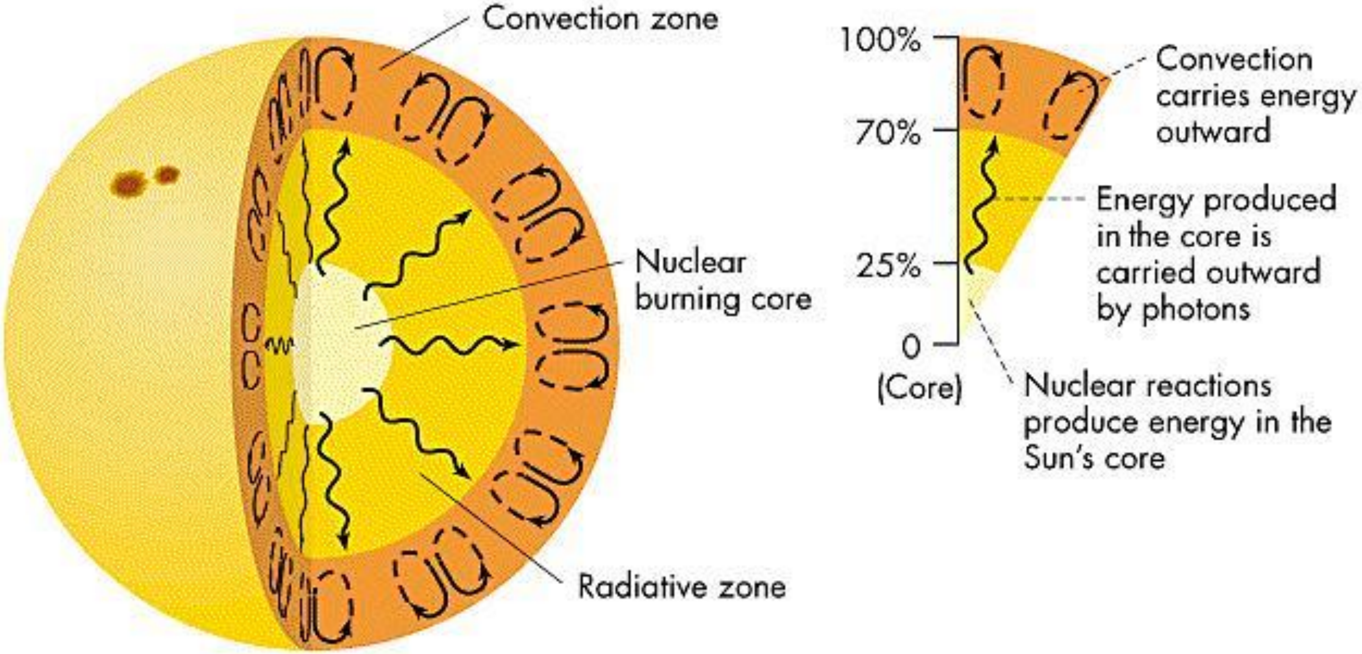
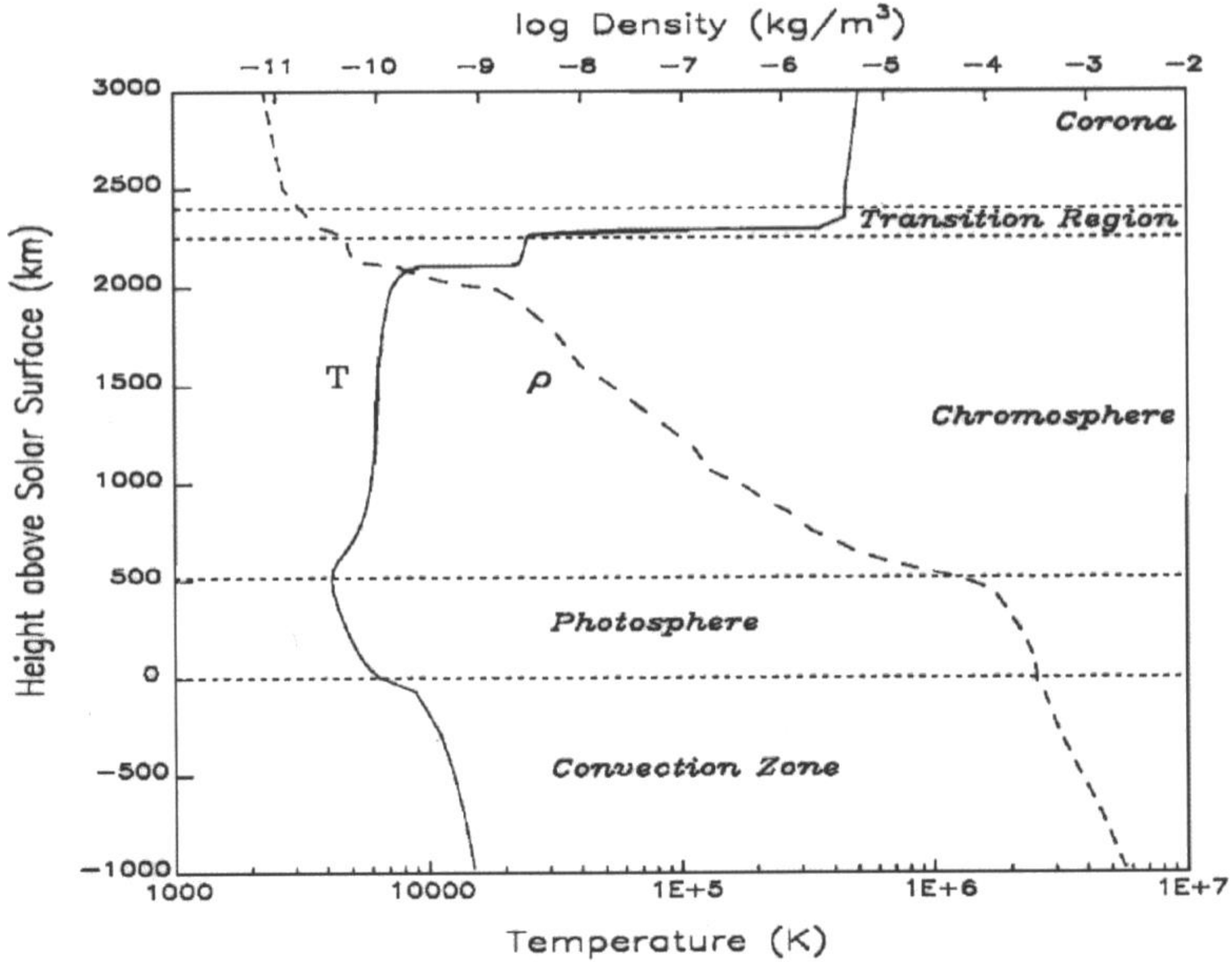
UiO : Department of Physics
University of Oslo

