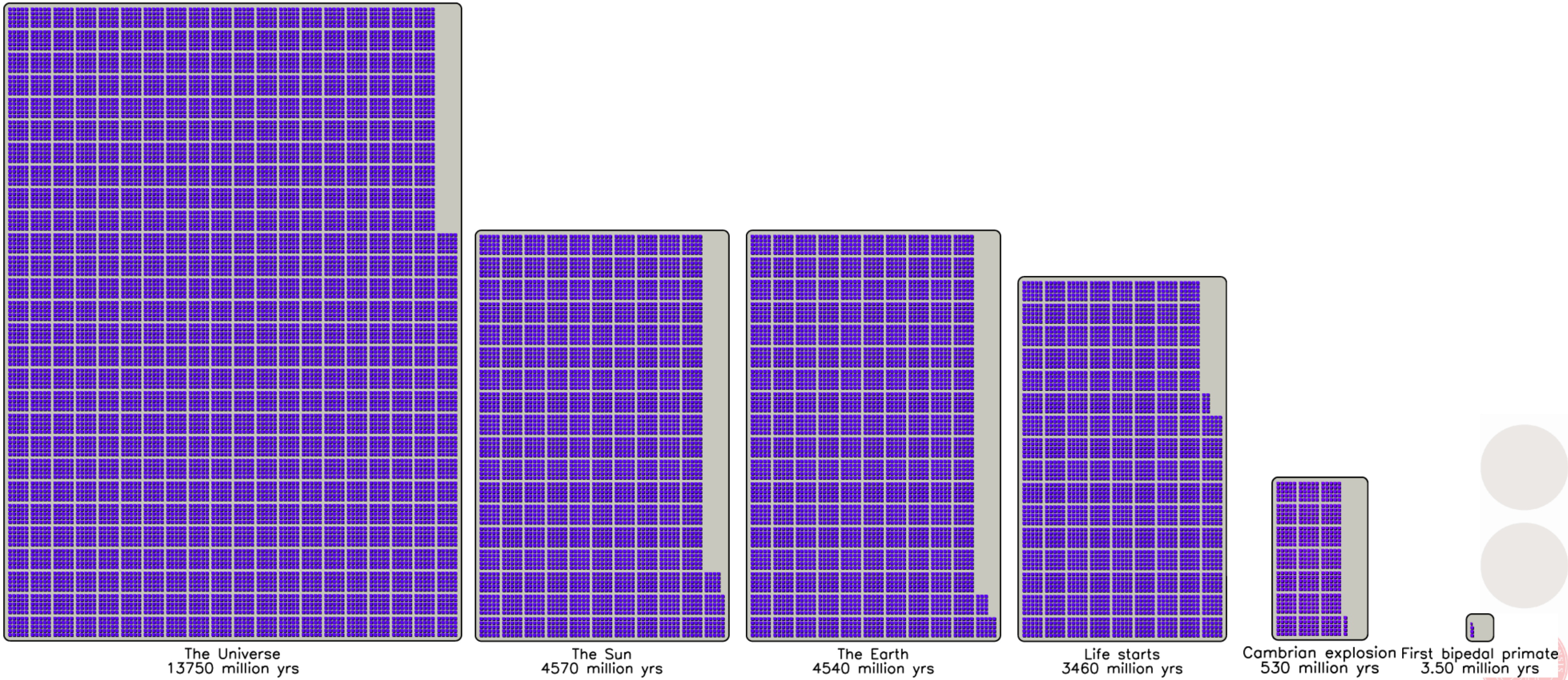
UiO : **Department of Physics**
University of Oslo

Dynamics of the Sun

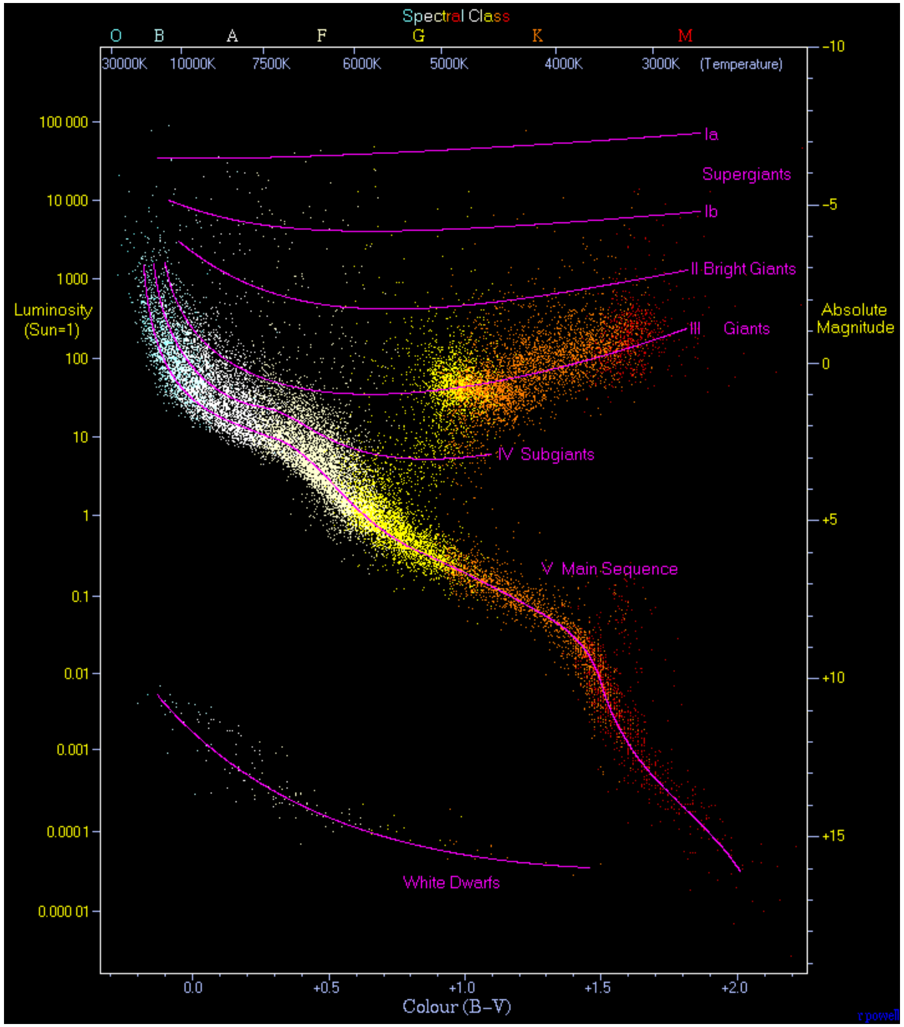
Some facts about the Sun

Mass	2×10^{30} kg
Distance	150 million km
Radius	700 000 km
Surface temperature	6000 K
Age	4.6 billion years

To put things into perspective…



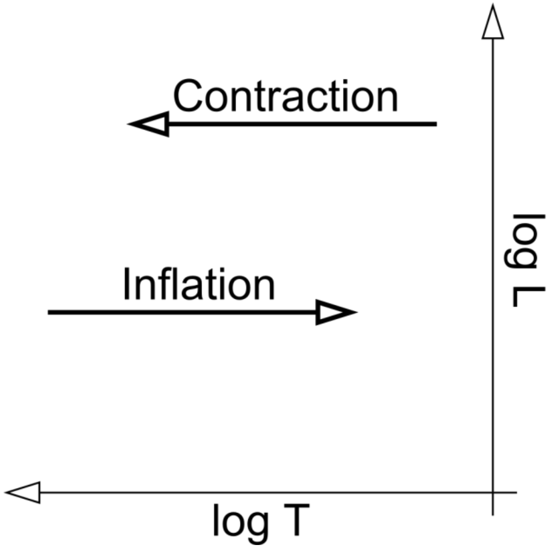
Hertzsprung-Russell diagram

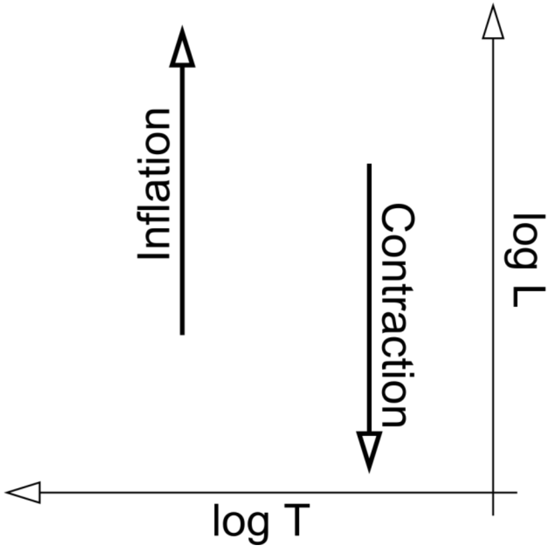


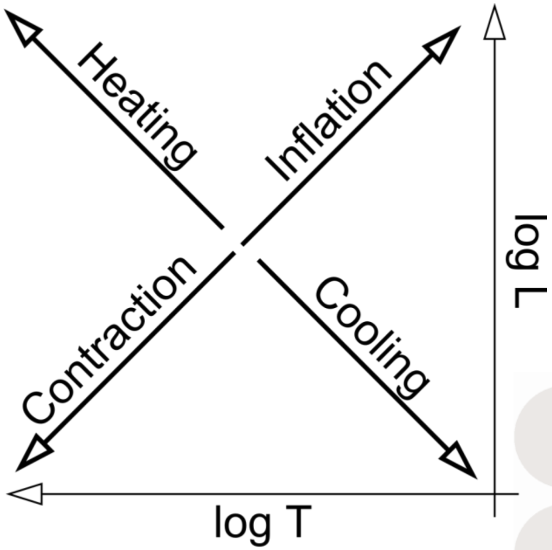
- Luminosity vs. surface temperature
- Luminosity is surface area times energy flux
- Energy flux is proportional T^4 (Stefan-Boltzmann-Law)
- $L = 4\pi R^2 \sigma T^4$
- Source of energy is fusion, i.e., lighter atoms fuse to form heavier elements, which leads to energy release

Stellar Evolution

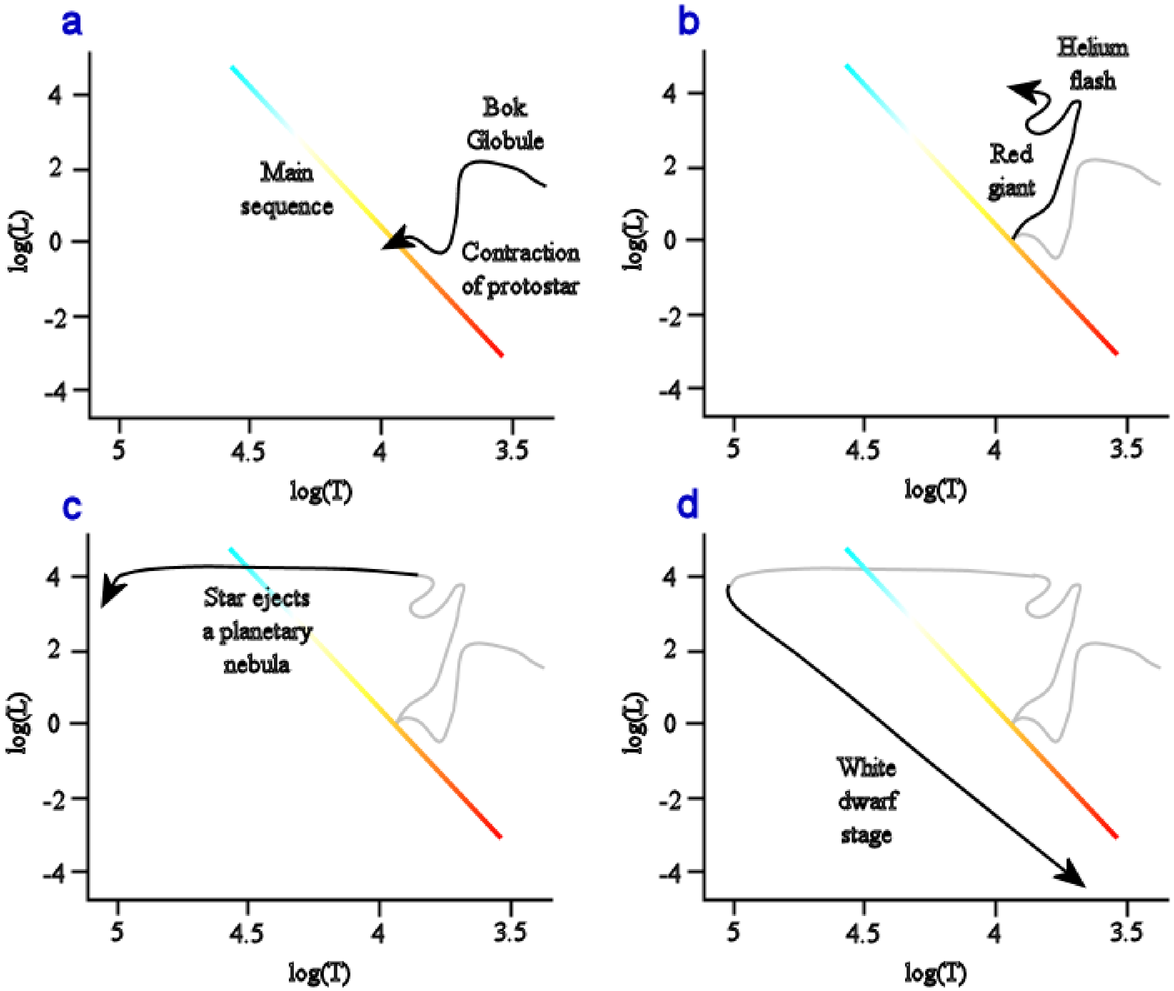
$$L = 4\pi R^2 \sigma T^4$$





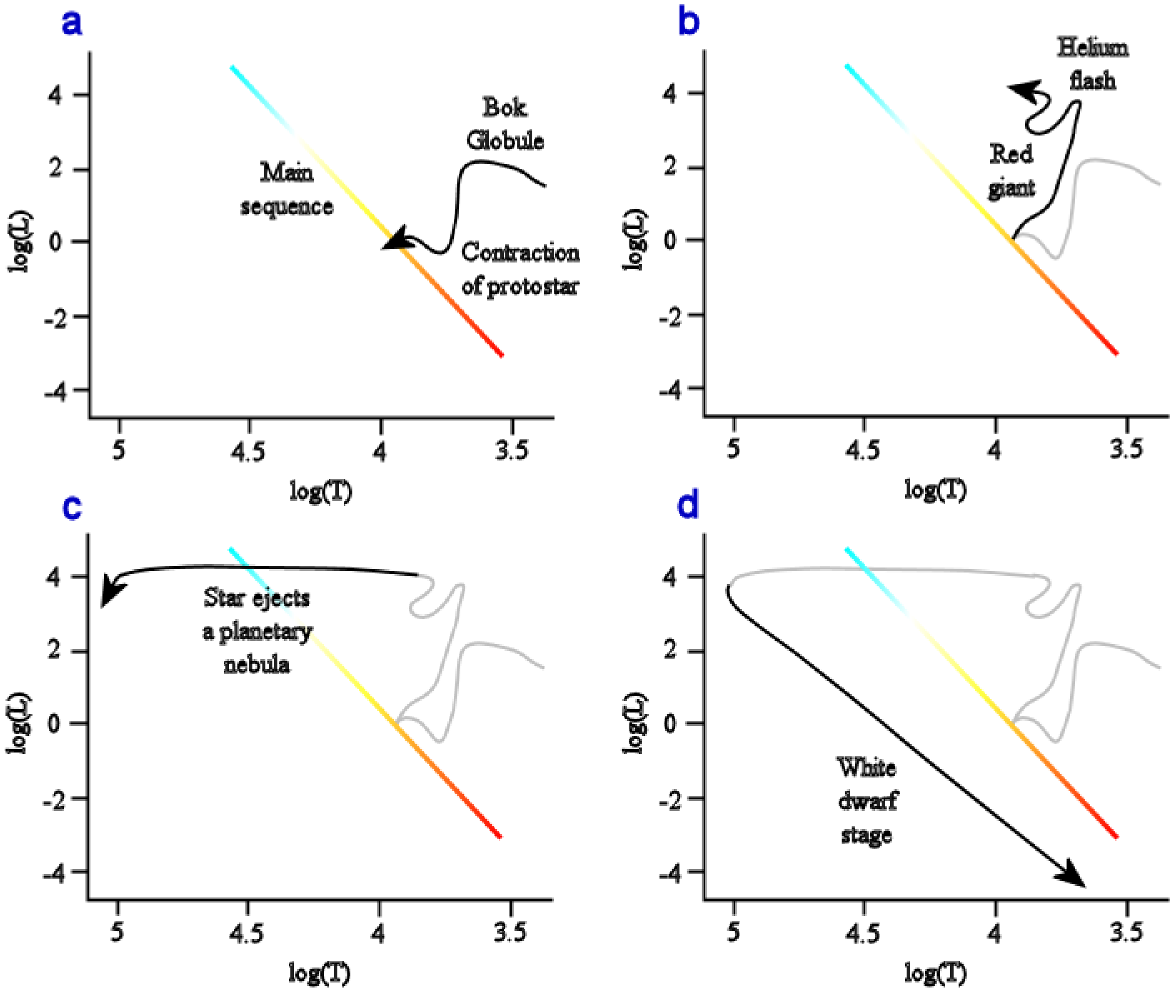


Life of a star



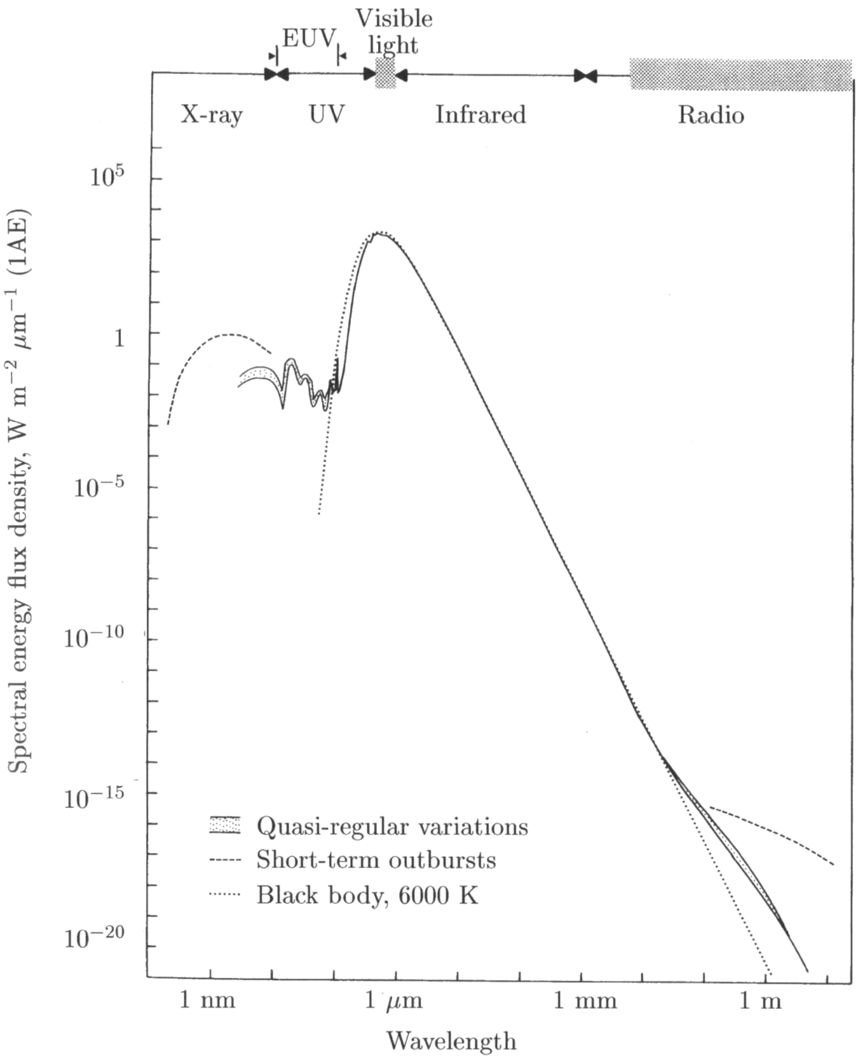
- Gas cloud collapses under gravity, if mass is large enough, hydrogen fusion is initiated in its core
- As hydrogen is burnt, the core shrinks, which leads to higher temperatures in core, expanding and cooling the outer gas
- At some point, helium fusion is initiated in core
- Further contraction of the core, further expansion outer envelope

