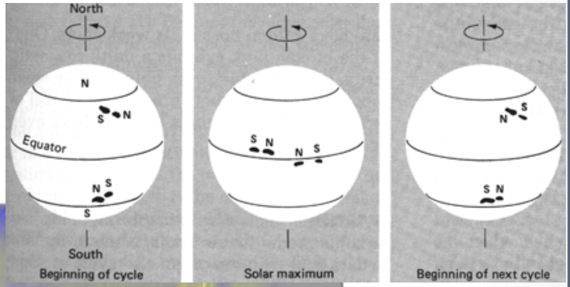
SUN: solar activity

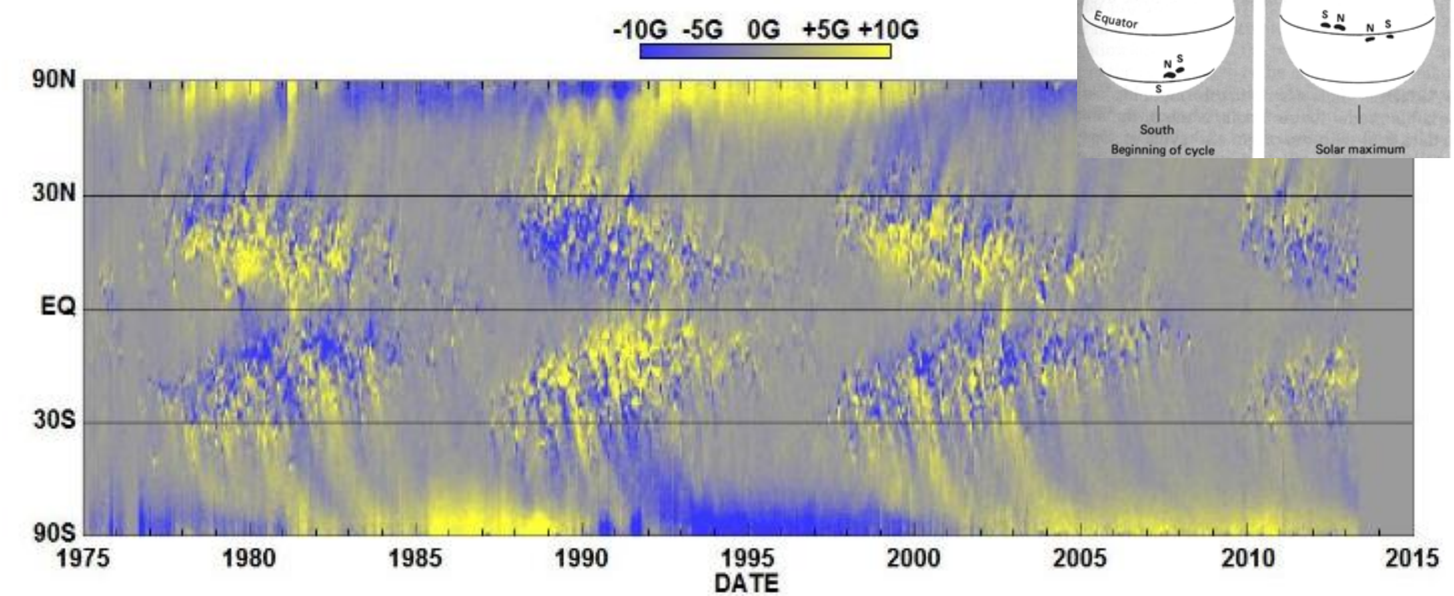
- Joy's law:
  - Sunspot groups originate with a tilt angle with respect to equator and the leading spot is nearer to it. The tilt angle becomes larger with latitude but is very different for each group



SUN: solar activity

- Hale's law
  - "…the preceding and following spots … are of opposite polarity, and that the corresponding spots of such groups in the Northern and Southern hemispheres are also opposite in sign. Furthermore, the spots of the present cycle are opposite in polarity to those of the last cycle" Hale et al. (1919).
- Polarity inversion in proximity of solar maximum