Dynamics of the Sun

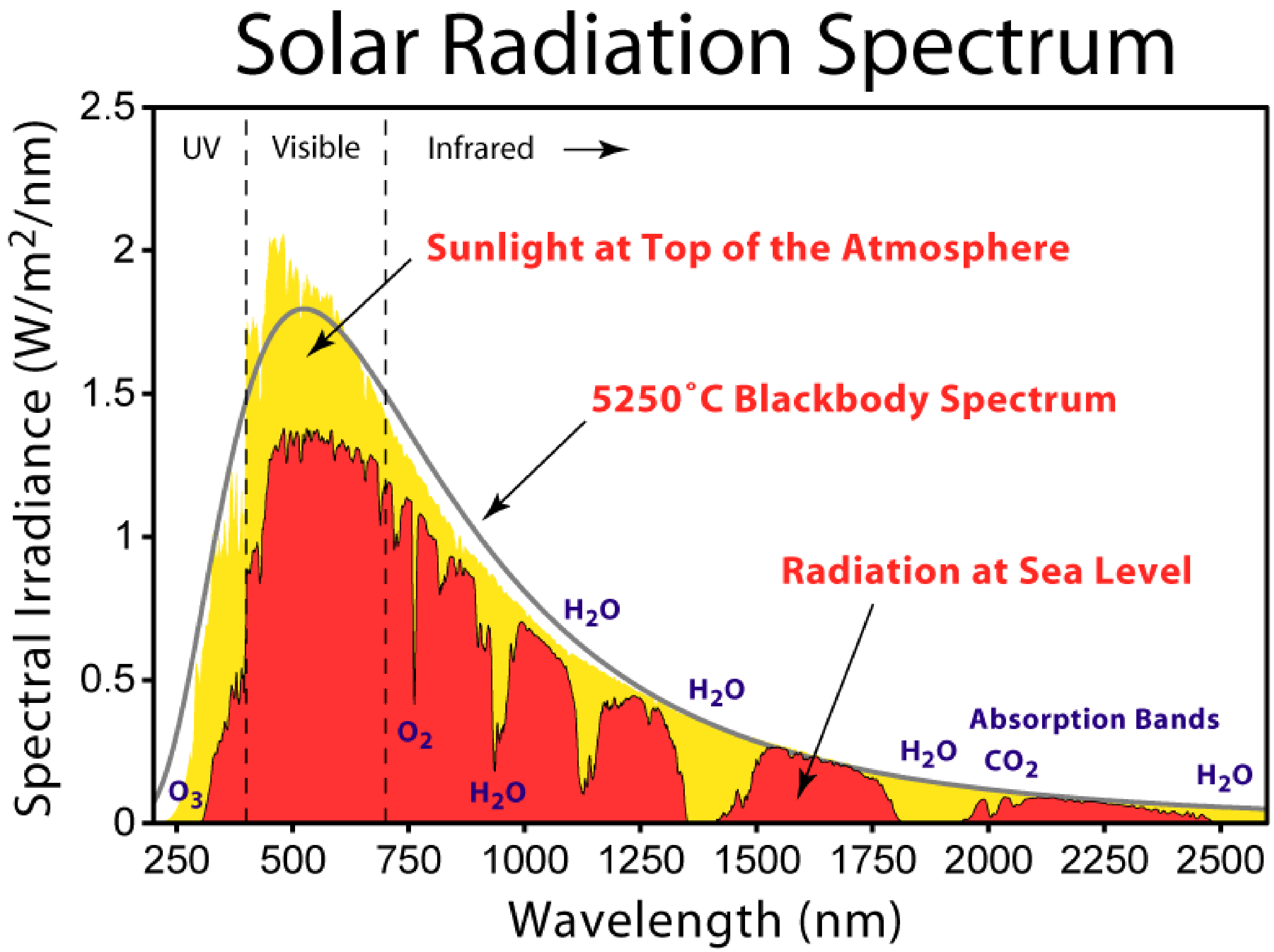
Interior structure of the Sun



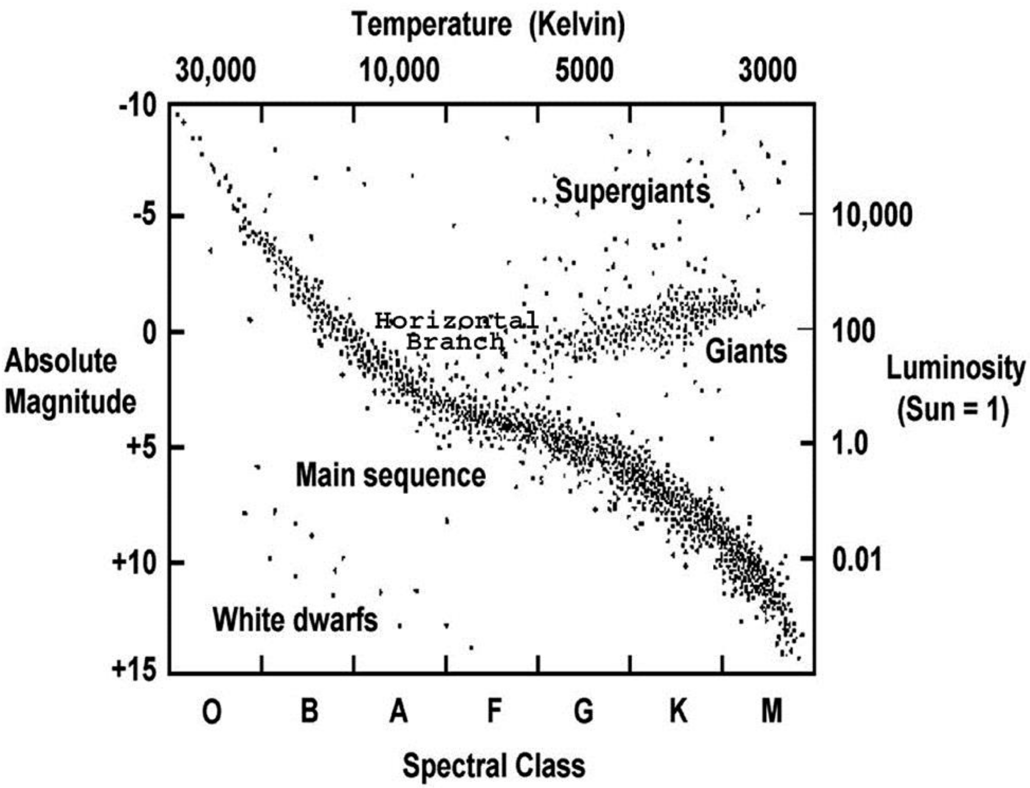
Some parameters



Solar spectrum

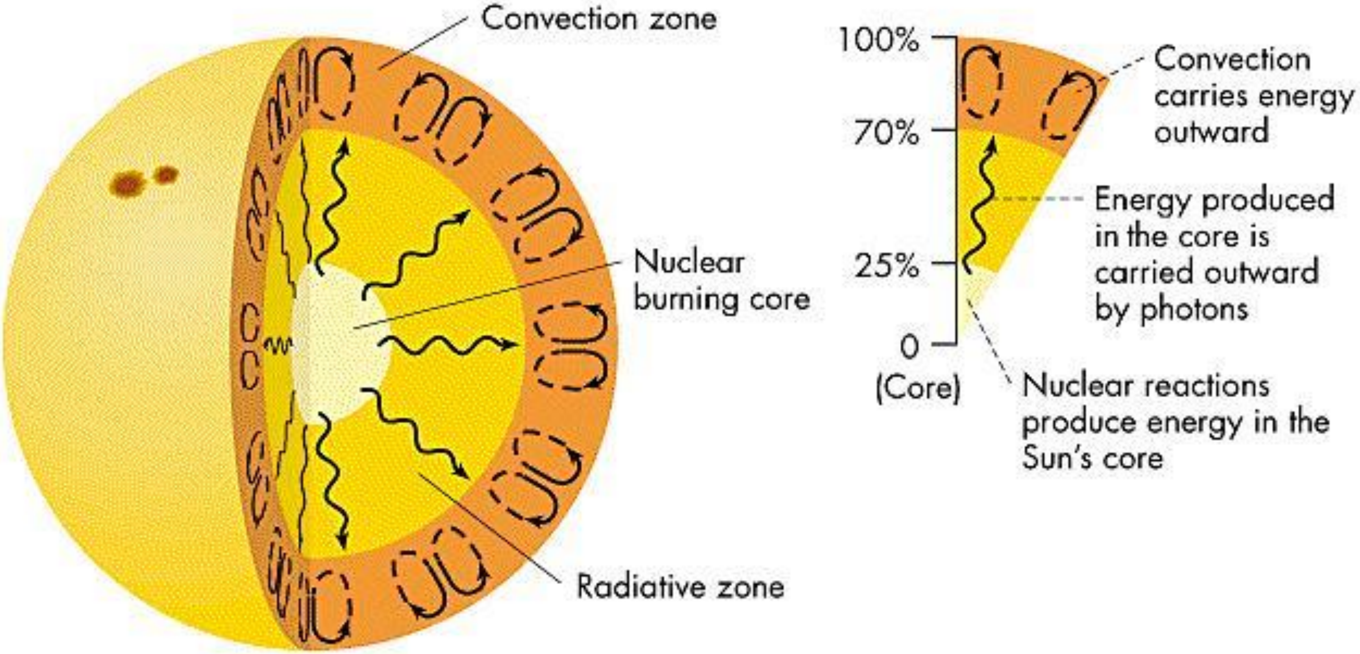


Hertzsprung-Russell diagram

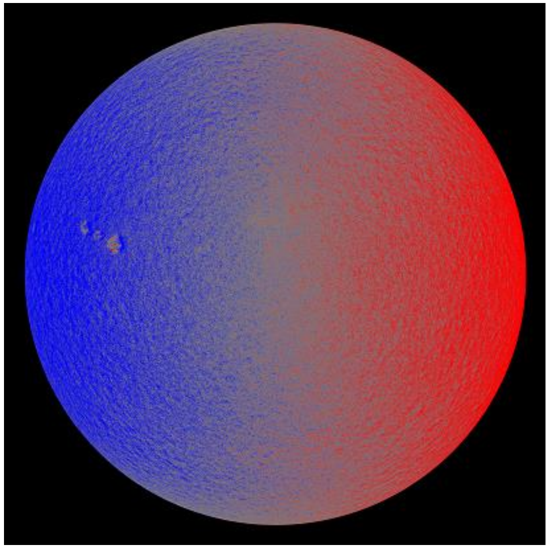