Life of a star

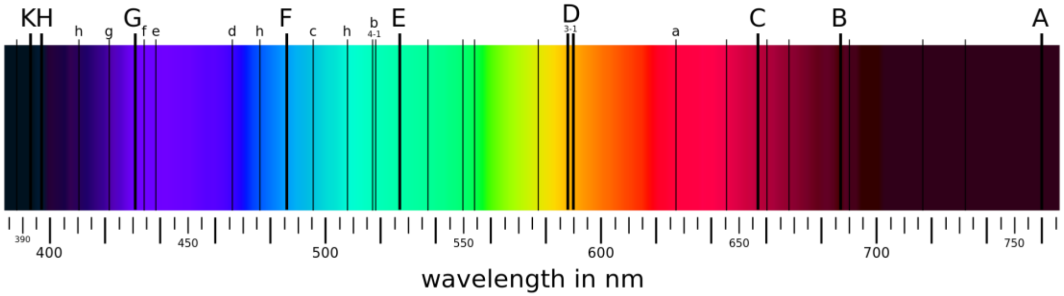


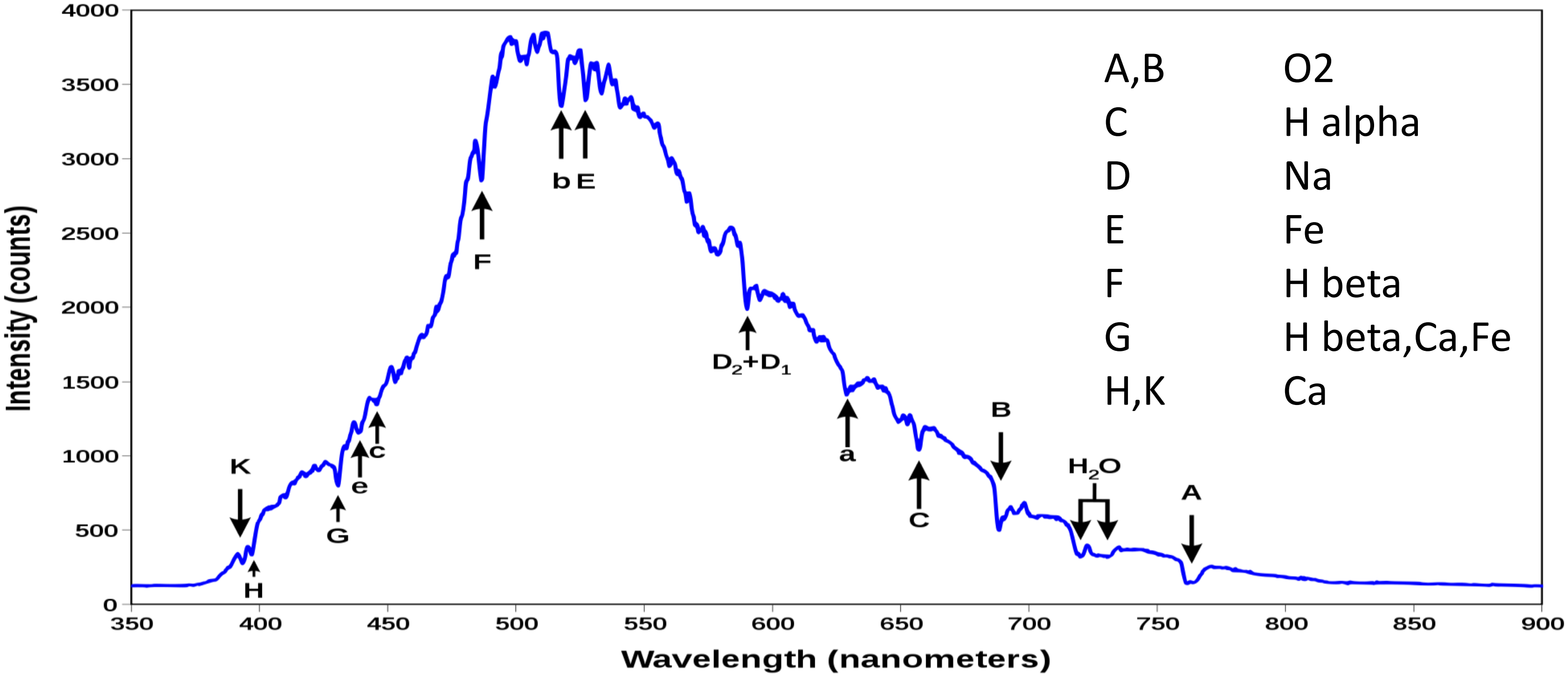
- At some point, all fusion fuel is spent, temperature of core not high enough to cause carbon fusion, outer envelope is ejected and all that remains is a very hot core that slowly radiates its remaining energy into space

Solar spectral energy flux



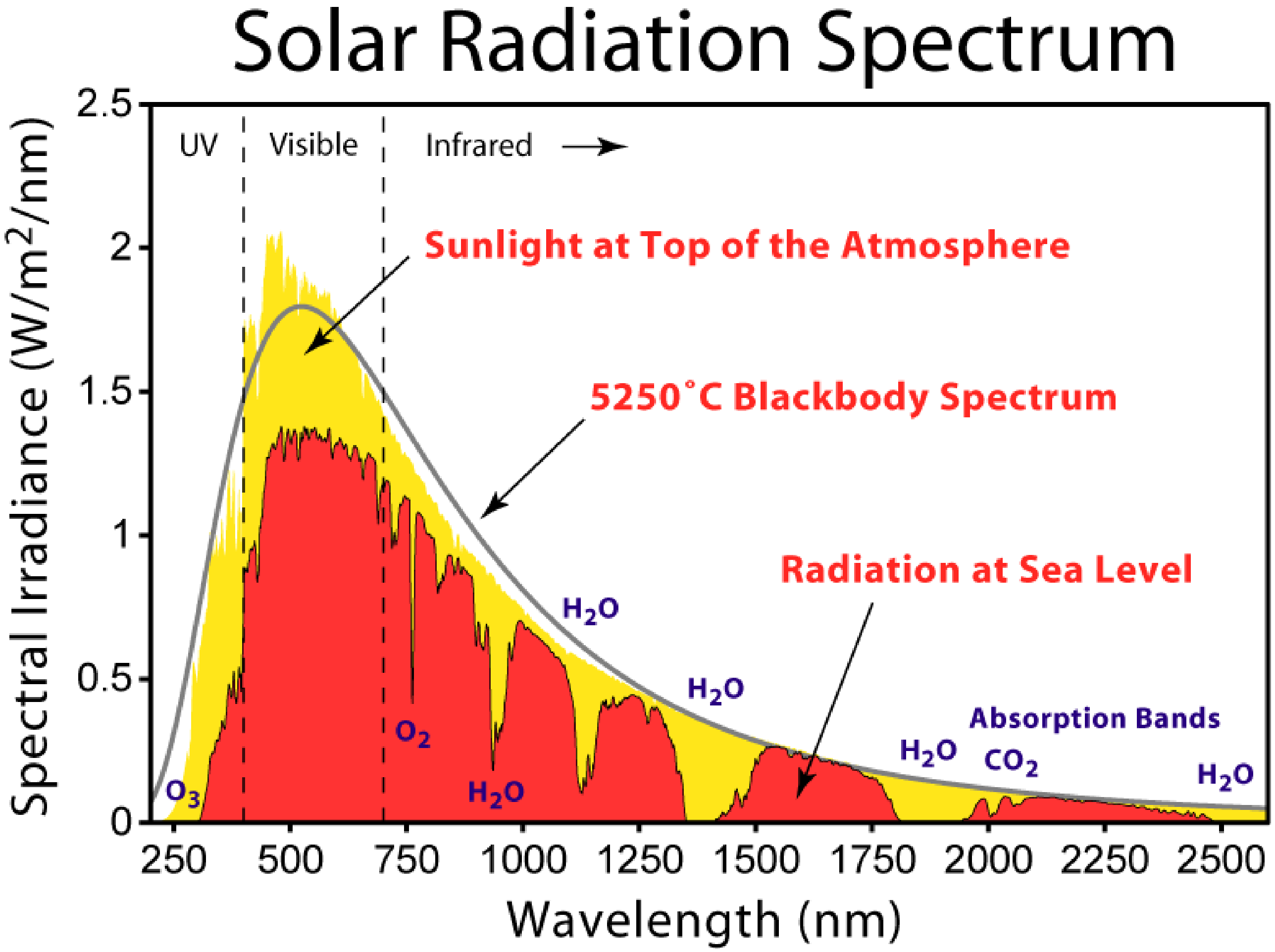
Fraunhofer lines



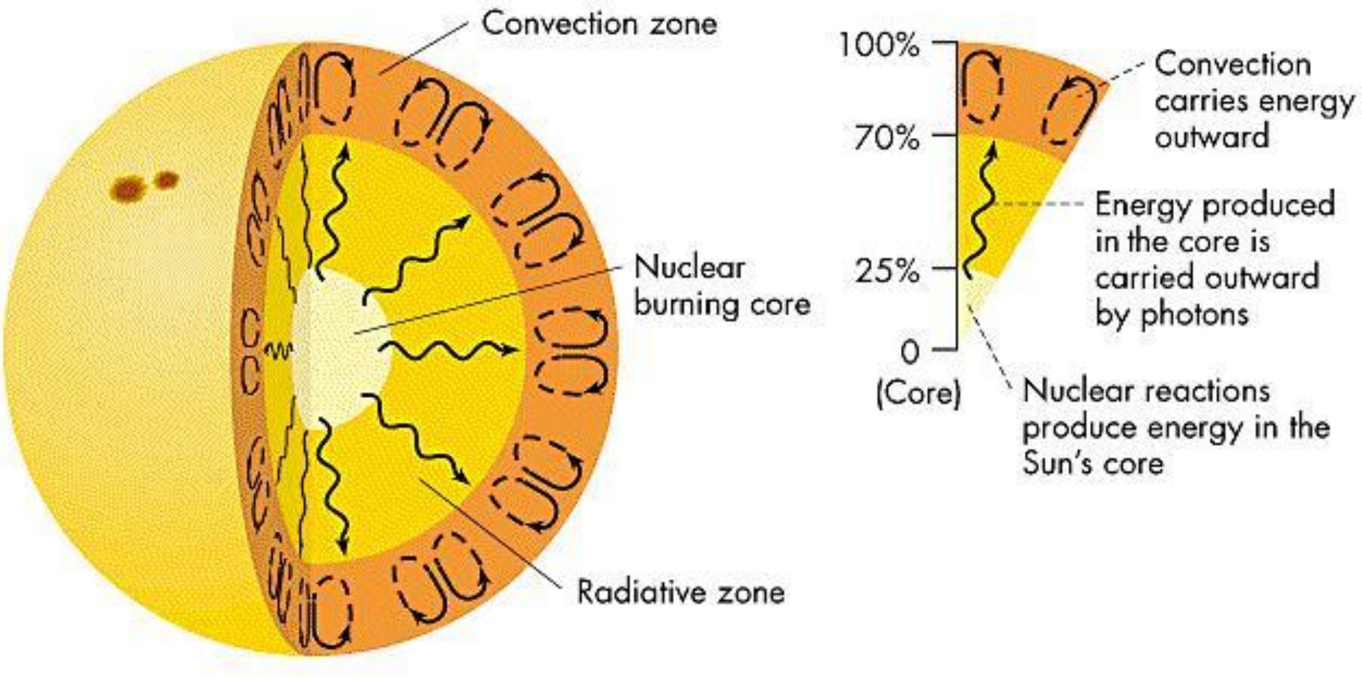


A,B	O2
C	H alpha
D	Na
E	Fe
F	H beta
G	H beta,Ca,Fe
H,K	Ca

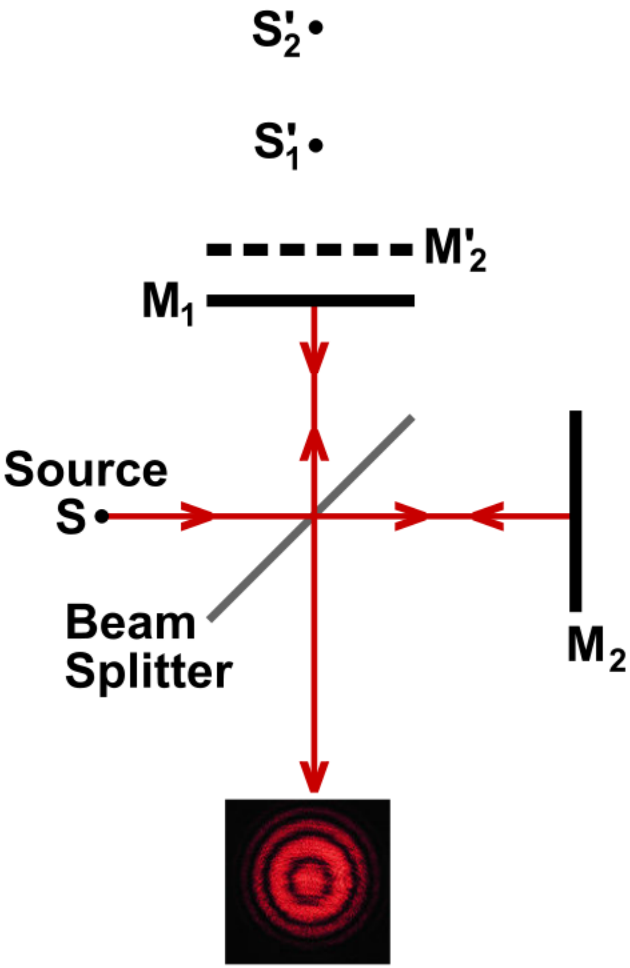
Solar spectrum



Interior structure of the Sun

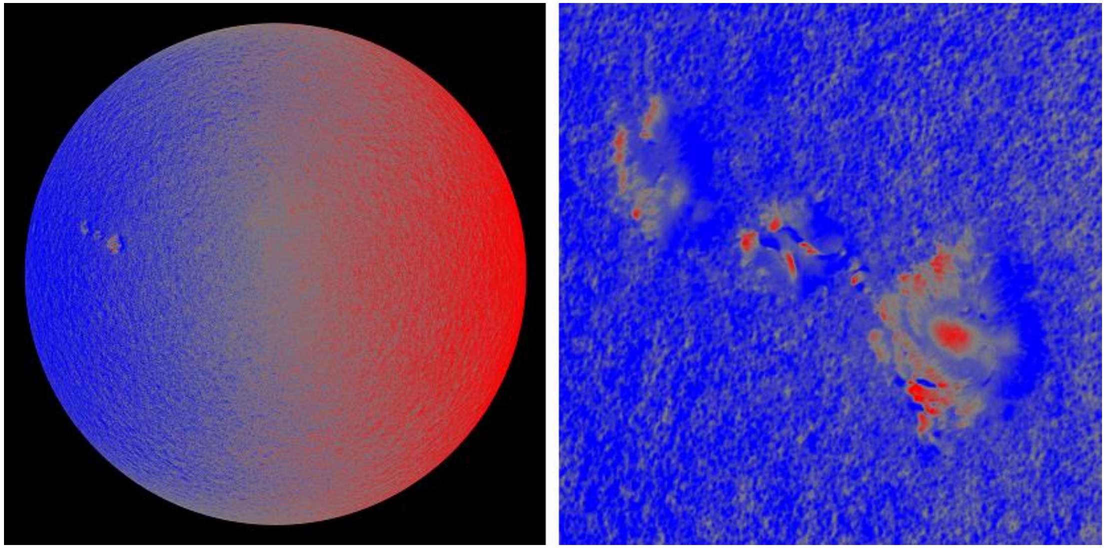


Michelson Interferometer



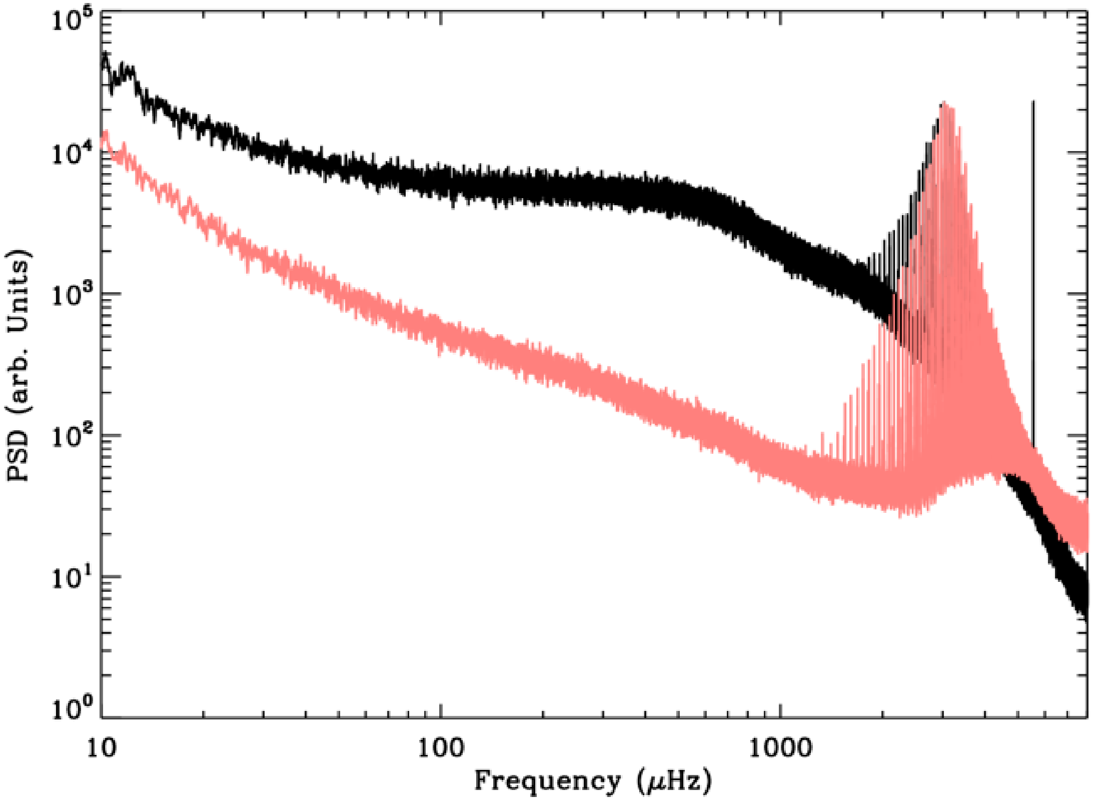
- Light is split and brought to interfere on a detector
- If one mirror (or alternatively the source) moves in the direction of the light propagation, interference pattern changes shape.
- This might give you change of interference pattern, but difficult to evaluate.
- Hence, continuously monitor the pattern of a certain spectral line to determine its Doppler shift

Solar Dynamics Observatory



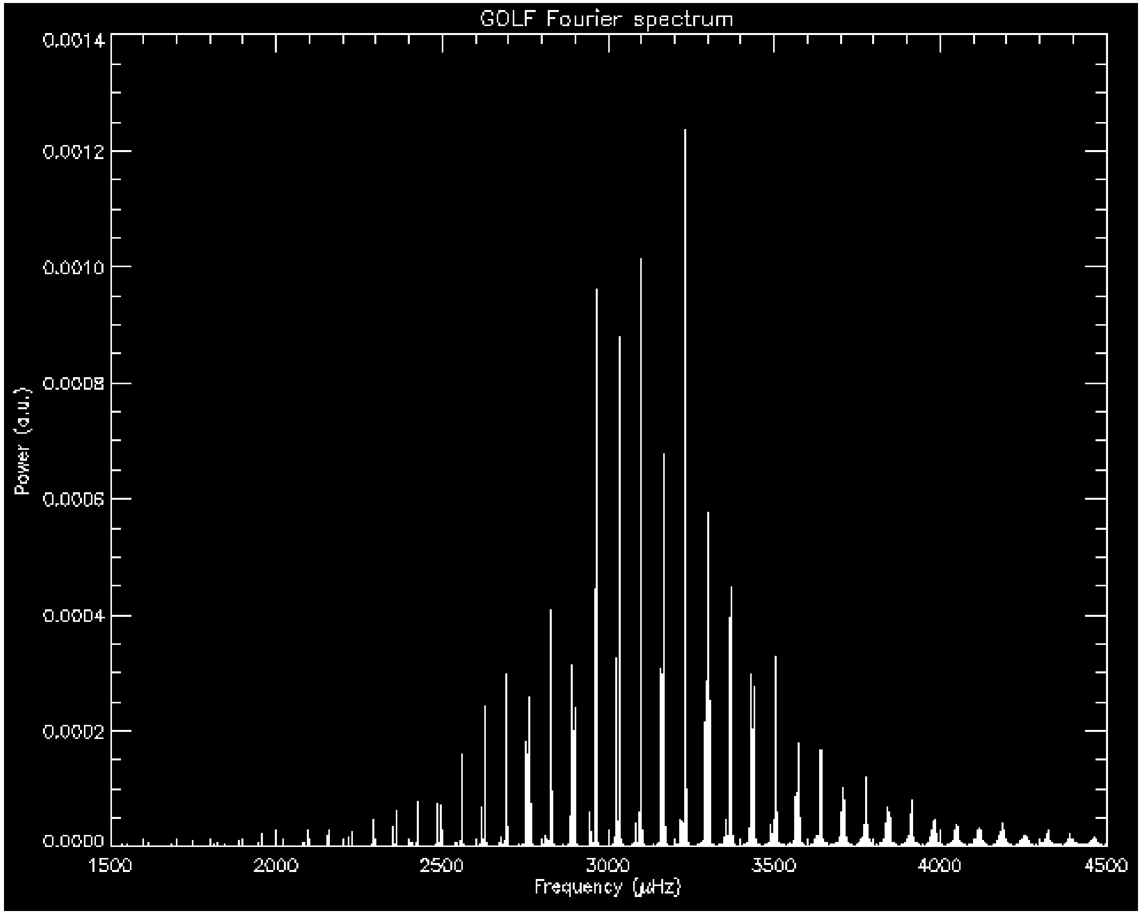
- Satellite carries a Michelson Interferometer
- Doppler shift of one spectral line is measured, giving the line-of-sight velocity of the Sun
- Blue represents motion toward the observer, red away
- Strongest signal is rotation of the Sun, but sun spots show different dynamics

Oscillation spectrum of the Sun



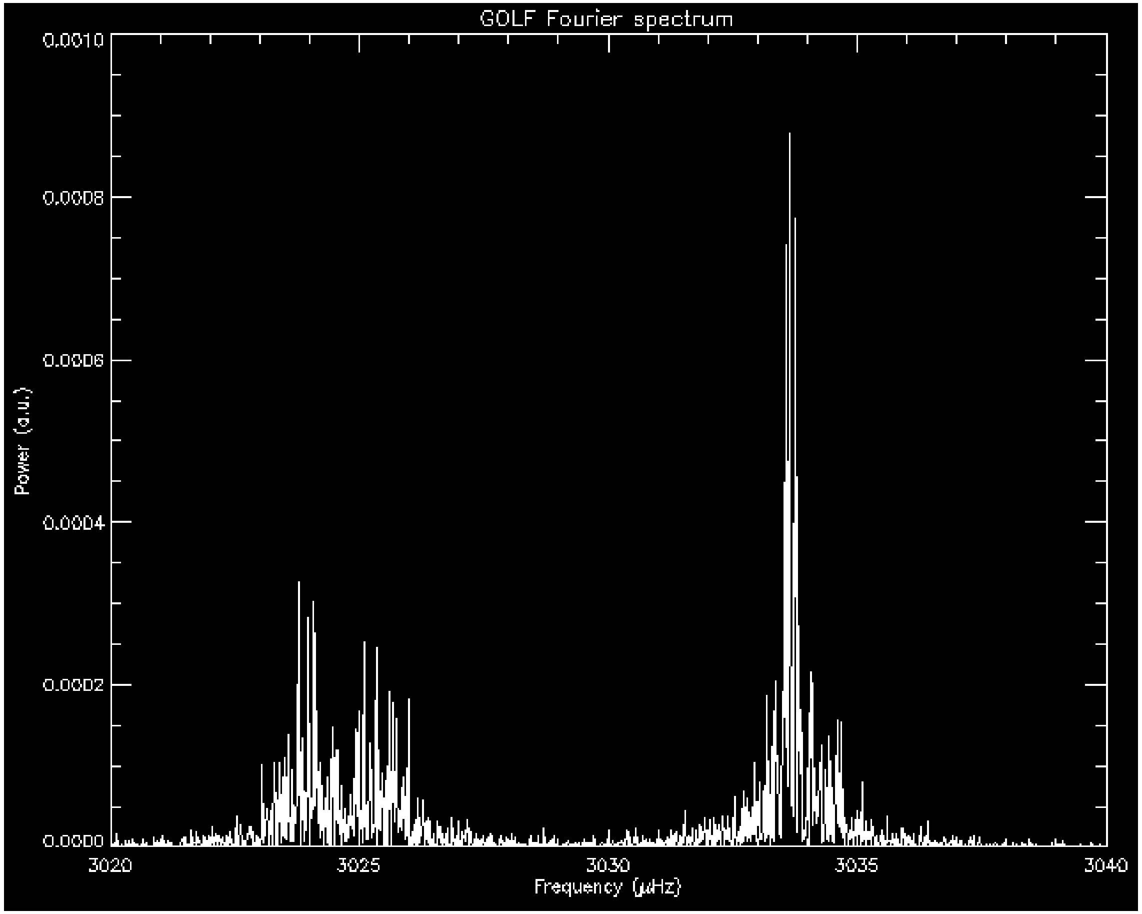
- Entire Sun vibrates in a complex pattern of acoustic waves (called p-modes), with a period of around 5 minutes.
- The oscillations are best seen as Doppler shifts of spectral lines, but are also visible as intensity variations.
- 10^7 modes are present on the surface of the Sun at any given time (all interfering linearly with each other).