Hathaway/NASA/MSFC 2013/07

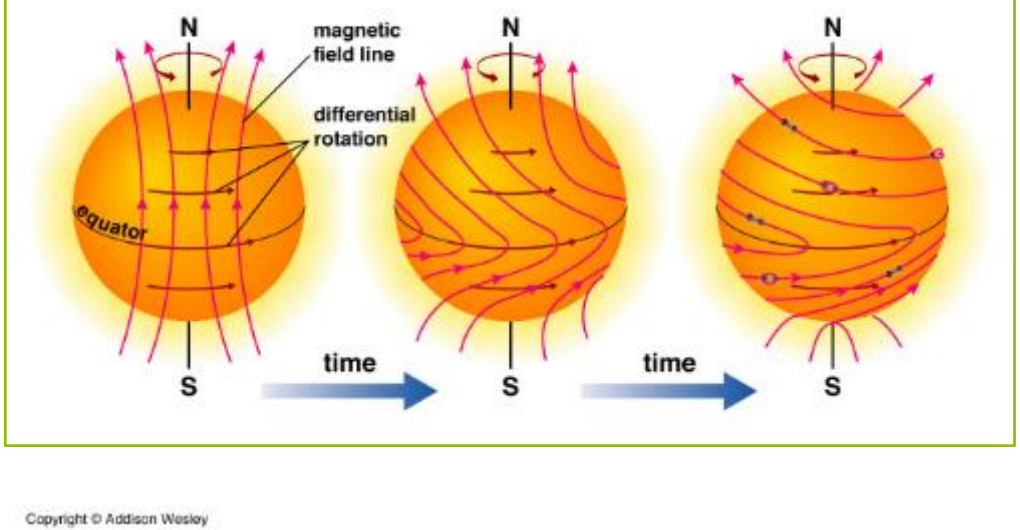
SUN: solar activity

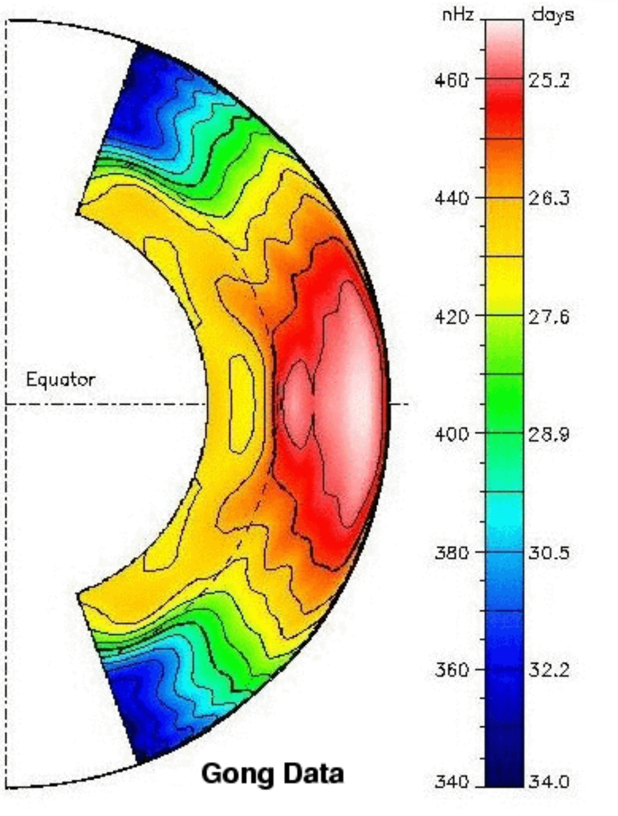
- Kinetic dynamo related to the α-Ω effect

ω_{eq} ~ 2.9 ×10^{-6} rad/s (T ~ 24.9 days)

ω_{poli} ~ 2.0 ×10^{-6} rad/s (T ~ 31.5 days)

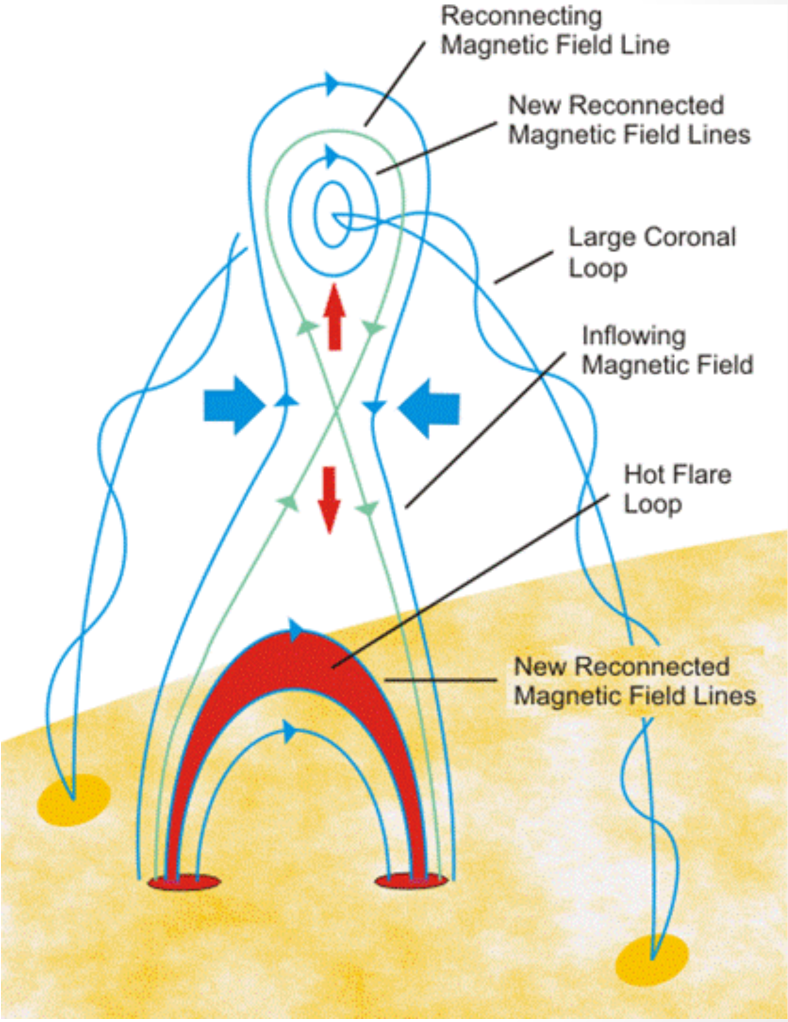
Poloidal -> Toroidal -> Poloidal->…





SUN: flare

- Magnetic reconnection



SUN: coronal mass ejection

- Correlation relation between the radial speed and the expansion speed measured across the full CME width in the direction perpendicular to the radial direction:

  $v_{rad} = 0.88\, v_{exp}$

- $M_{ej} = 10^{10} \div 10^{13}$ kg
- $E_{tot} = E_{cin} + E_{potenial} = 10^{20} \div 10^{26}$ J
- $V = 300 \div 2000\ kms^{-1}$

- Interfere with solar wind for example by the creation of a shock wave that moves ahead the CME, accelerating solar wind particles to high energies