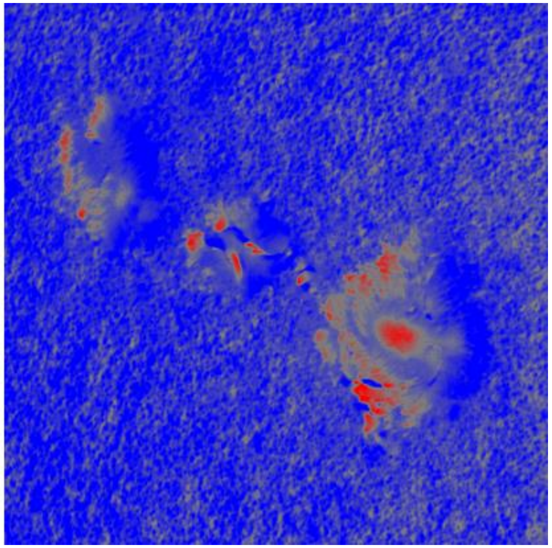
- Luminosity vs. surface temperature
- Luminosity is surface area times energy flux
- Energy flux is proportional T^4 (Stefan-Boltzmann-Law)
- $L = 4\pi R^2 \sigma T^4$
- Source of energy is fusion, i.e., lighter atoms fuse to form heavier elements, which leads to energy release