Oscillation spectrum of the Sun



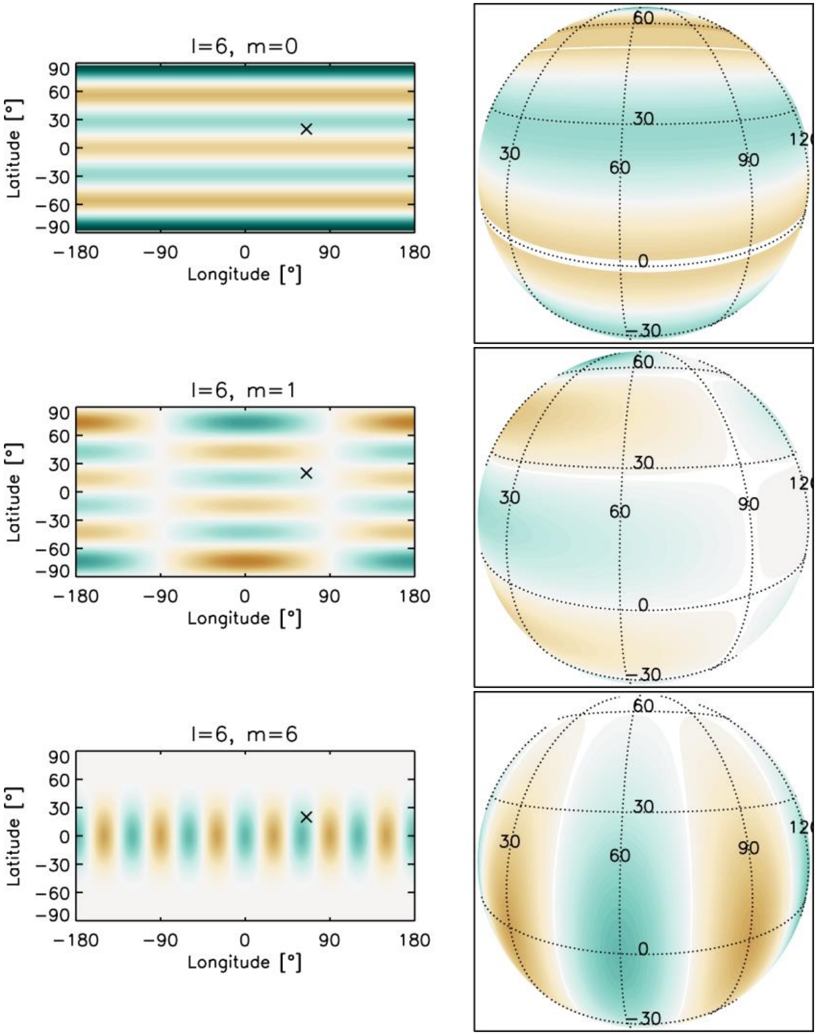
- Power spectrum of oscillations of the entire Sun shows peak around periods of 5-minutes
- Spectrum shows distinct peaks.

Oscillation spectrum of the Sun



- Power spectrum of oscillations of the entire Sun shows peak around periods of 5-minutes
- Spectrum shows distinct peaks.
- And even structure of peaks.

Spherical eigenmodes

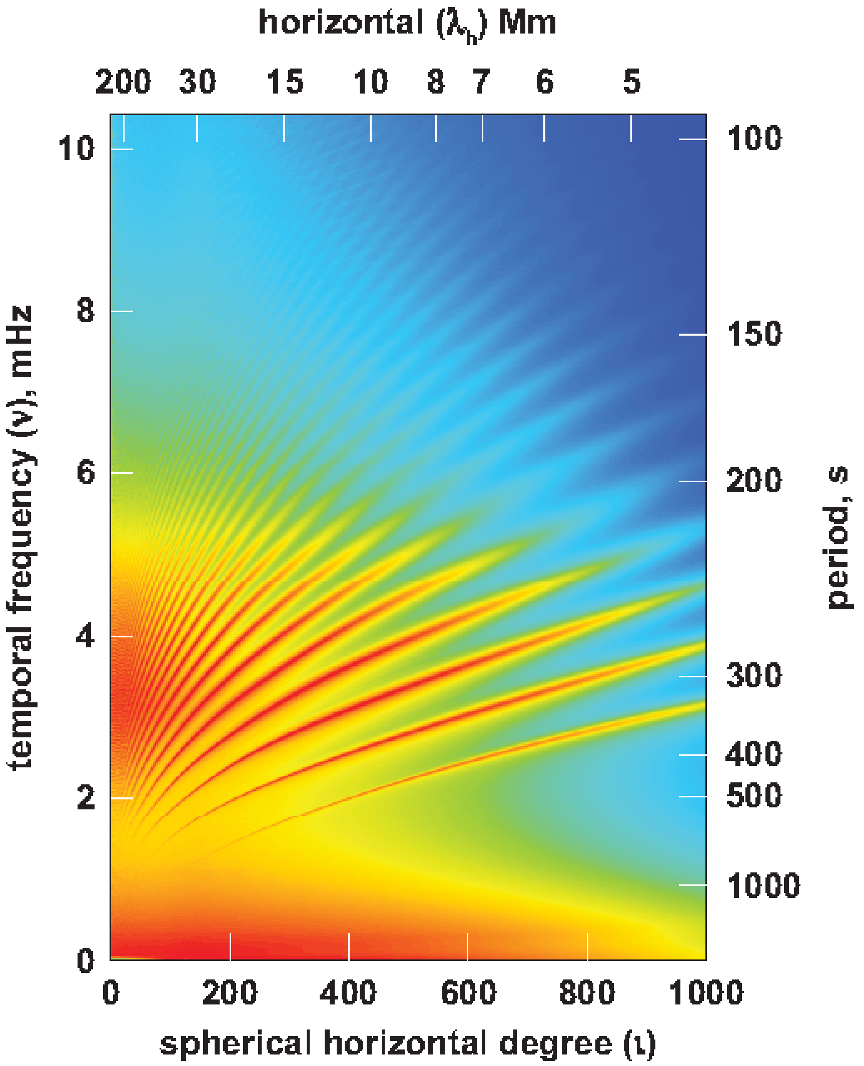


- Eigenmodes of sphere can be described as spherical harmonics.
- These are characterized by three numbers:
  - n: the number of radial half-wavelengths (nodes)
  - l : the number of half-wavelengths along the polar direction
  - m : the number of half-wavelengths along the azimuthal direction

Global helioseismology

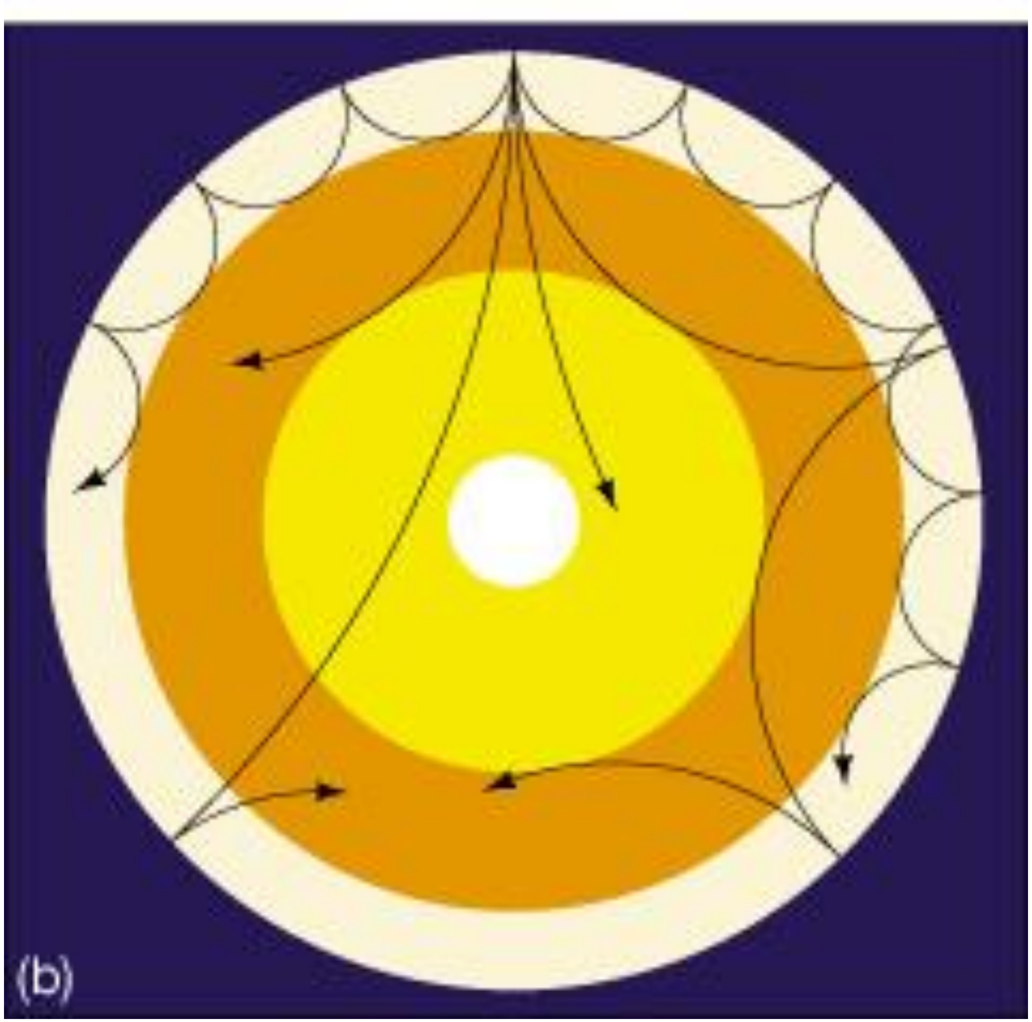
- Spatial variations of Doppler shift in spectral lines reveals radial motion of solar surface.
- Typical amplitude of a single mode: < 20 cm/s
- Total velocity of all 10^7 modes: a few 100 m/s
- Accuracy of current instruments: better than 1 cm/s
- Spatio-temporal properties of oscillations best revealed by 3-D Fourier transforms (2-D space + 1-D time)

Spectrum of solar eigenmodes



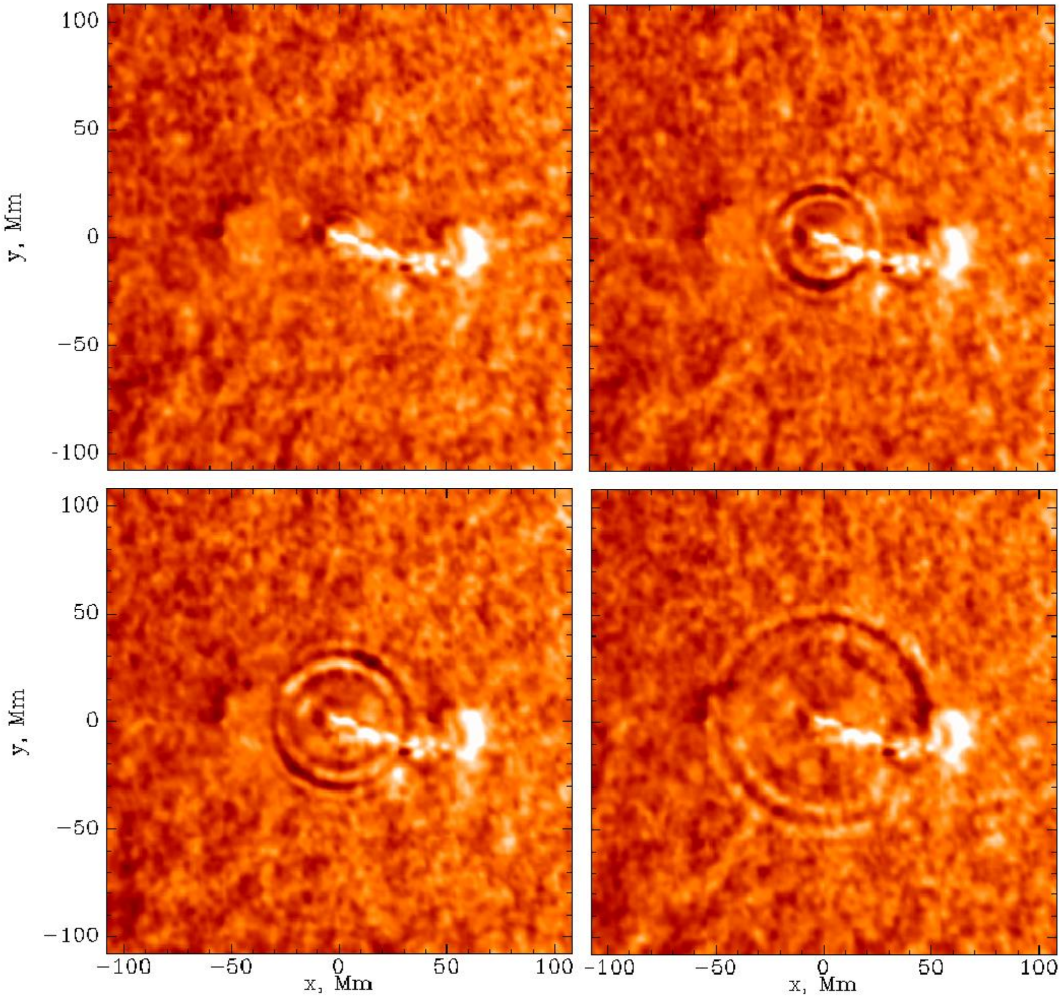
- p-modes show a distinctive dispersion relation ($\omega - k$ diagram: $k \propto \omega^2$)
- Important: there is power only in certain ridges, i.e. for a given spacial scale, only certain frequencies contain power. This discrete spectrum suggests the oscillations are trapped, i.e. eigenmodes of the Sun

Ray paths

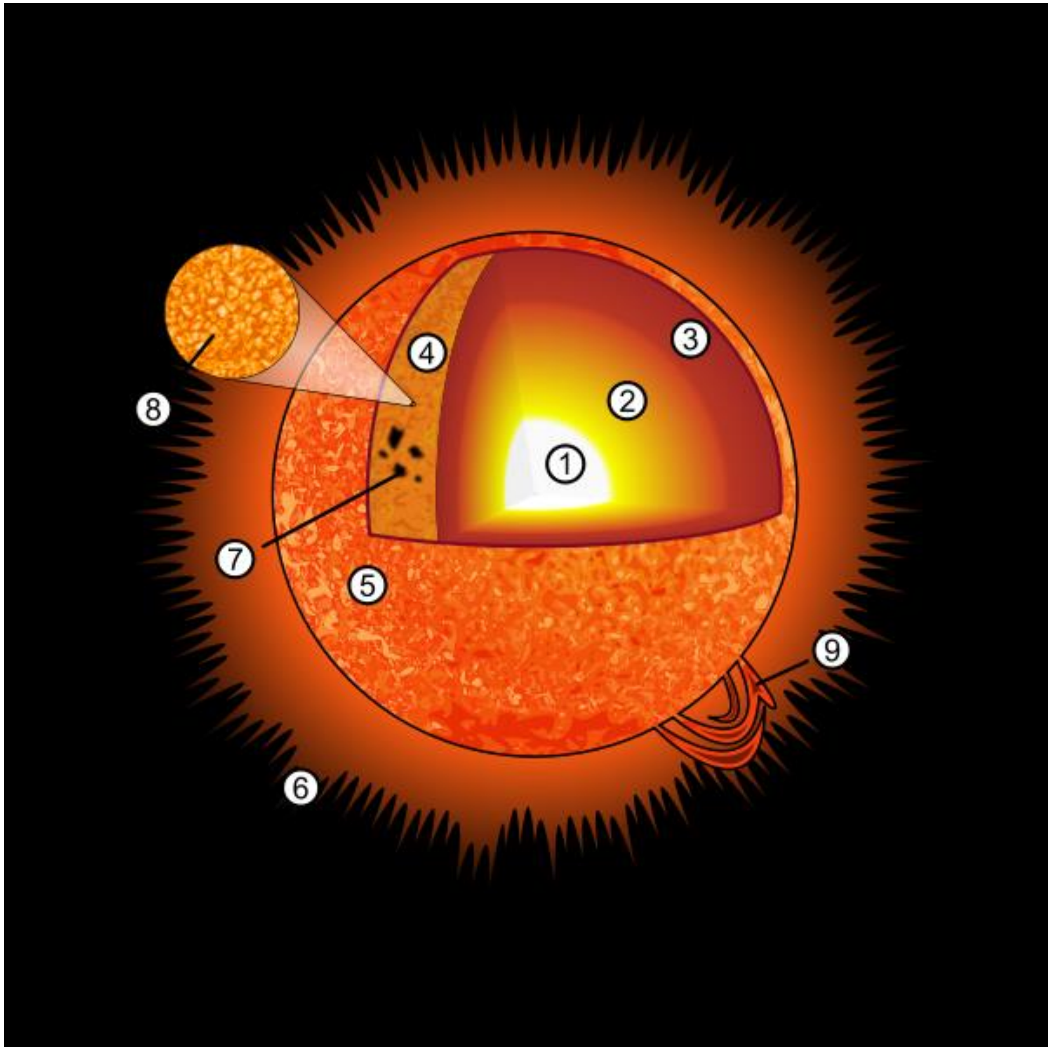


- Local disturbance creates perturbations that travel through the Sun (p-modes).
- Due to changes in background density and temperature, the wave paths are refracted.
- Superposition of waves creates interference pattern which can be inverted to learn something about the internal structure of the Sun – or star.

Local helioseismology

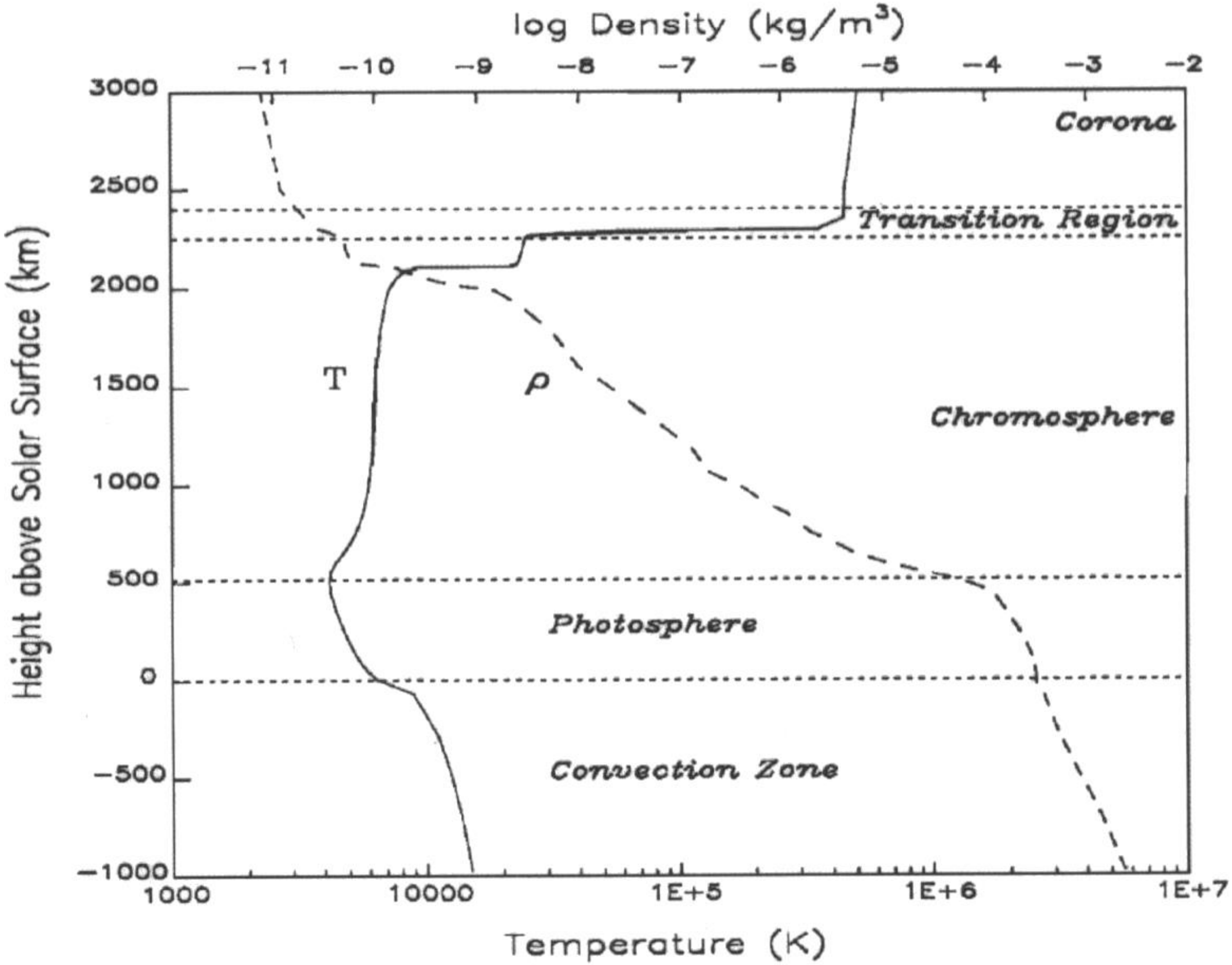


Some solar features

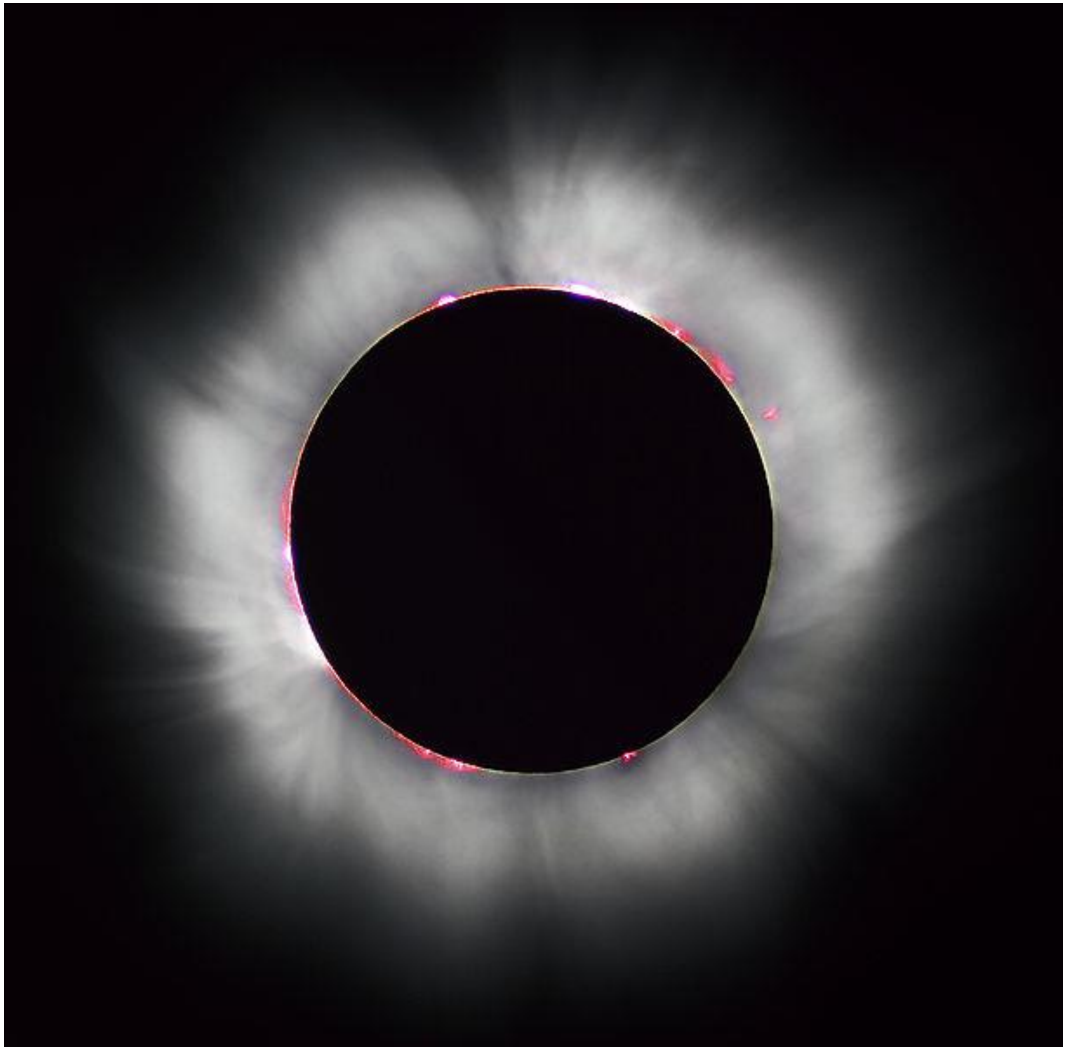


1) Core
2) Radiative zone
3) Convective zone
4) Photosphere
5) Chromosphere
6) Corona
7) Sunspot
8) Granulae
9) Prominence