Interior structure of the Sun



Solar Dynamics Observatory



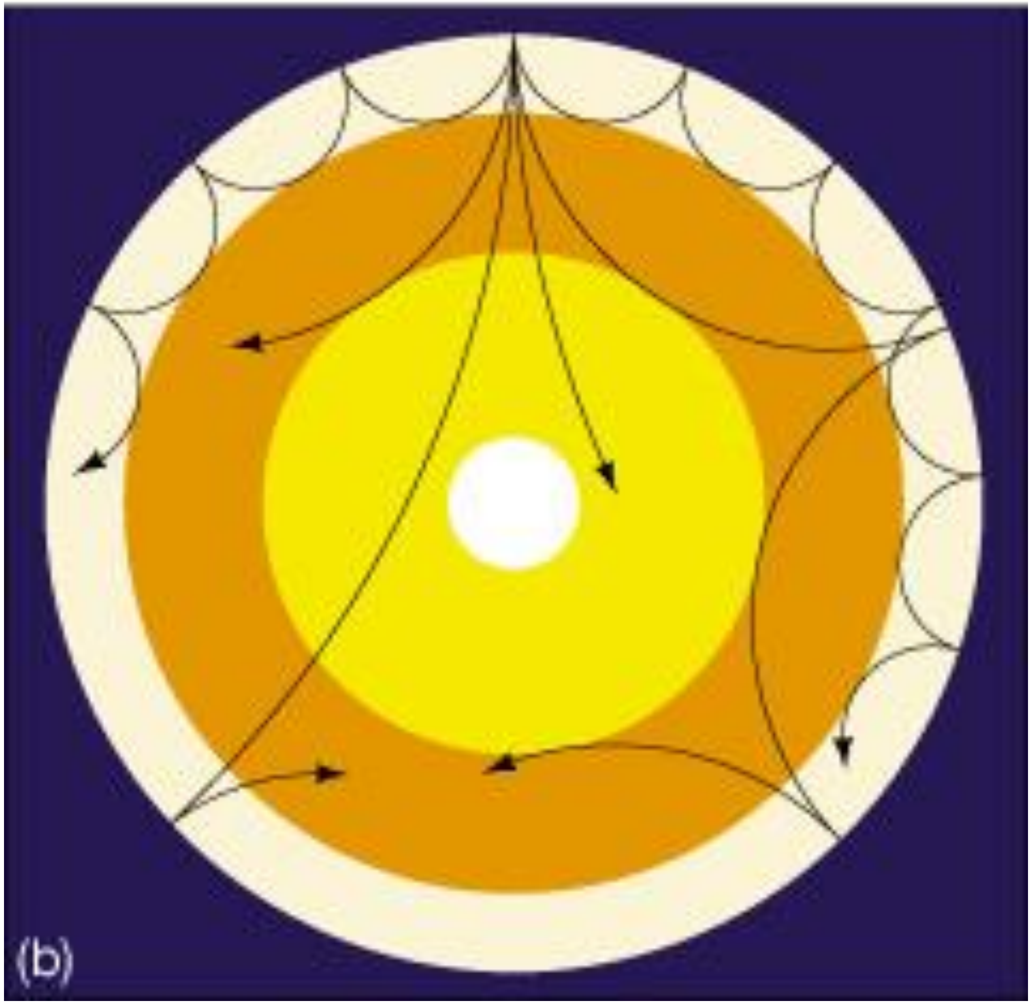


- Satellite carries a Michelson Interferometer
- Doppler shift of one spectral line is measured, giving the line-of-sight velocity of the Sun
- Blue represents motion toward the observer, red away
- Strongest signal is rotation of the Sun, but sun spots show different dynamics

Global helioseismology

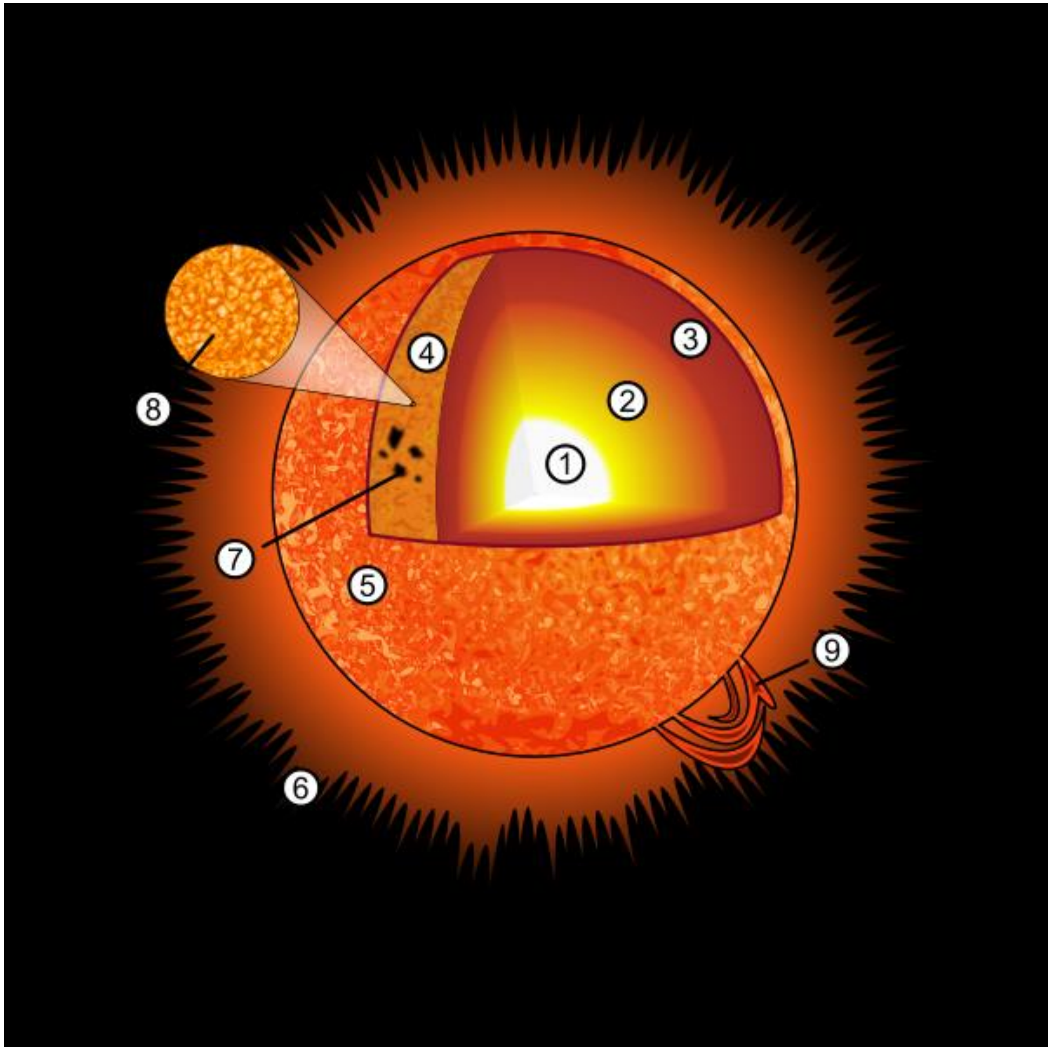
- Spatial variations of Doppler shift in spectral lines reveals radial motion of solar surface.
- Typical amplitude of a single mode: < 20 cm/s
- Total velocity of all 10^7 modes: a few 100 m/s
- Accuracy of current instruments: better than 1 cm/s
- Spatio-temporal properties of oscillations best revealed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