Some parameters

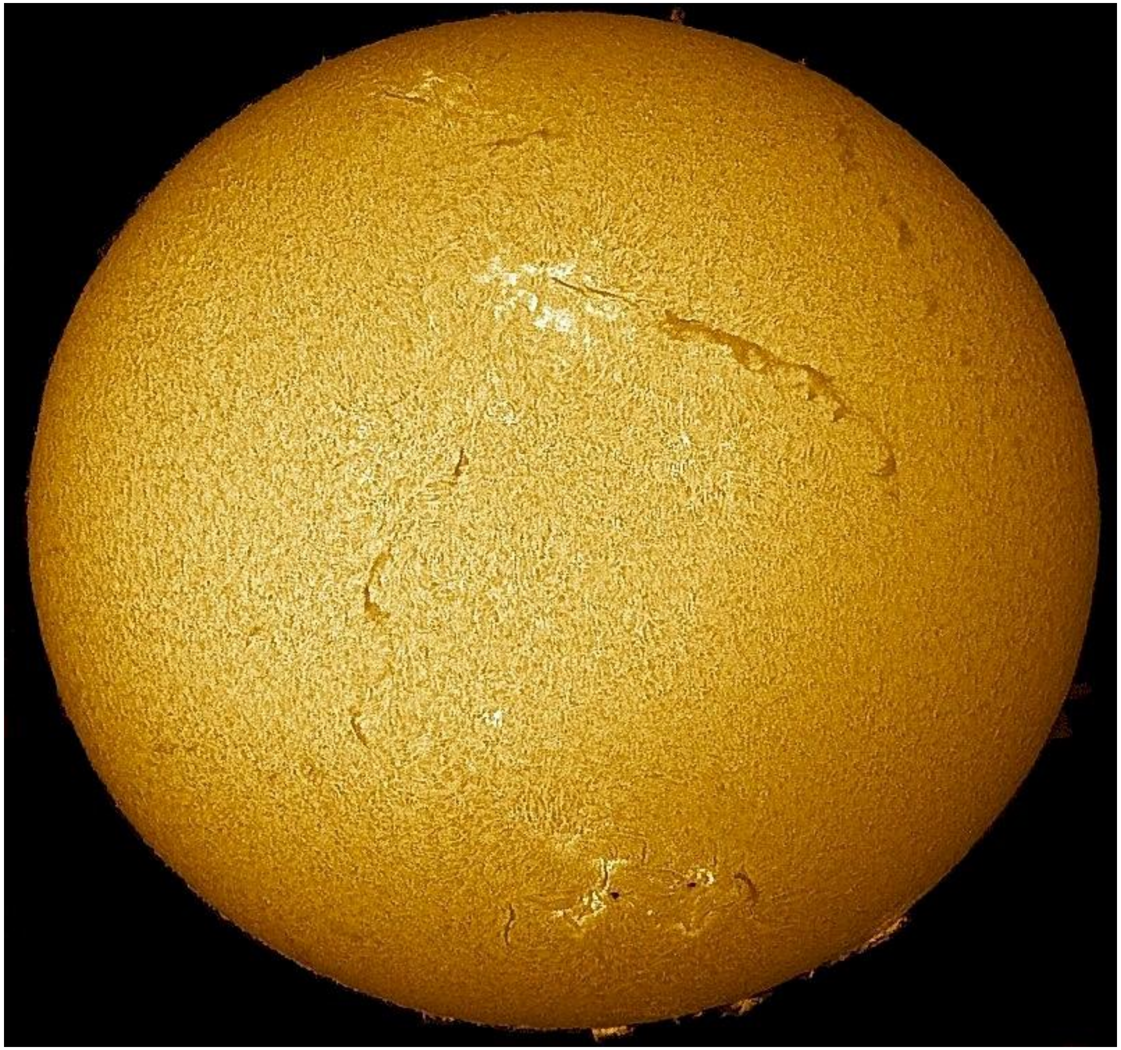


Chromosphere



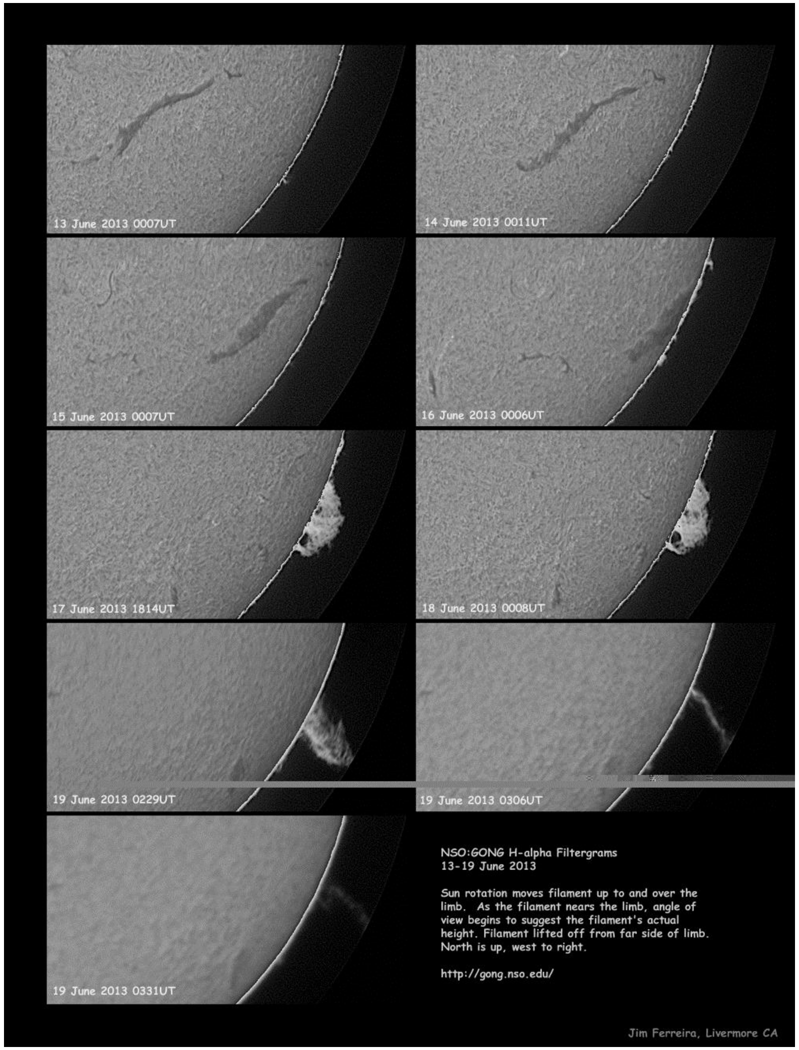
- Region between photosphere and corona
- Temperatures between 4,000K and 10,000K
- Consists mainly of neutral hydrogen and is hence best observed in the Lyman alpha line in the UV.

Filaments



- Filaments are regions which appear darker than the background.
- They appear darker because the plasma is colder.
- They have chromospheric densities.

Prominences/filaments



NSO:GONG H-alpha Filtergrams
13-19 June 2013

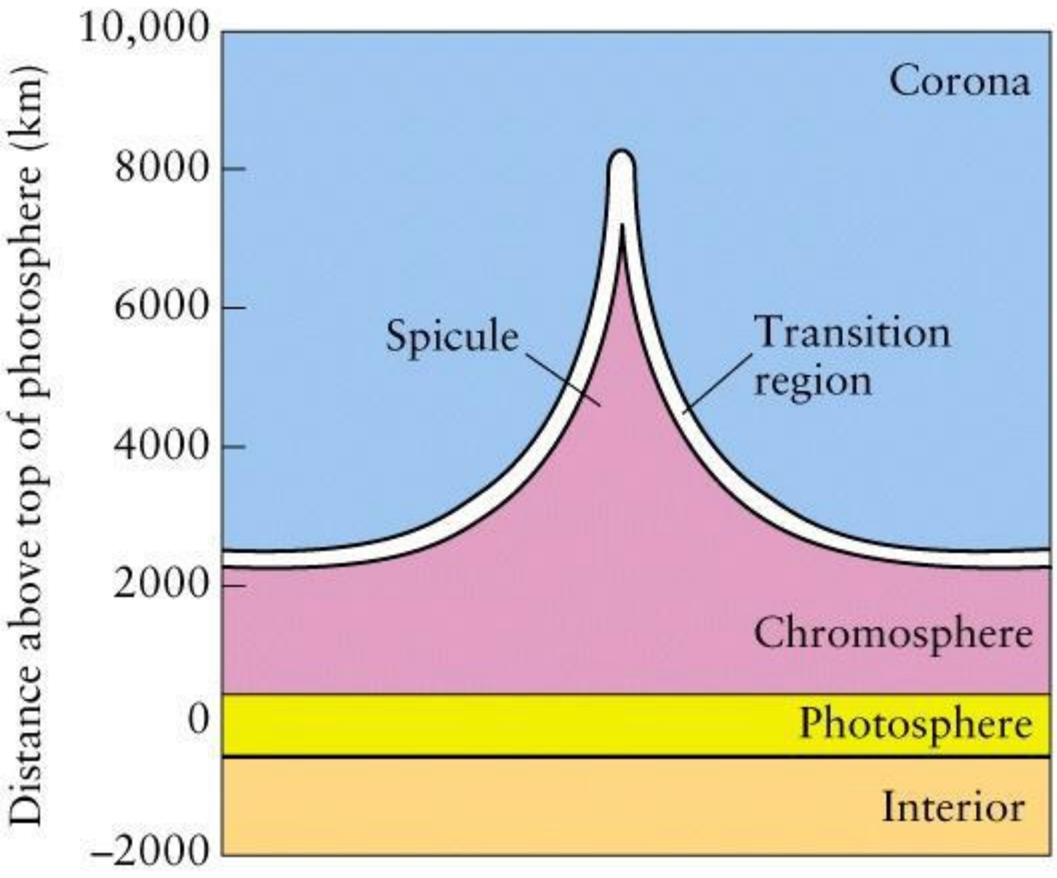
Sun rotation moves filament up to and over the limb. As the filament nears the limb, angle of view begins to suggest the filament's actual height. Filament lifted off from far side of limb. North is up, west to right.

http://gong.nso.edu/

Jim Ferreira, Livermore CA

- Actually, prominences are filaments seen from the side, stretching beyong the limb of the Sun.
- Prominences are loops of chromospheric plasma held up by magnetic fields: frozen-in flux, i.e., the plasma is tied to the magnetic field and if that arcs over the Sun, so will the plasma on these field lines.

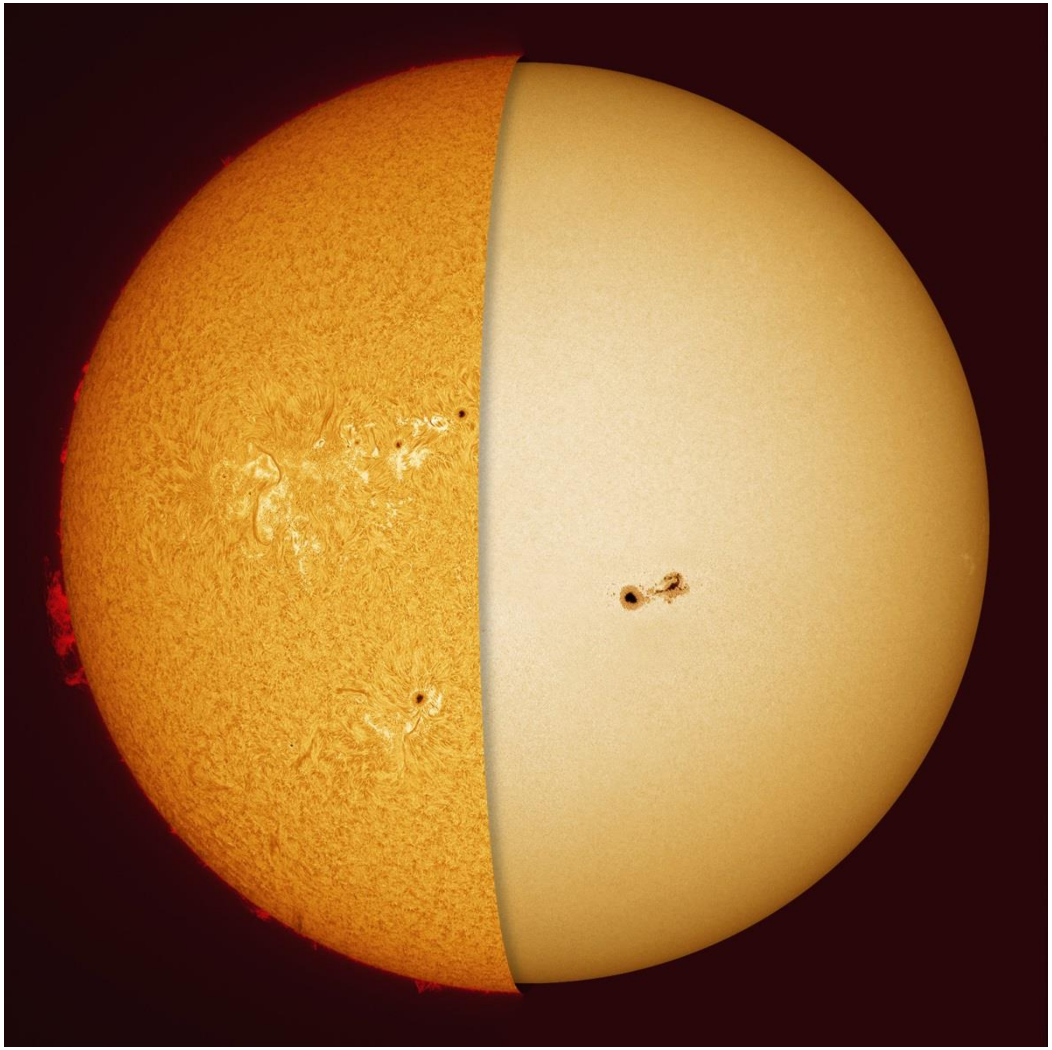
Spicules



- Spicules are jets of chromospheric plasma rising with speeds of about 30 km/s.
- They extend about 5000km into the solar corona.
- They last for about 5 minutes before disappearing.
- Might be an injection mechanism of plasma into the corona.

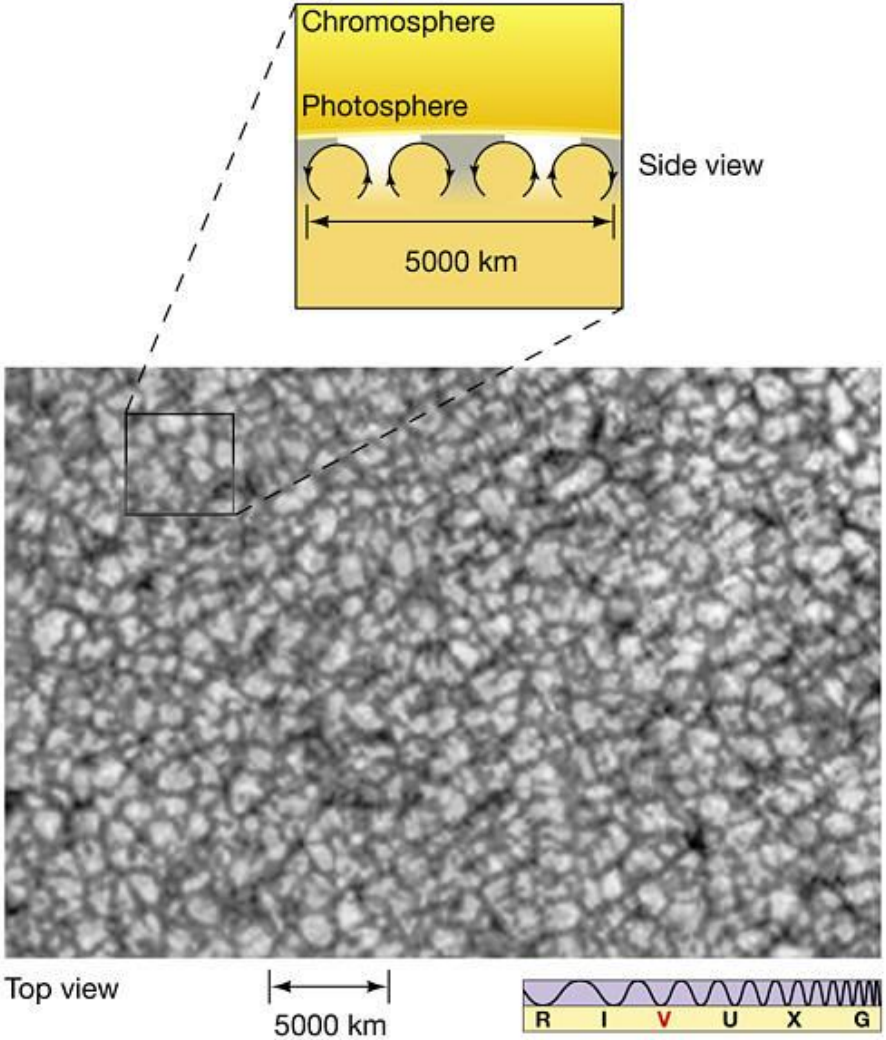
Spicules

Chromosphere/photosphere



- Comparisson between the chromosphere (left) and the photosphere (right) of the Sun.
- Chromosphere shows prominences/filaments and sunspots.
- Photosphere shows granulation and sunspots.

Granules



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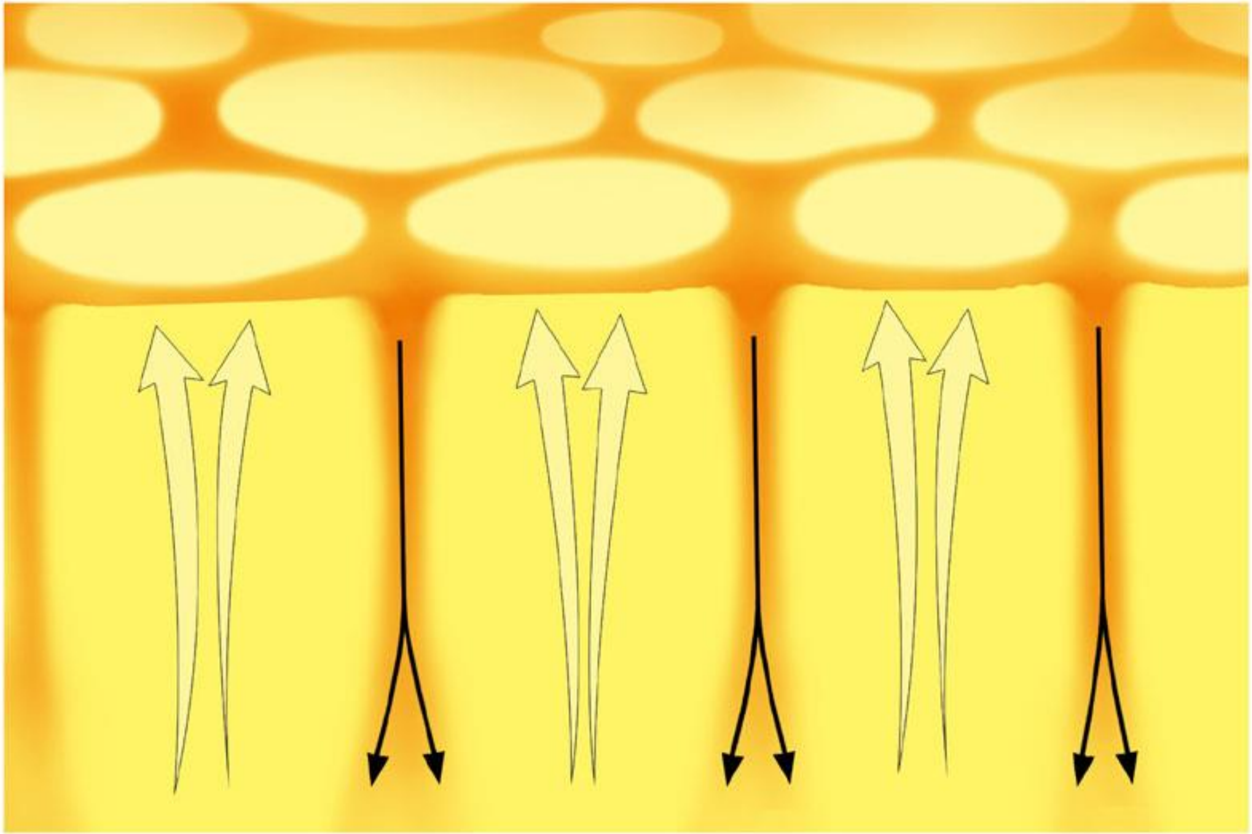
- Granules are about 1000km diameter and last for about 10 minutes.
- Between granules you have the intergranular lanes which are made out of colder plasma, hence they appear darker.
- Inside the granules the plasma rises with about 1 km/s.

Convection cells/granules



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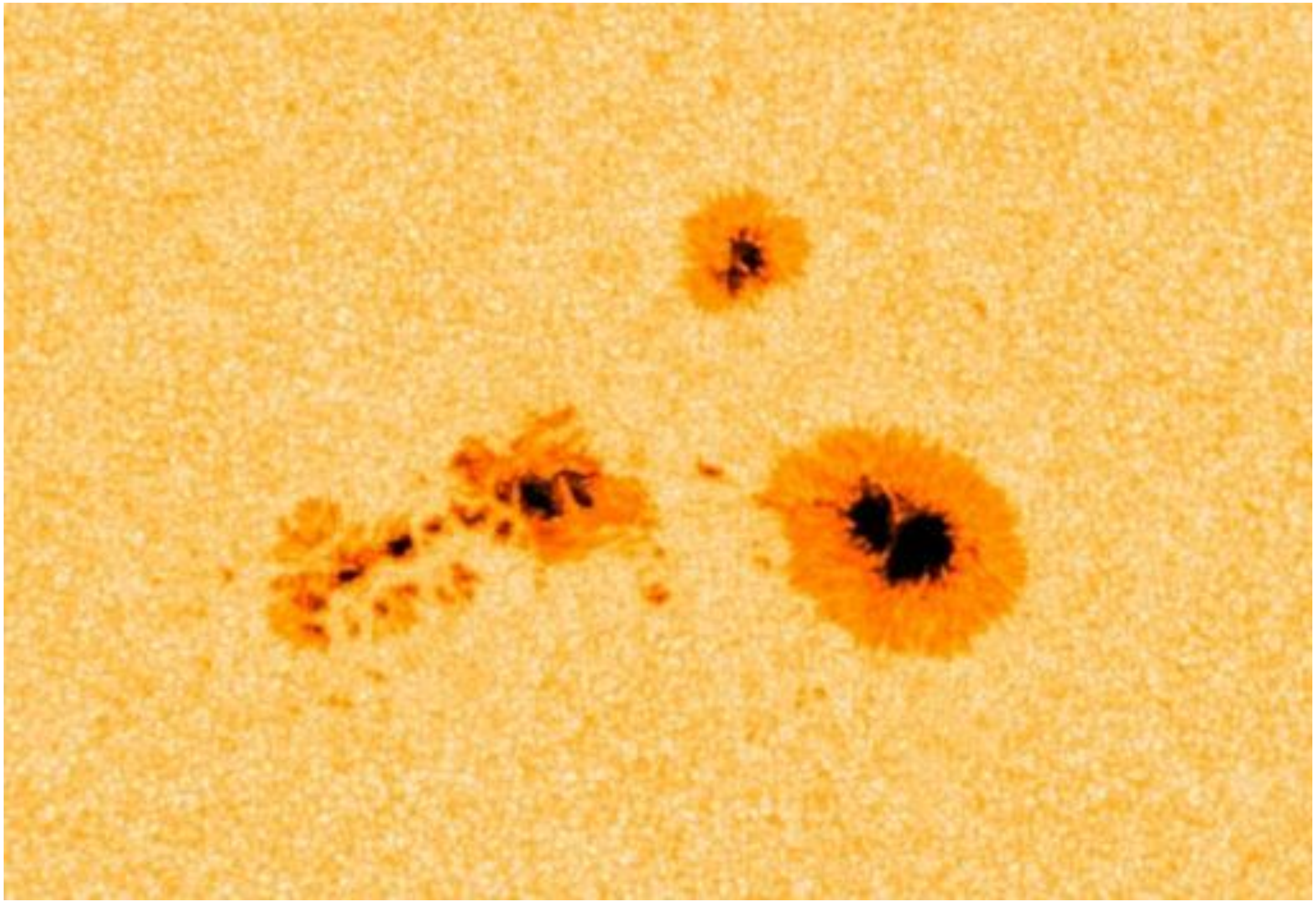
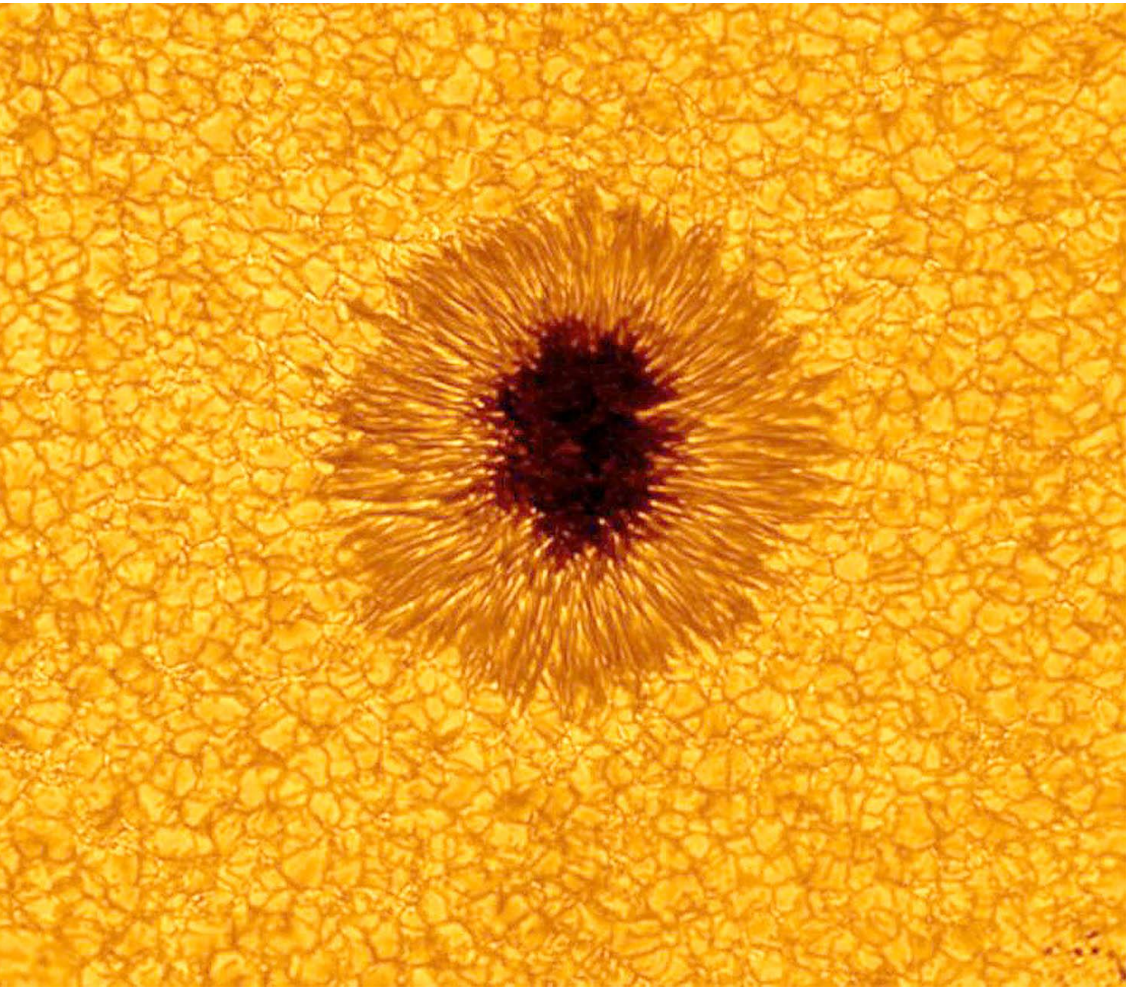
Sunspots

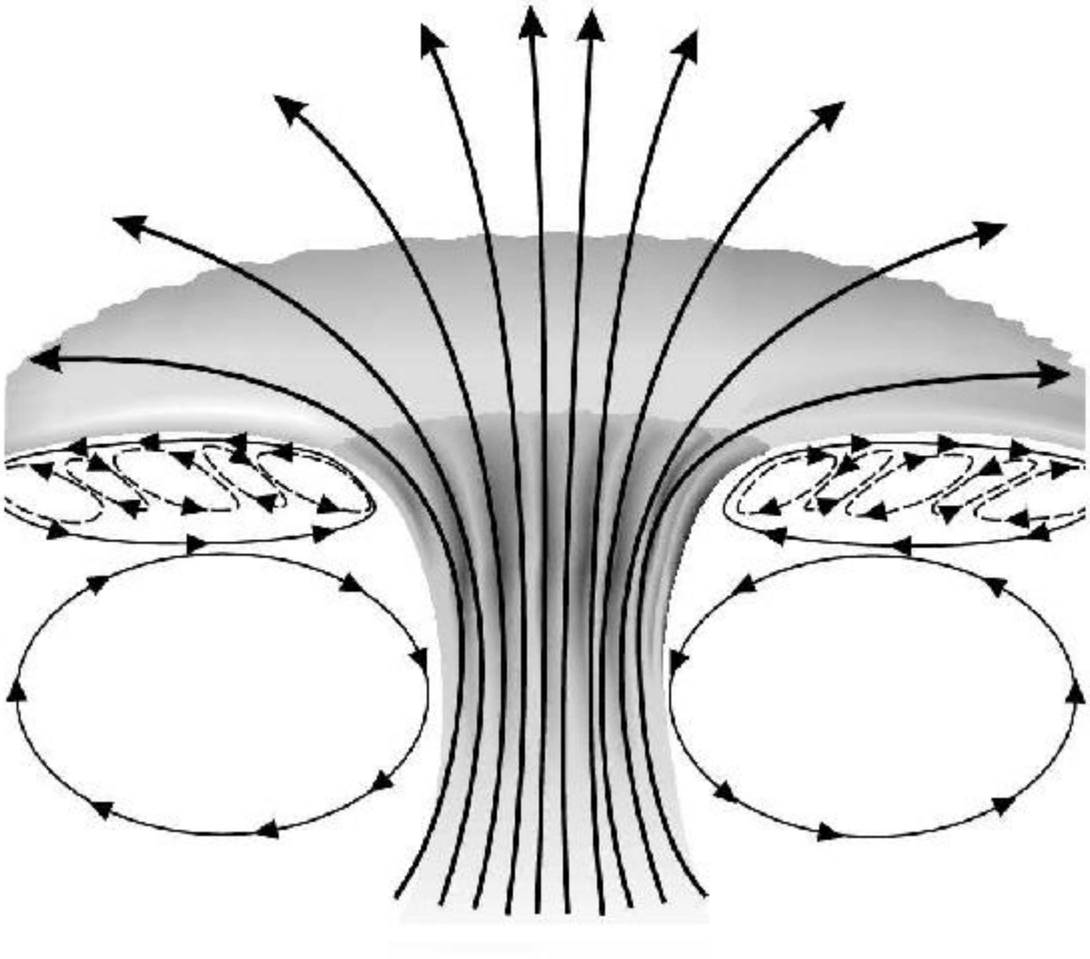


Sunspot



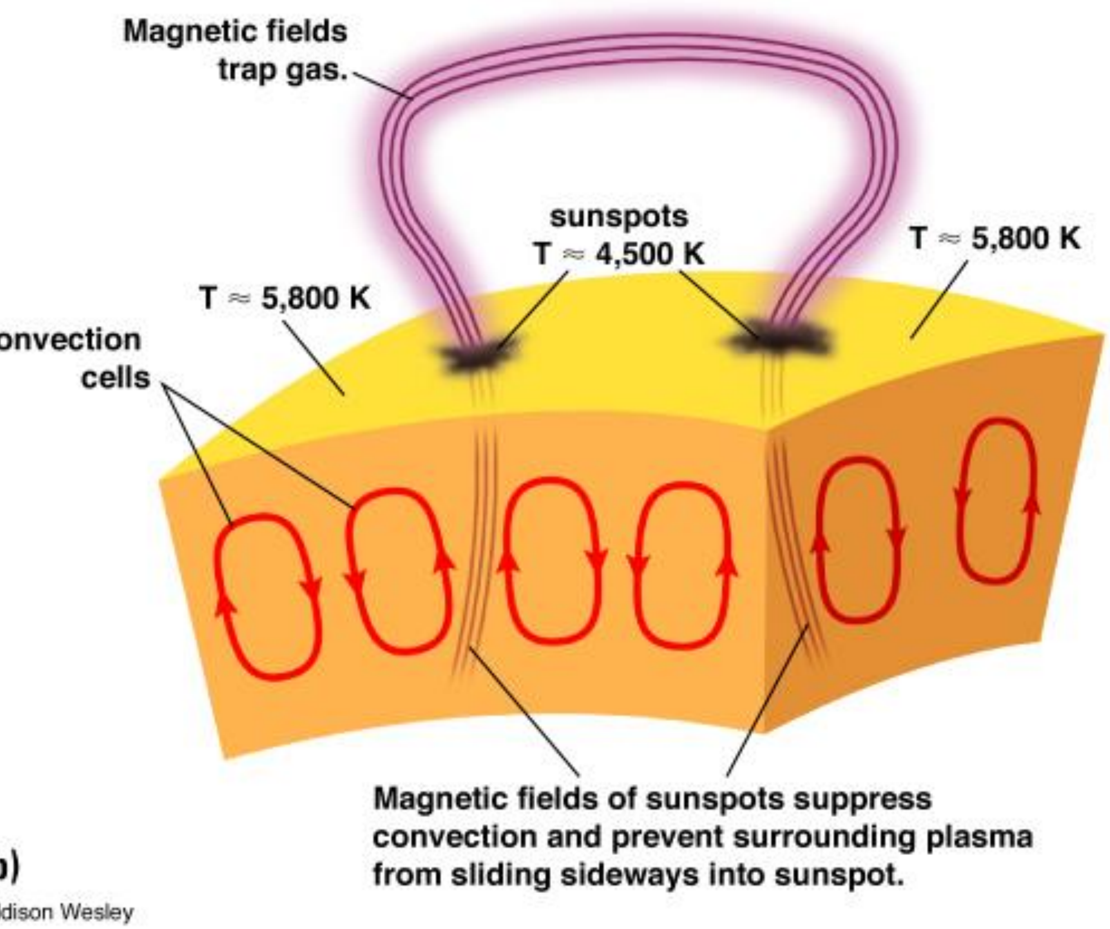
- Sunspots have two regions, the dark, inner region called umbra and the only slightly darker region called the penumbra.
- The umbra is characterized by relatively cold plasma of about 4000K, and strong magnetic fields (about 1000 times the normal photospheric field)
- Typical life times are several days to weeks

Convection associated with sunspot



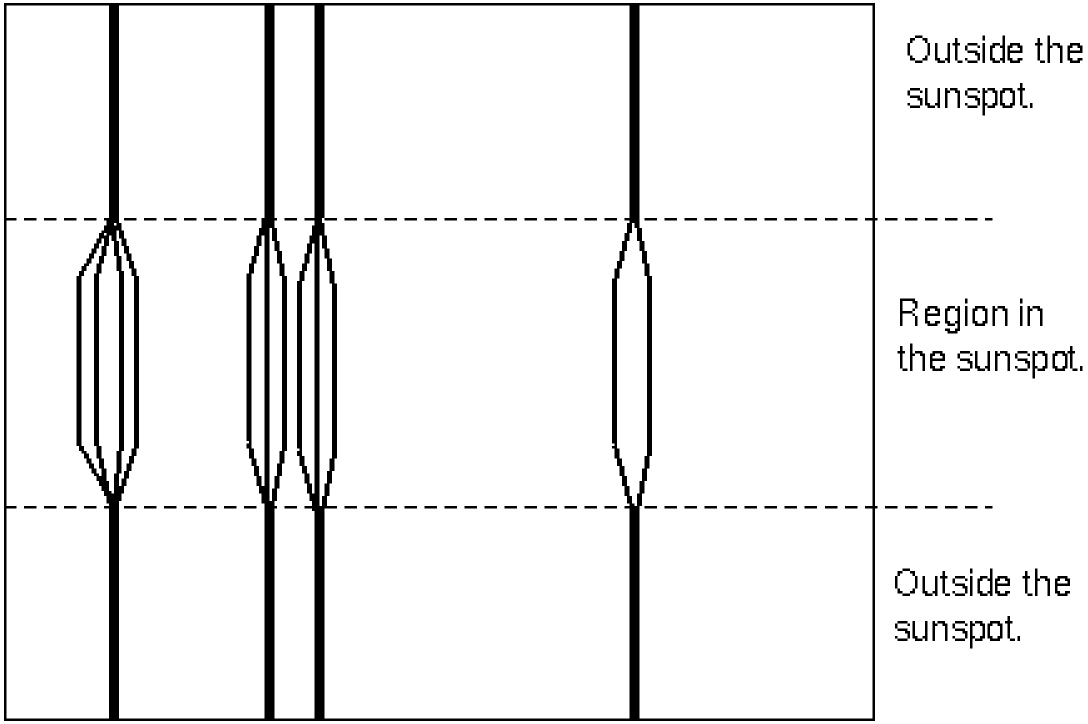
- At the center of teh sunspot (umbra), the magnetic field is nearly vertical.
- The plasma is frozen to the magnetic field, so it cannot moves sideways at the surface but just sits there and cools.
- The magnetic field is more inclined in the penumbra, allowing some convection movement, hence it is a little warmer than the umbra, but colder than the surrounding.

The inside of a sunspot



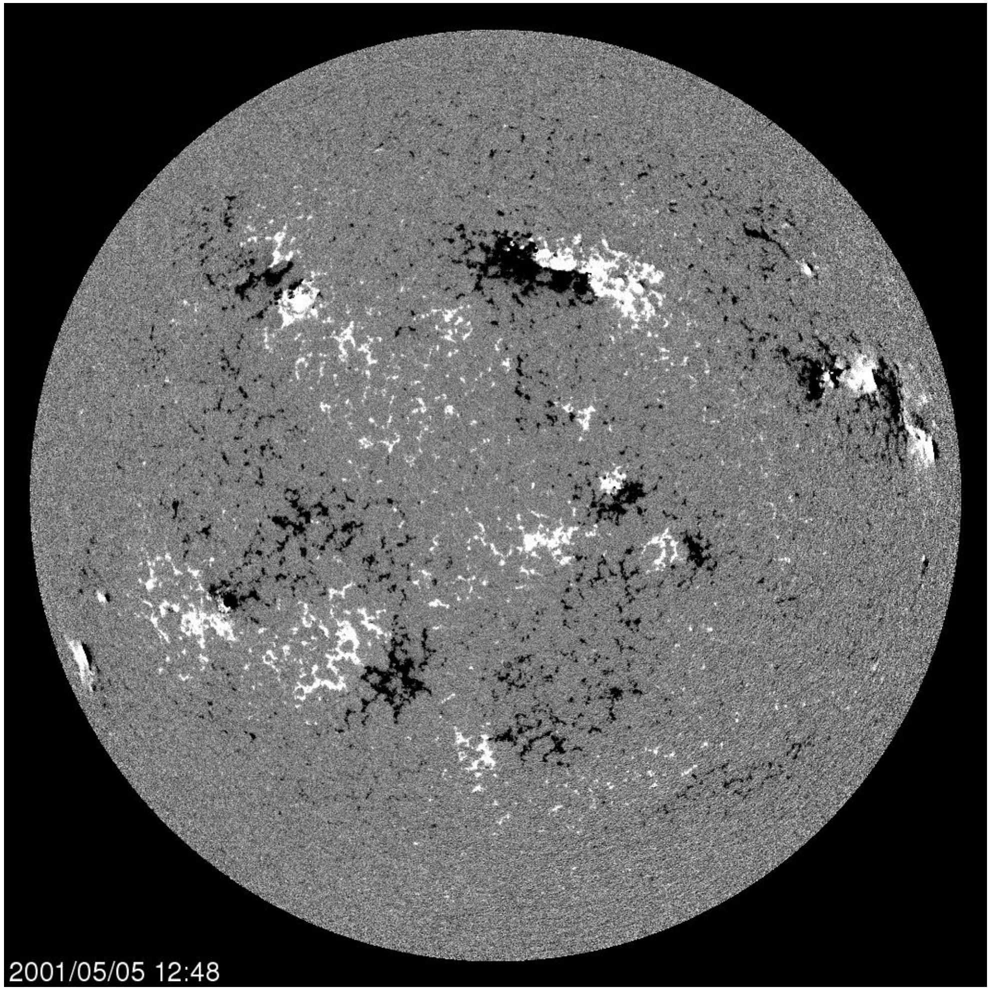
- Sunspots usually appear in pairs with opposite magnetic polarity.
- With the help of spectroscopy you can measure the magnetic field inside the sunspot.