Ray paths



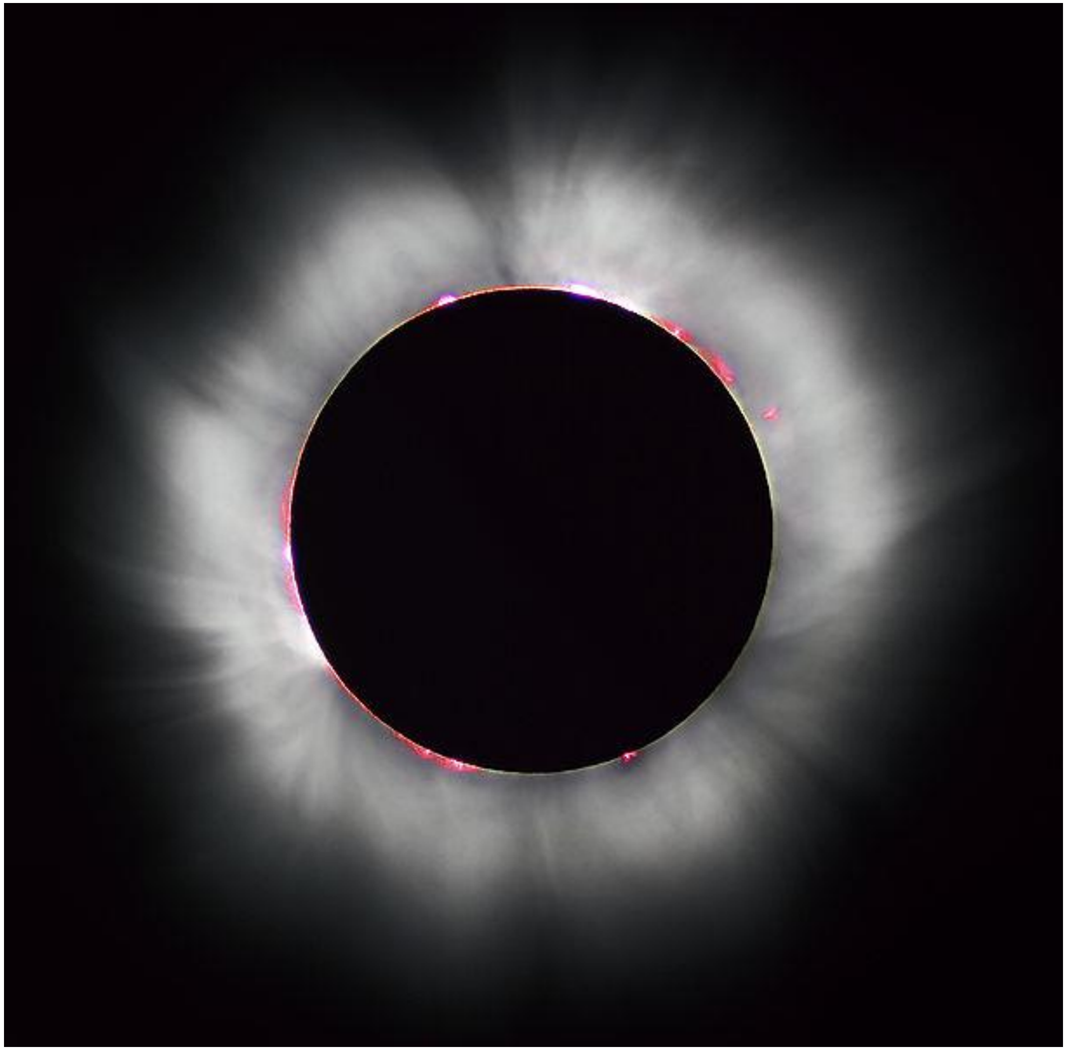
- Local disturbance creates perturbations that travel through the Sun (p-modes).
- Due to changes in background density and temperature, the wave paths are refracted.
- Superposition of waves creates interference pattern which can be inverted to learn something about the internal structure of the Sun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