Zeeman effect



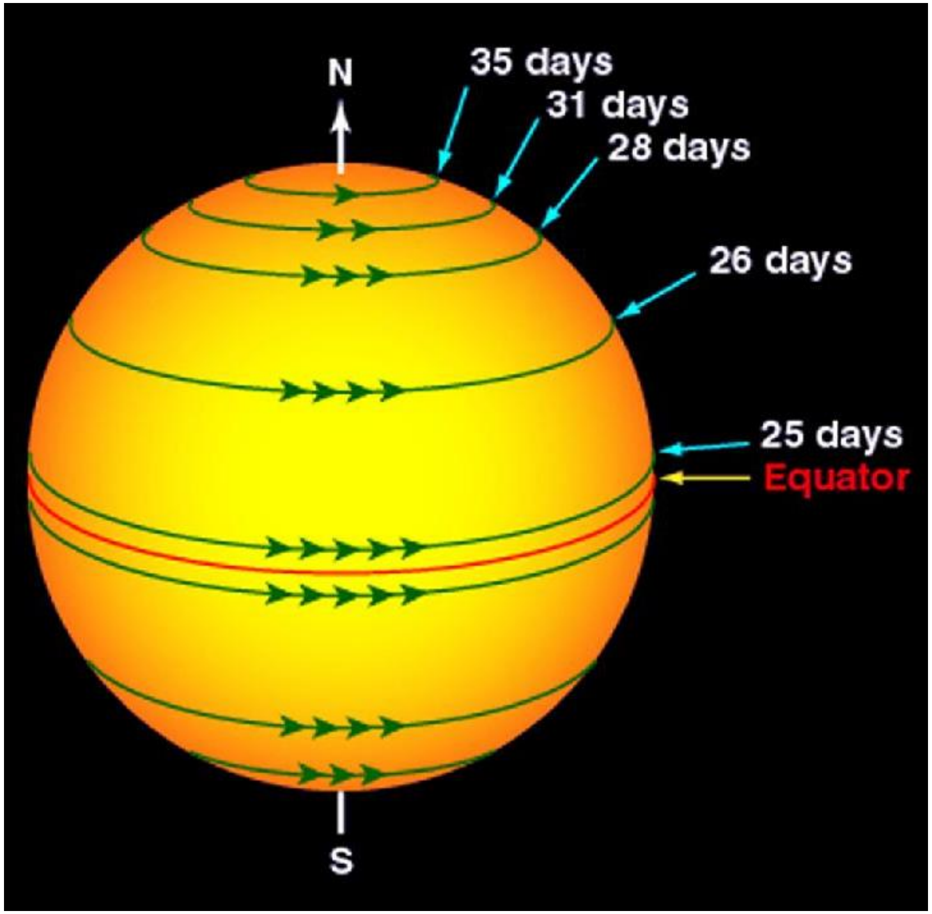
The Zeeman effect: a strong magnetic field splits the spectral lines into two or more components. The strength of the magnetic field can be measured from the amount of separation of the components. Sunspots are regions of strong magnetic fields.

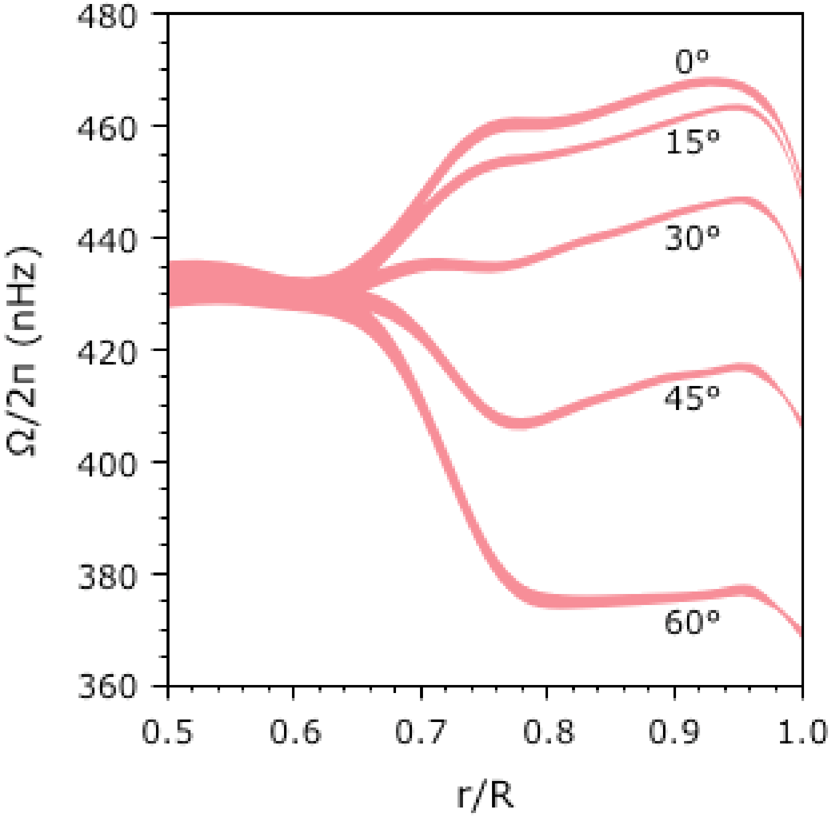
Solar magnetogram



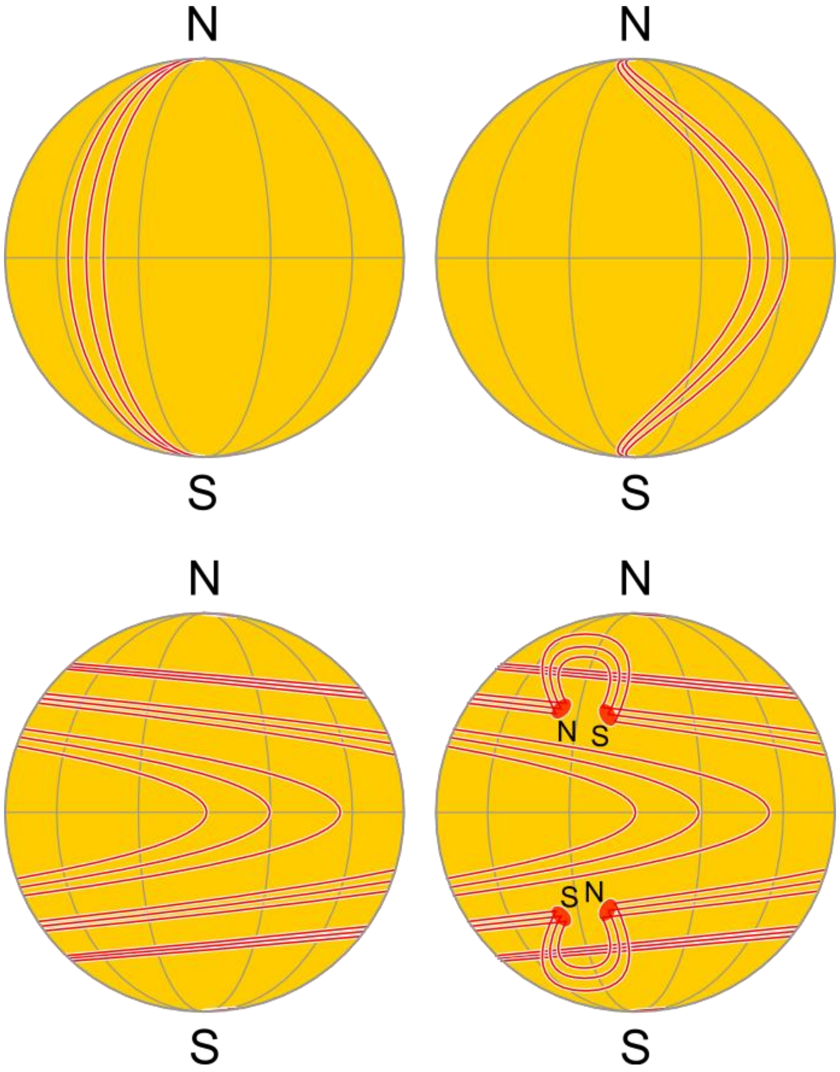
2001/05/05 12:48

Differential rotation



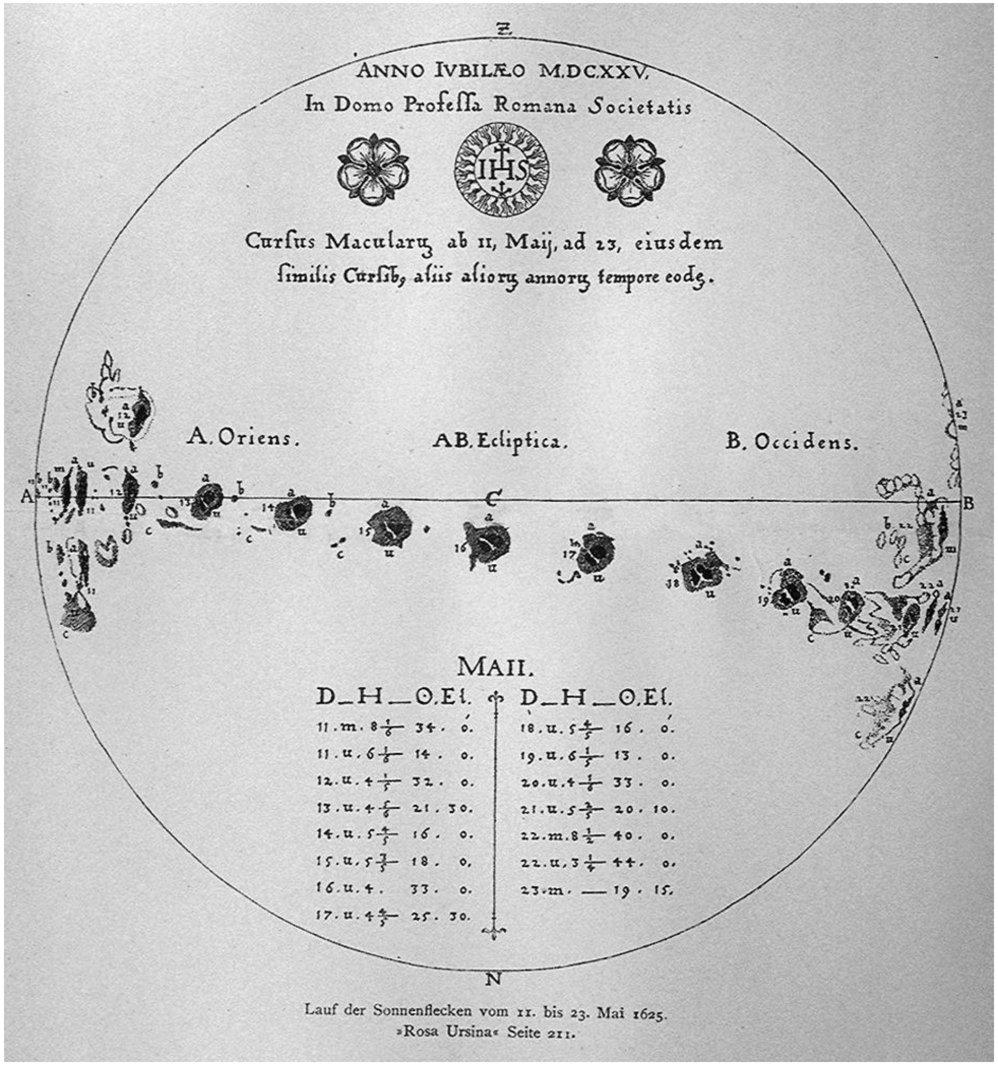


Formation of sunspots



- The velocity shear at the radiative zone/convection zone boundary creates the solar magnetic field.
- The differential rotation of the convection zone «winds up» the magnetic field lines over time.
- At some point, the magnetic field rises through the convection zone (it bubbles up) and breaks through the photosphere, creating a pair of sunspots with opposite polarities.

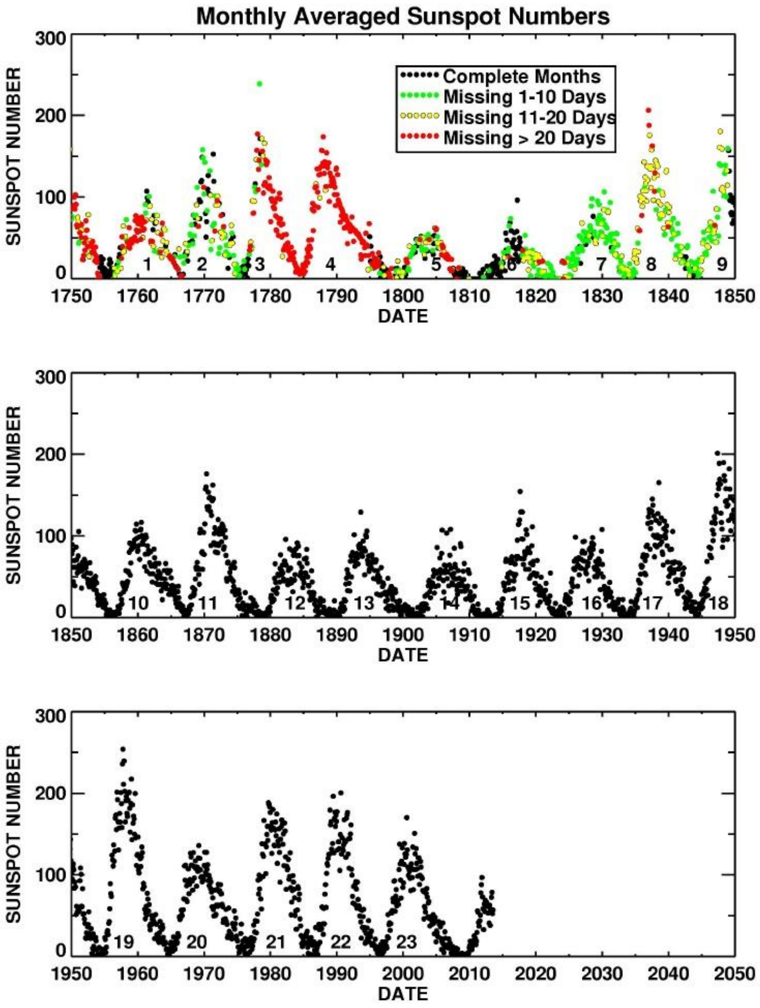
First sunspot observations



Lauf der Sonnenflecken vom 11. bis 23. Mai 1625.
»Rosa Ursina« Seite 211.

- In 1610, shortly after viewing the sun with his new telescope, Galileo Galilei (or was it Thomas Harriot?) made the first European observations of sunspots.
- Christoph Scheiner (1573-1650), a Jesuit mathematician began his study of spots in 1611
- Scheiner, wished to preserve the perfection of the Sun and the heavens and therefore argued that sunspots were satellites of the Sun.

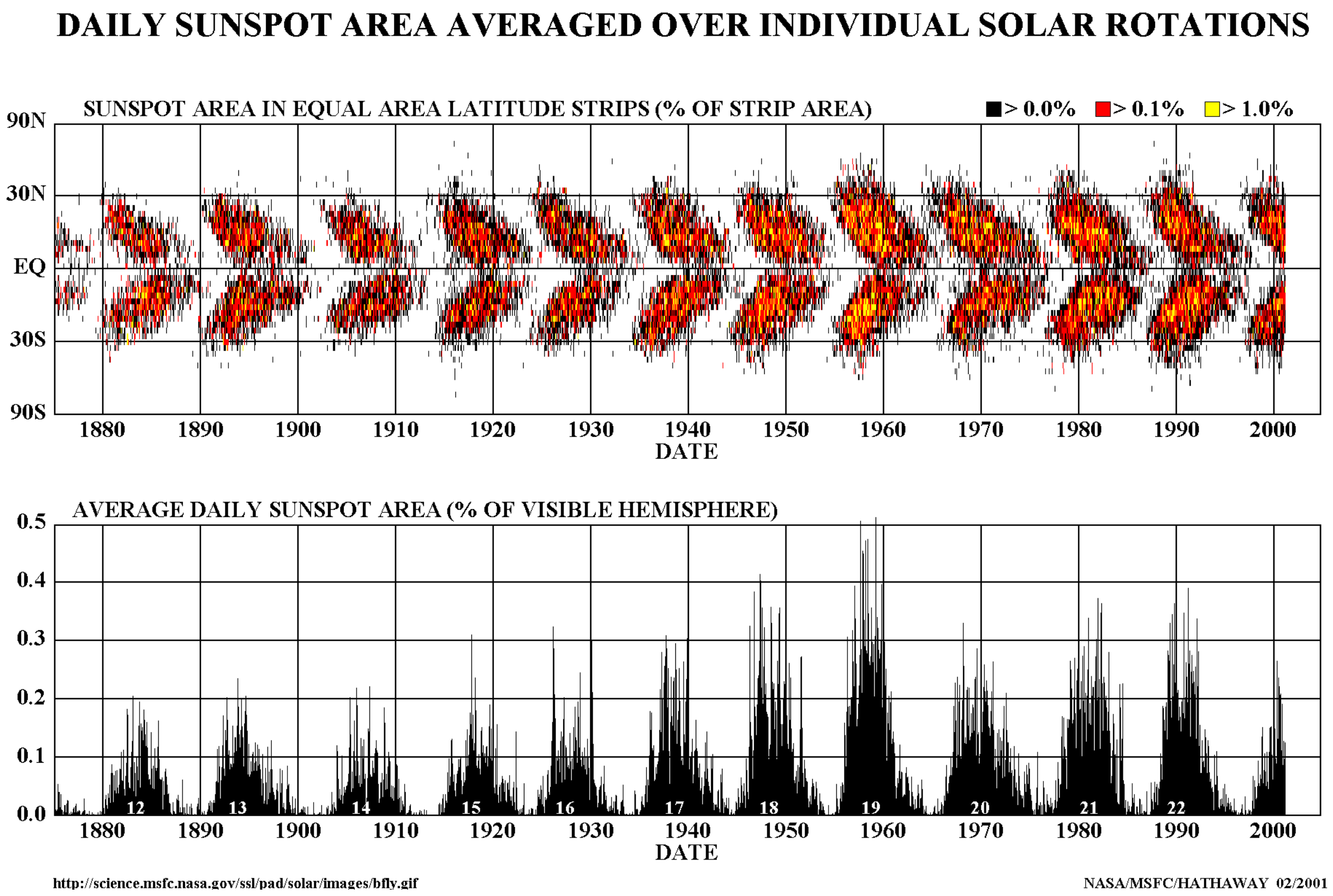
Sunspot observations



HATHAWAY/NASA/MSFC 2013/08

- Continuous daily observations were started at the Zurich Observatory in 1849 and earlier observations have been used to extend the records back to 1610.
- The sunspot number is calculated by first counting the number of sunspot groups and then the number of individual sunspots.
- The number of sunspots exhibits a 11-year cycle.

Butterfly diagram

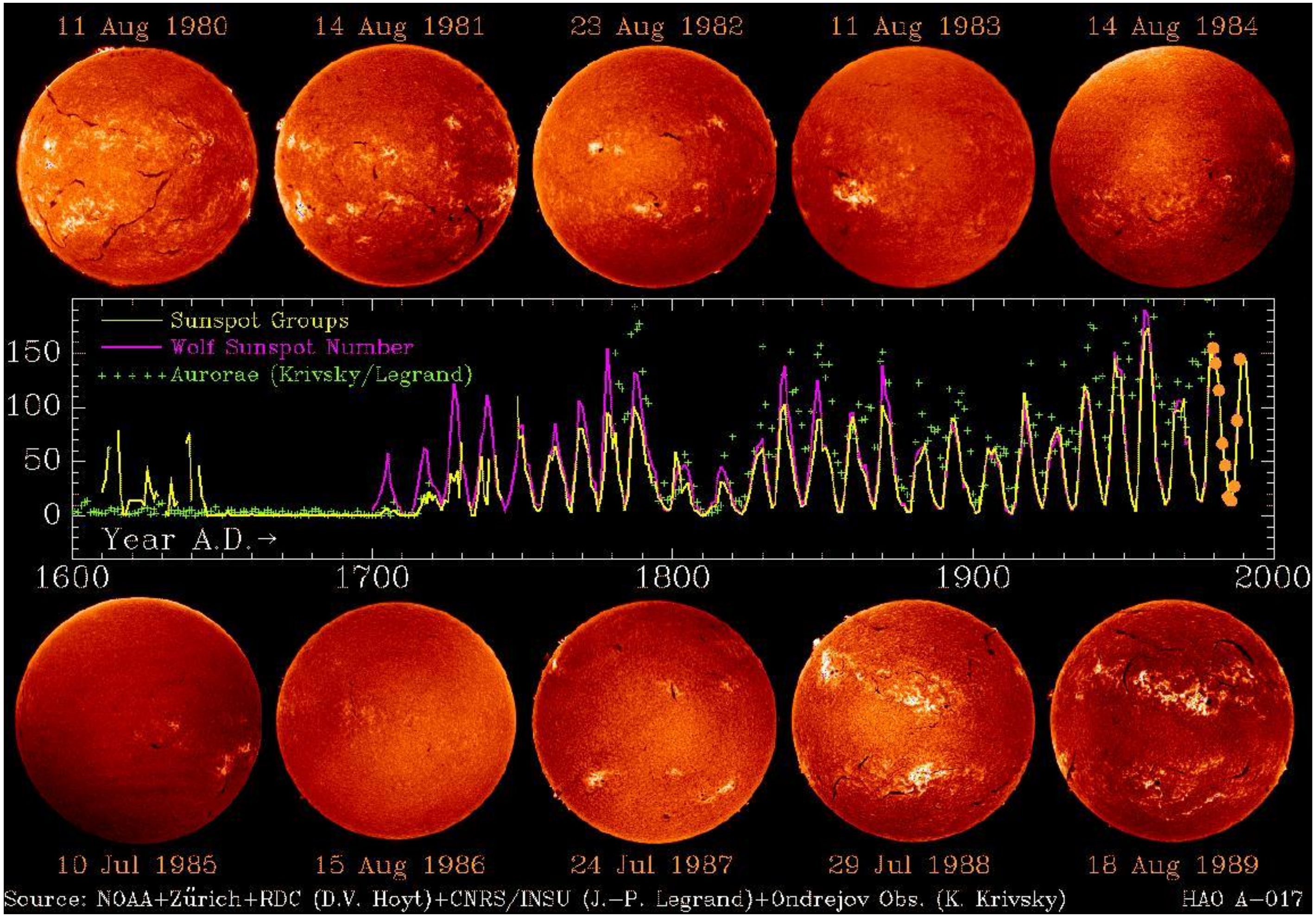


DAILY SUNSPOT AREA AVERAGED OVER INDIVIDUAL SOLAR ROTATIONS

http://science.msfc.nasa.gov/ssl/pad/solar/images/bfly.gif

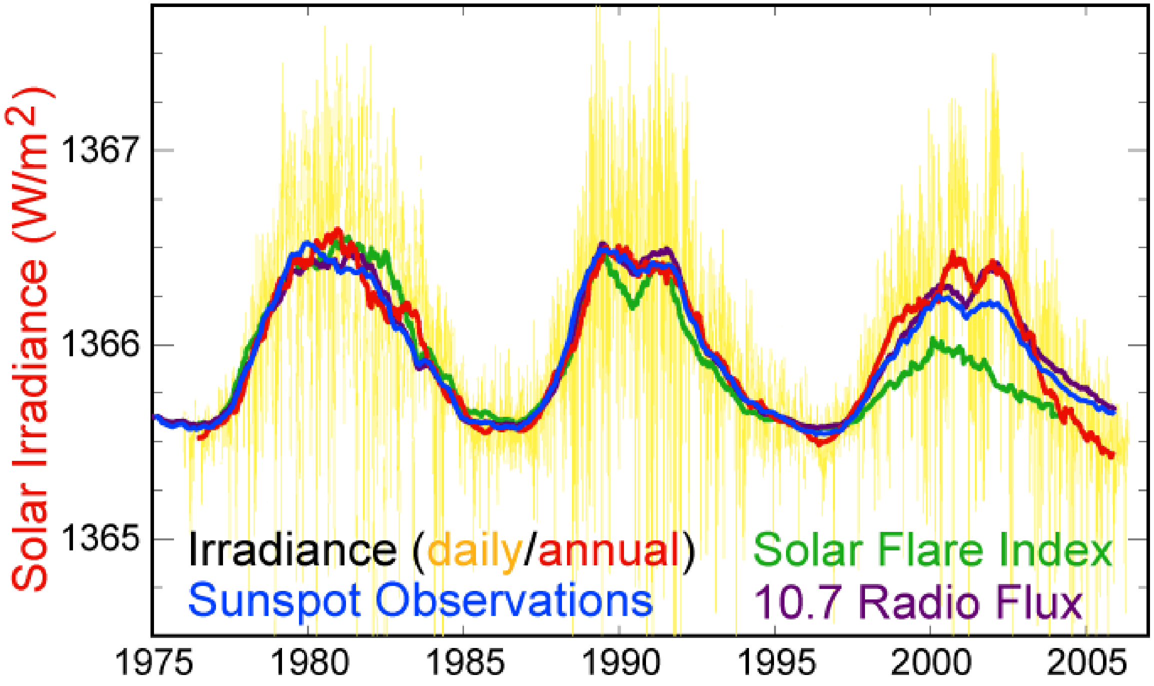
NASA/MSFC/HATHAWAY 02/2001

Sunspot numbers



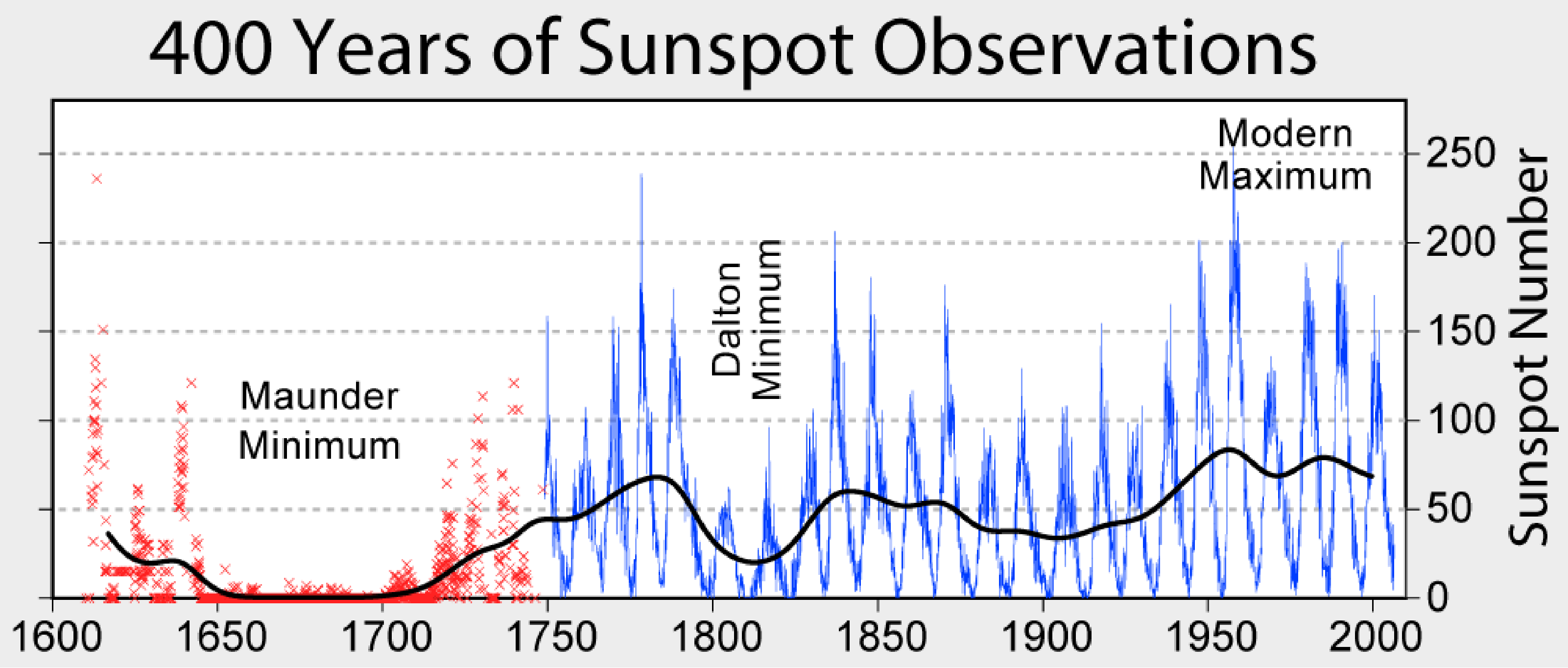
Source: NOAA+Zürich+RDC (D.V. Hoyt)+CNRS/INSU (J.-P. Legrand)+Ondrejov Obs. (K. Krivsky) HAO A-017

Solar cycle variations



- Not only the number of sunspots varies, but also other solar parameters like
  - The total irradiance («solar constant»)
  - The number of flares
  - The amount of electromagnetic radiation emitted in the UHF radio band (at 2800 MHz)

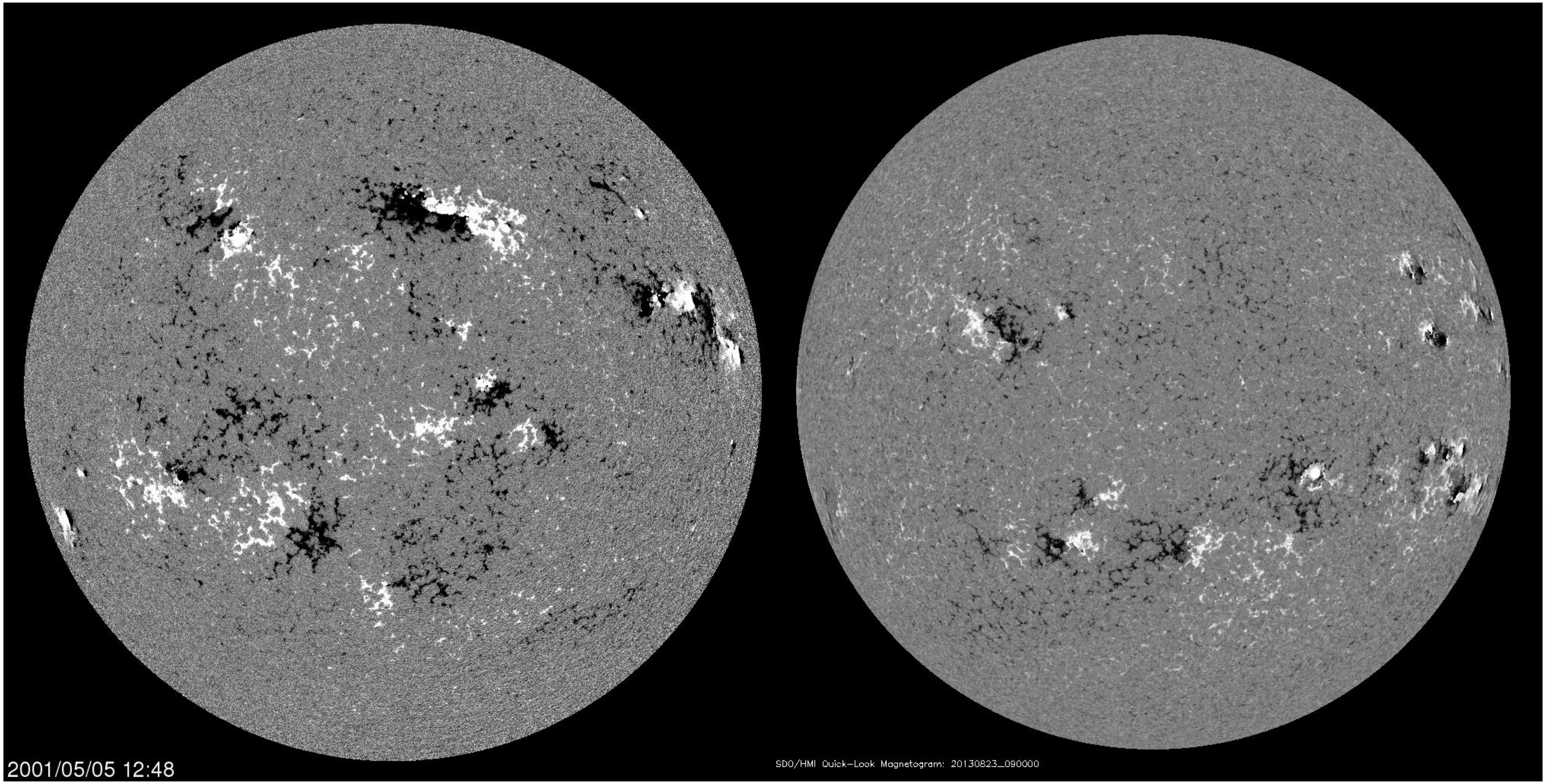
Maunder minimum



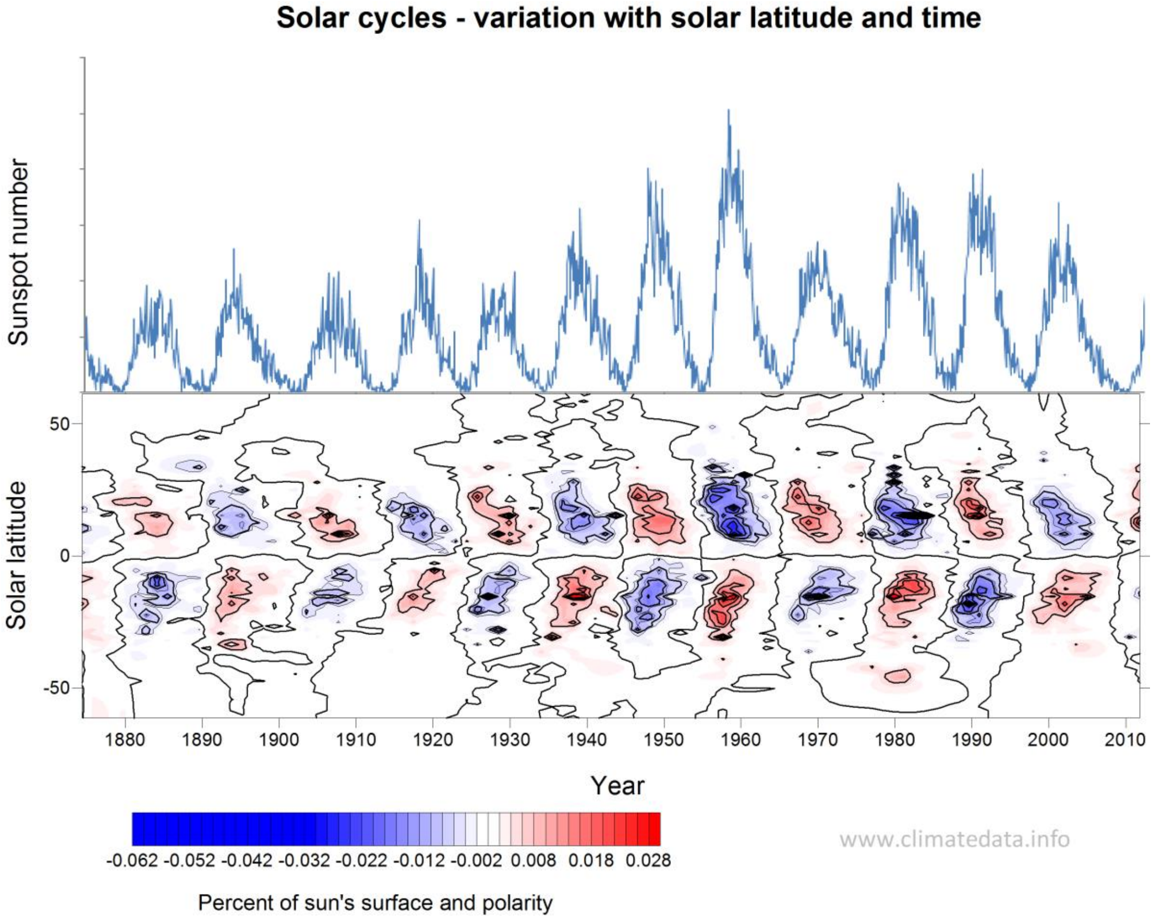
Ice on the Thames

- During Maunder minimum (1645–1715) historical records show very cold winters.
- It has been called the «little ice age».
- It is believed that sunspot activity can be linked to global climate changes.

Leading sunspot polarity



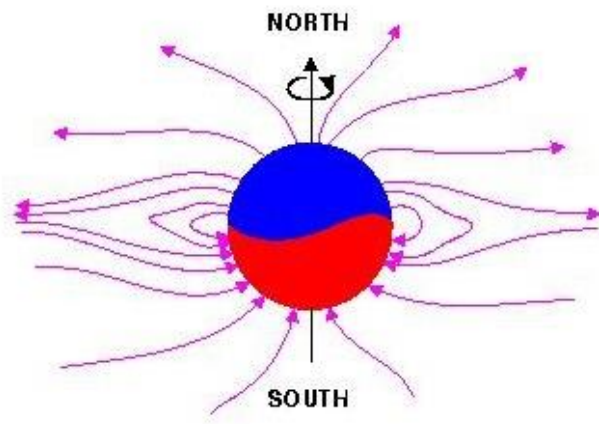
22-year cycle



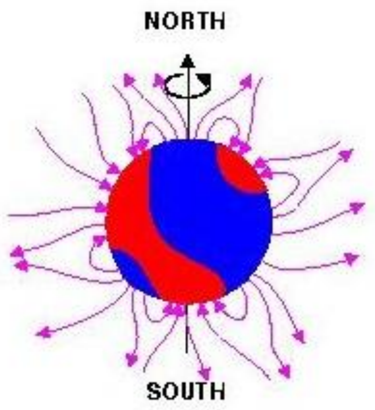
- The leading polarity of sunspot pairs changes between solar cycles – known as Hale’s Polarity Law.
- The change occurs during solar minimum.
- The polar magnetic field of the Sun changes at solar maximum, is hence out of phase with the sunspot magnetic fields.

Change of polar solar magnetic field

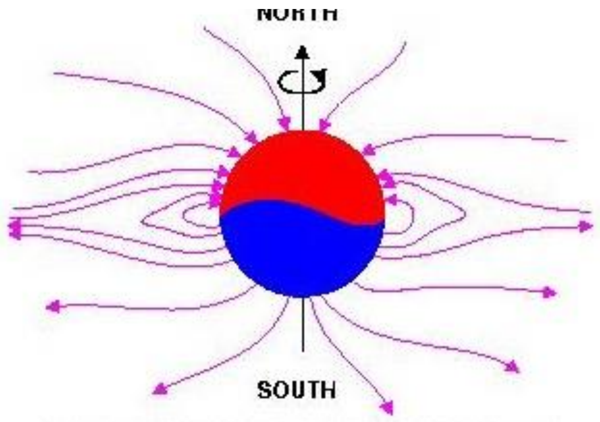
- The polar magnetic field of the Sun changes at solar maximum
- This change is hence out of phase with the sunspot magnetic fields.