Some solar features



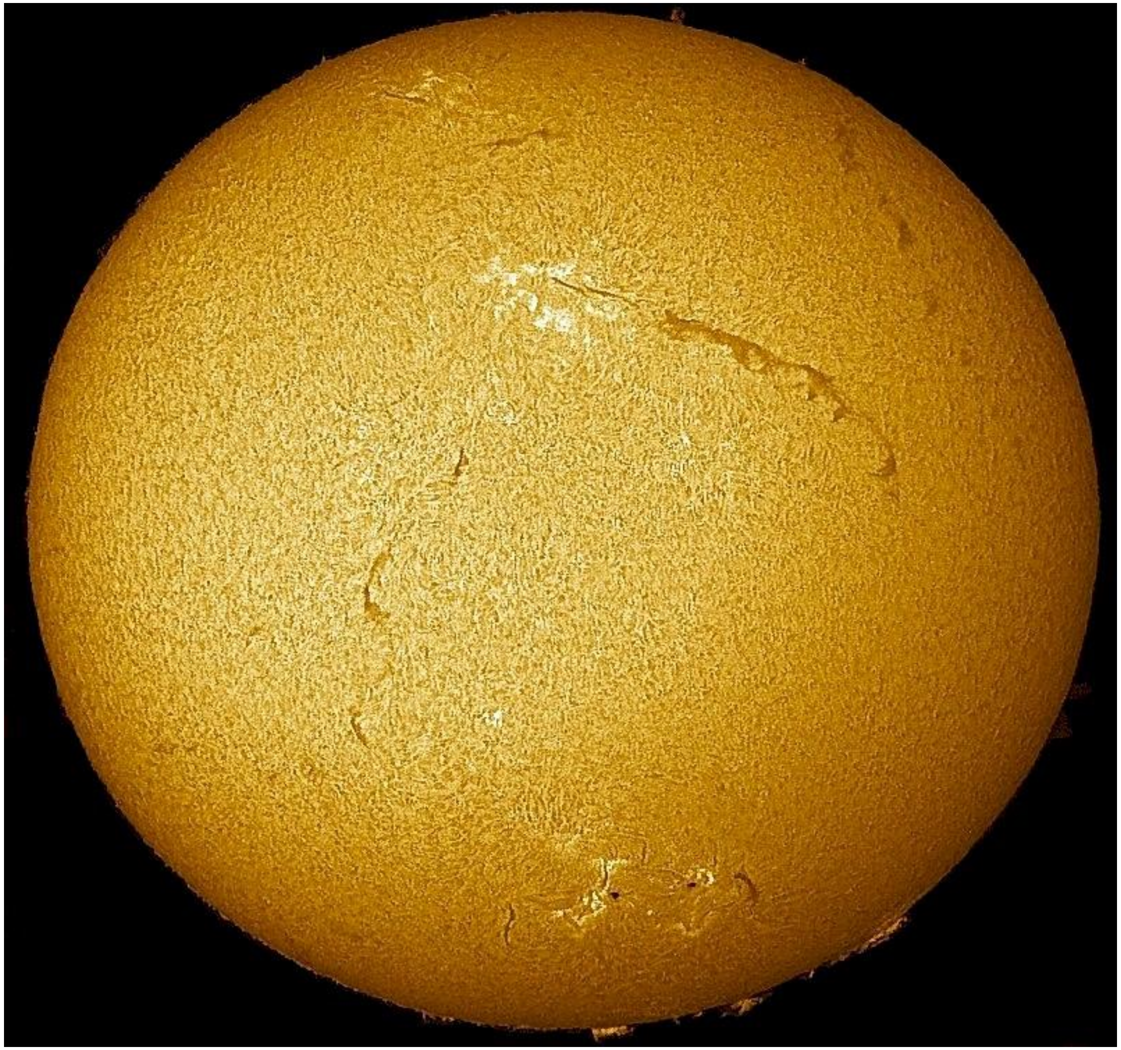
1) Core
2) Radiative zone
3) Convective zone
4) Phtotosphere
5) Chromosphere
6) Corona
7) Sunspot
8) Granulae
9) Prominence