CORONAL MAGNETIC FIELD LINES AT
SOLAR MINIMUM ACTIVITY

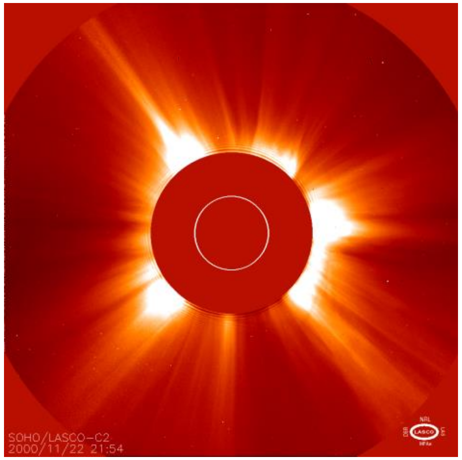


CORONAL MAGNETIC FIELD LINES AT
SOLAR MAXIMUM ACTIVITY



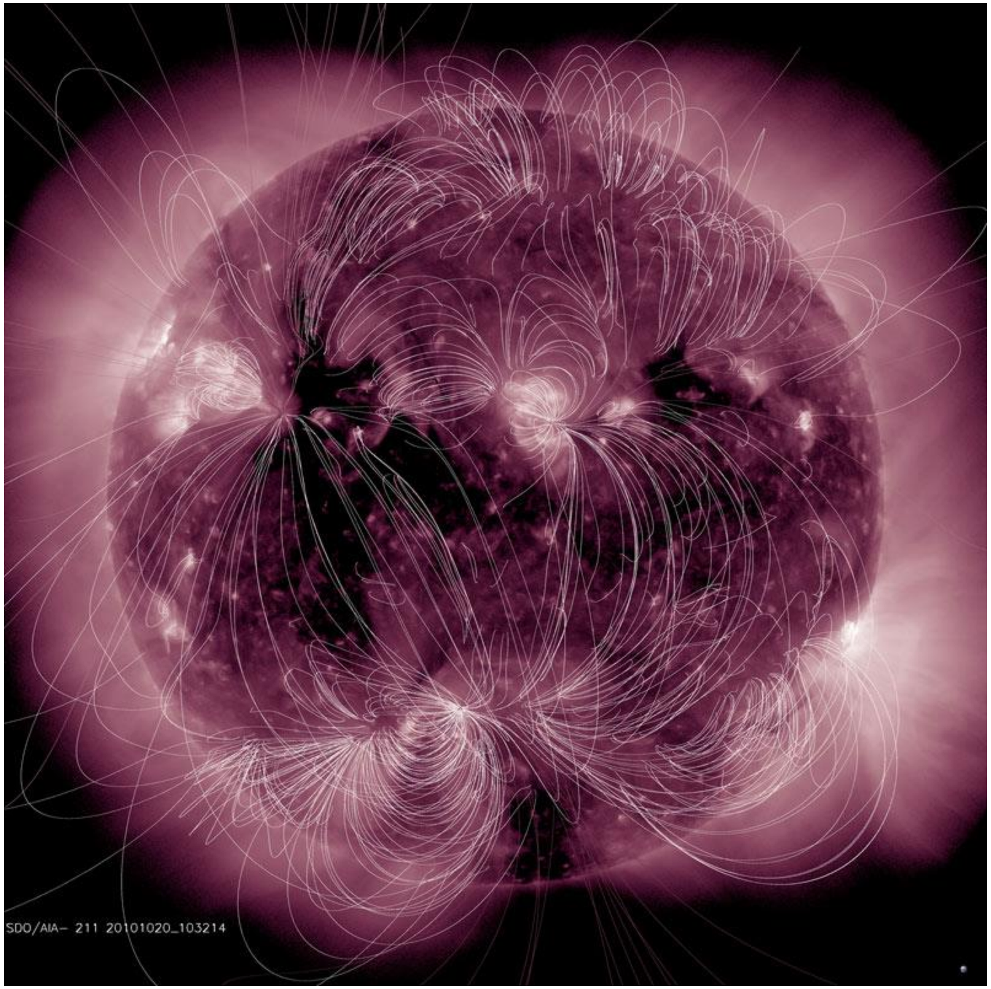
CORONAL MAGNETIC FIELD LINES AT
NEXT SOLAR MINIMUM

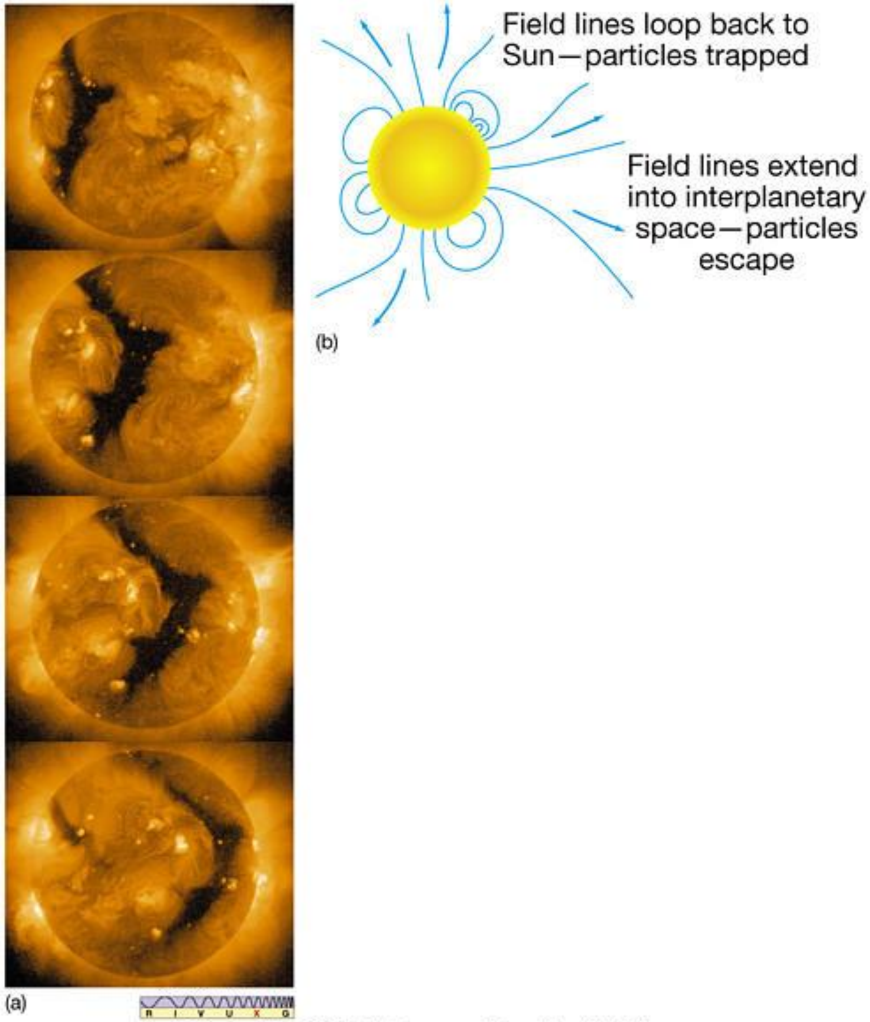
1995



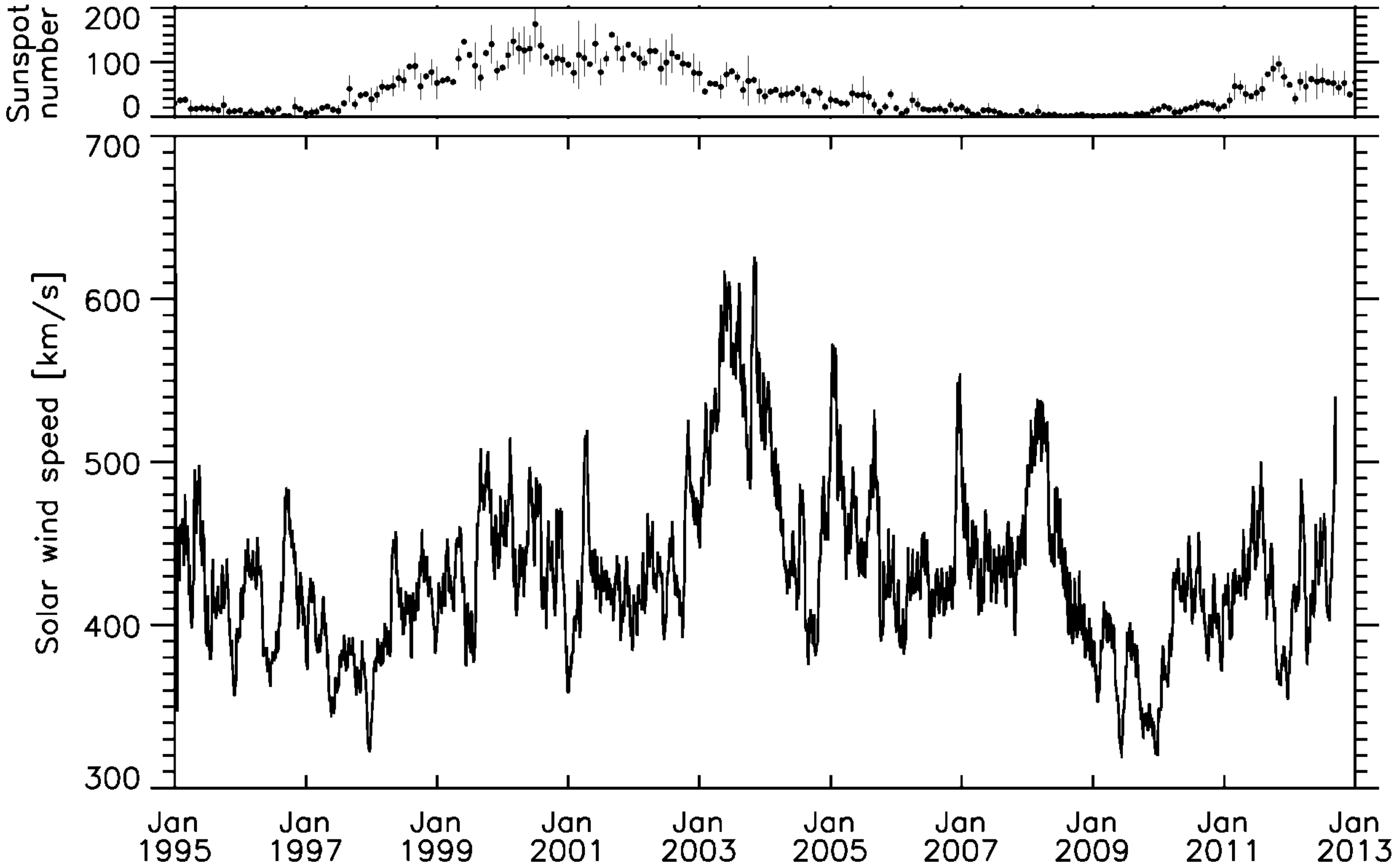
2000

Coronal holes

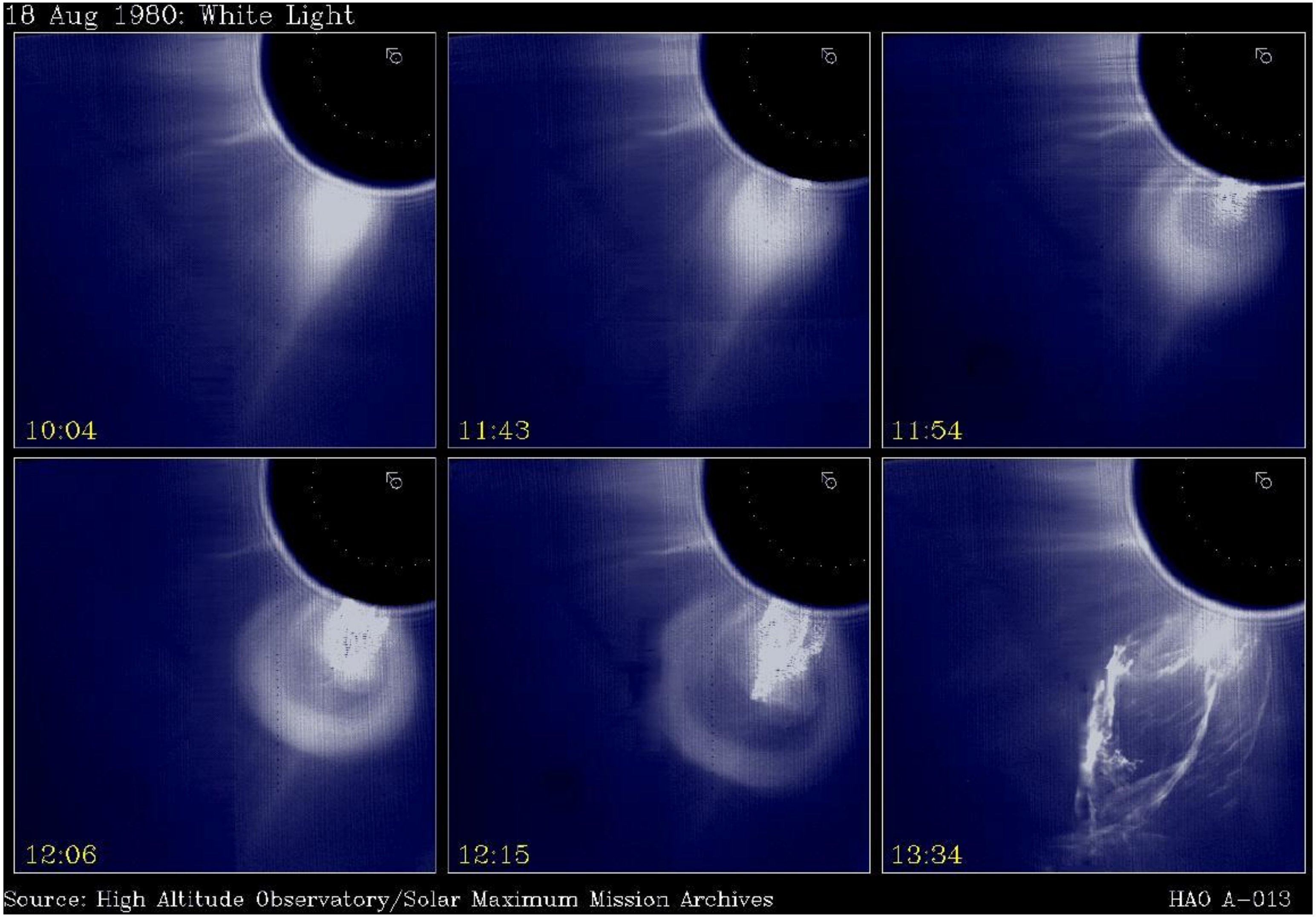


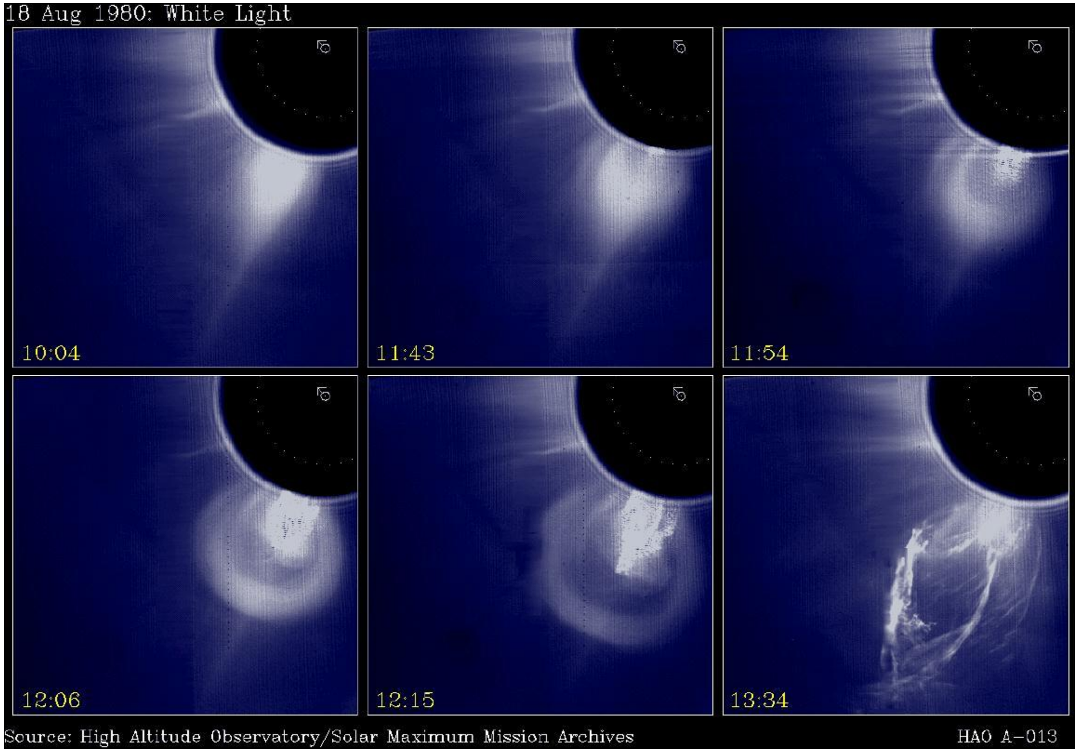


Solar wind speed vs. sunspot number



Coronal mass ejections (CMEs)

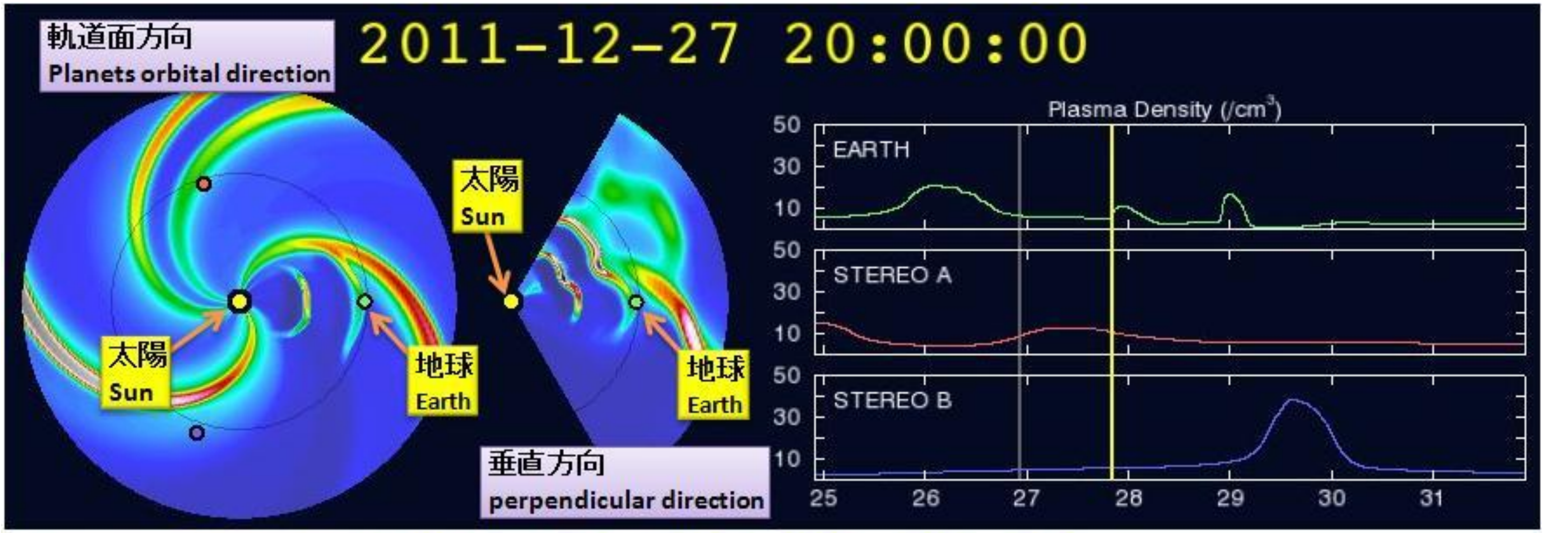


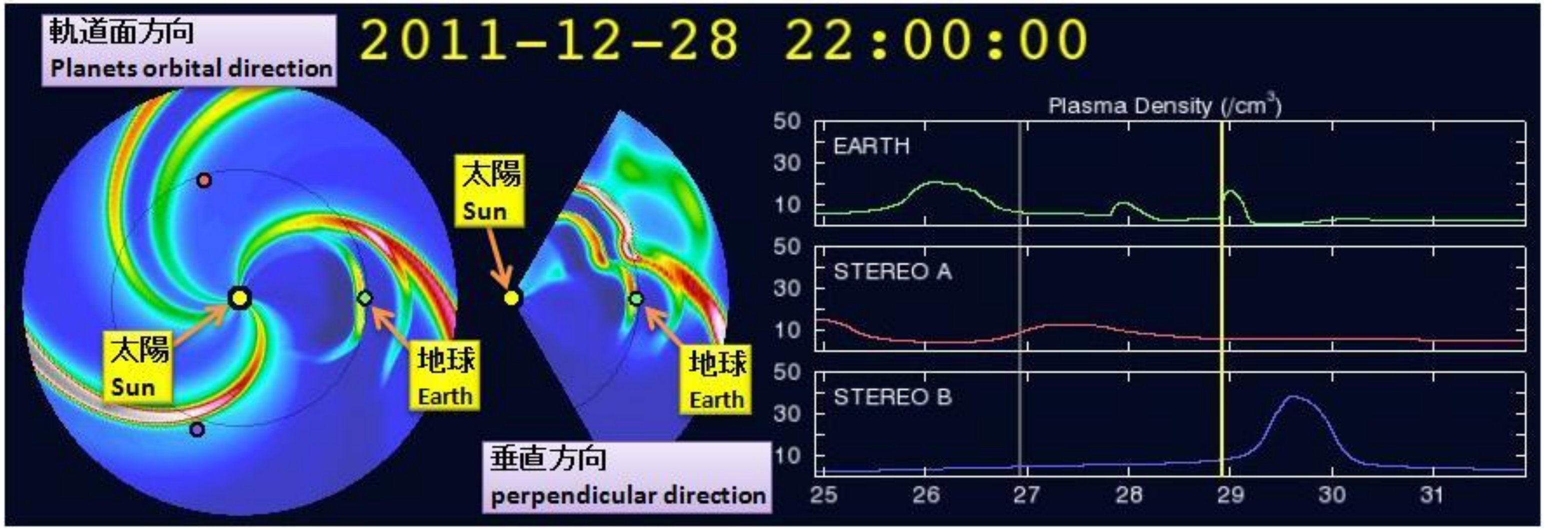


Source: High Altitude Observatory/Solar Maximum Mission Archives

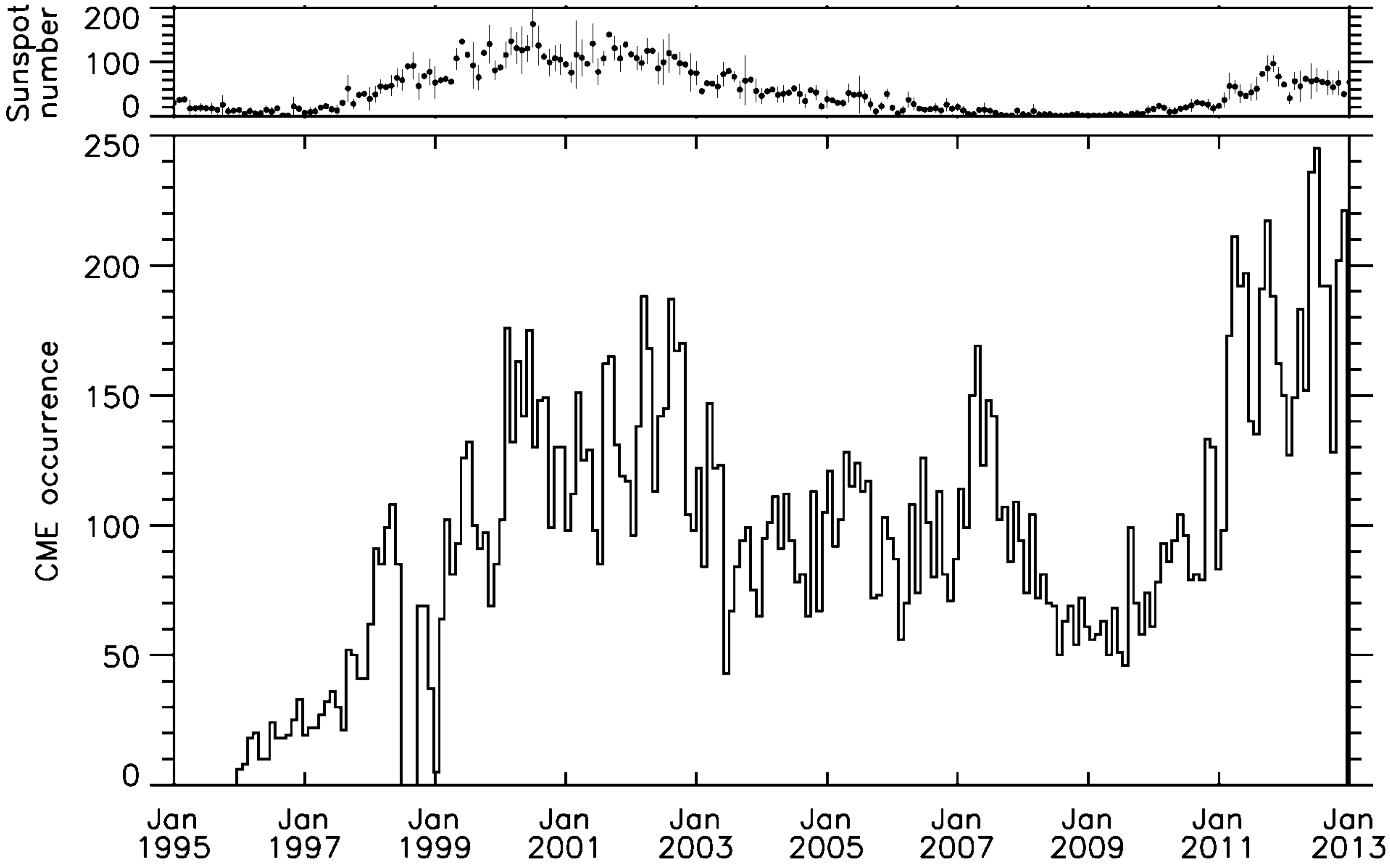
- Coronal mass ejections (CMEs) are balloon-shaped bursts of solar wind rising above the solar corona
- Solar plasma is heated to tens of millions of degrees, and electrons, protons, and heavy nuclei are accelerated to near the speed of light.
- Each CME releases up to 100 billion kg of plasma, and the speed of the ejection can reach 1000 km/s in some flares.
- CMEs are currently the biggest "explosions" in our solar system

CMEs in the solar wind

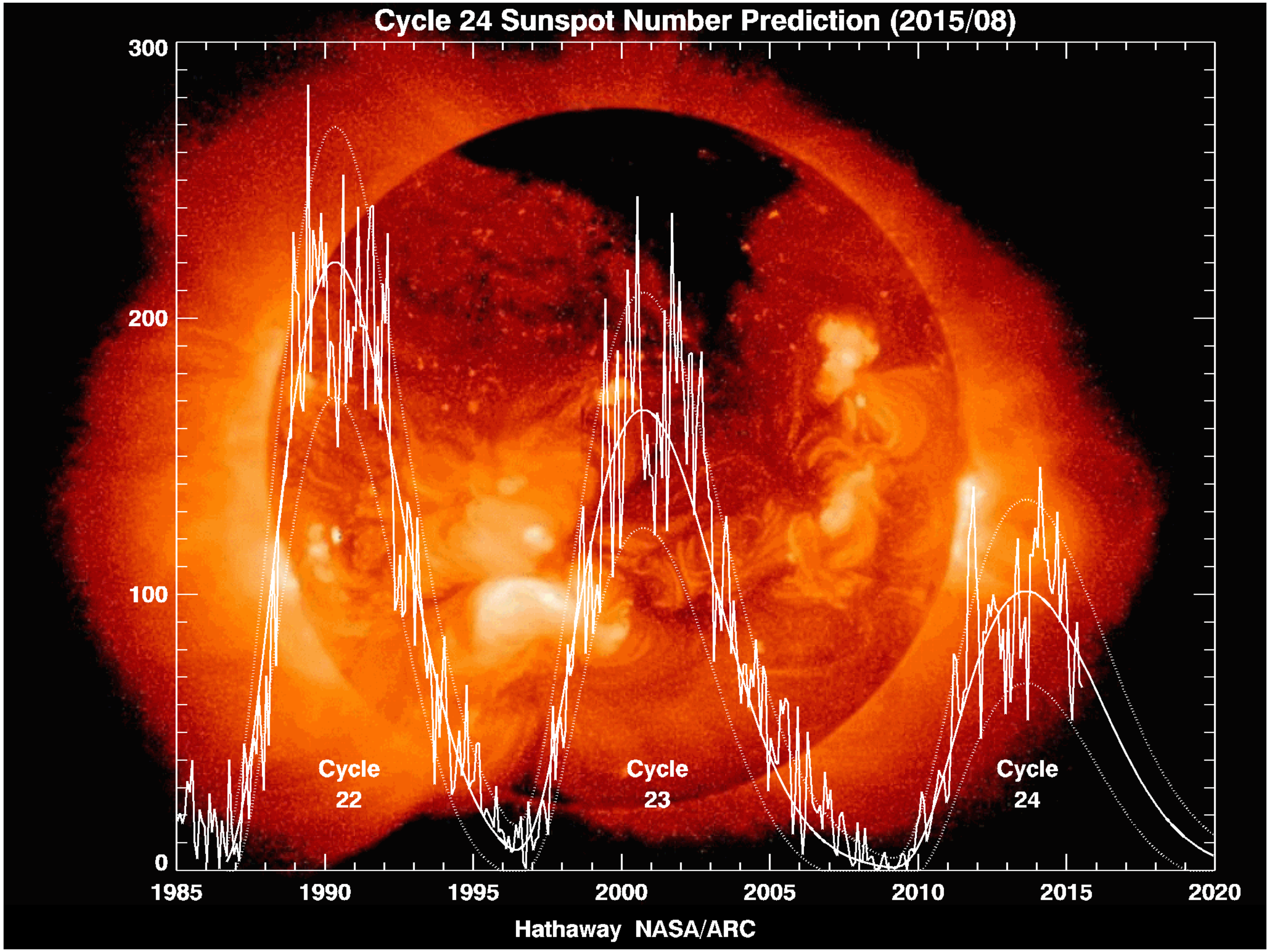




CME occurrence vs. sunspot number



Current solar cycle



The Sun yesterday