Chromosphere



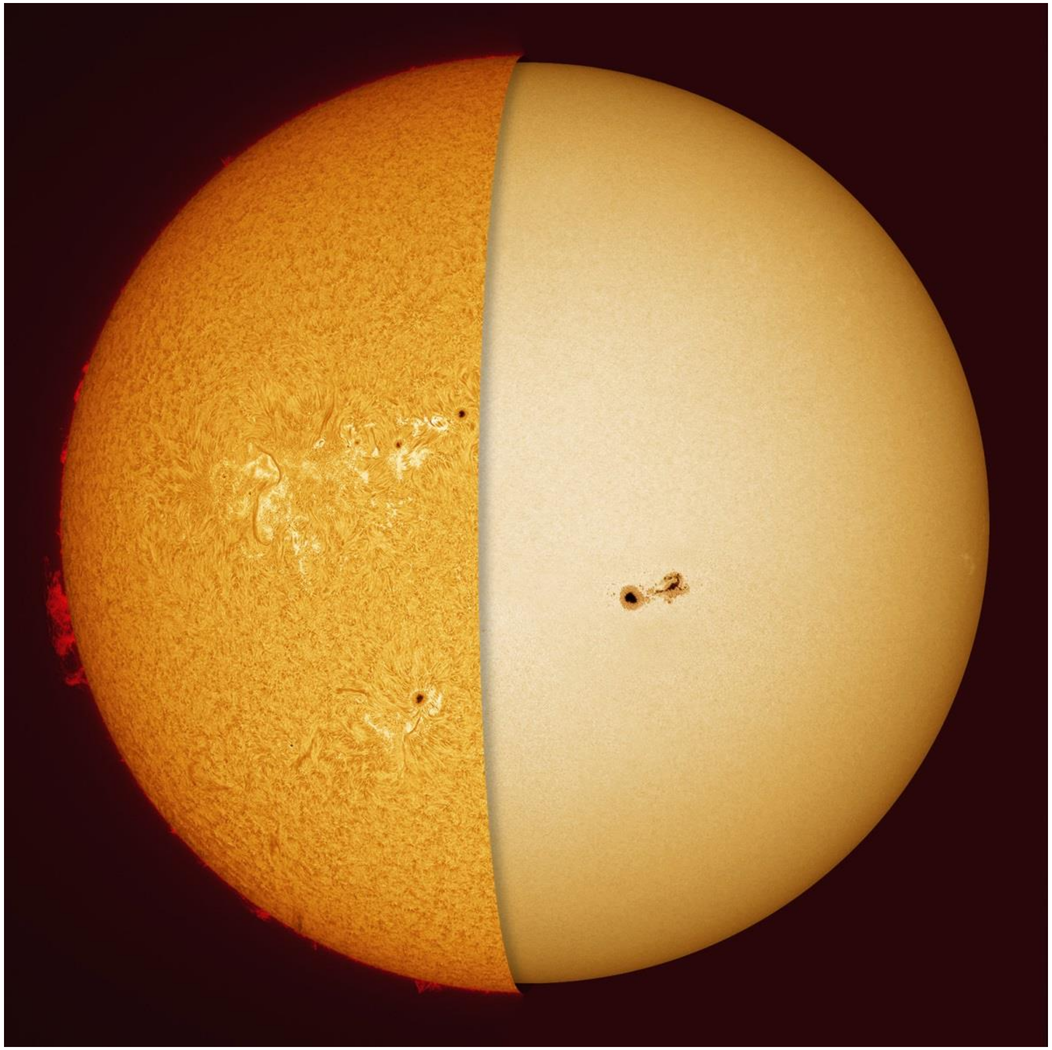
- Region between photosphere and corona
- Temperatures between 4,000K and 10,000K
- Consists mainly of neutral hydrogen and is hence best observed in the Lyman alpha line in the UV.

Filaments



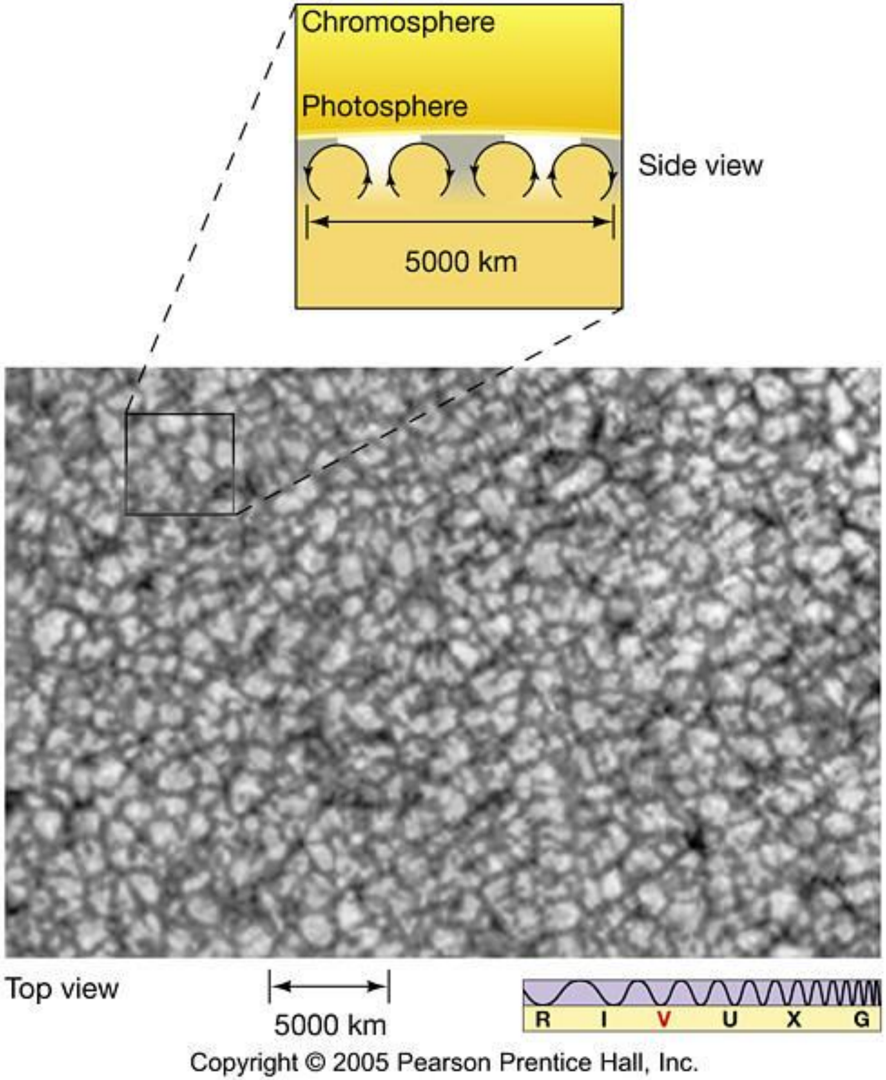
- Filaments are regions which appear darker than the background.
- They appear darker because the plasma is colder.
- They have chromospheric densities.

Chromosphere/photosphere



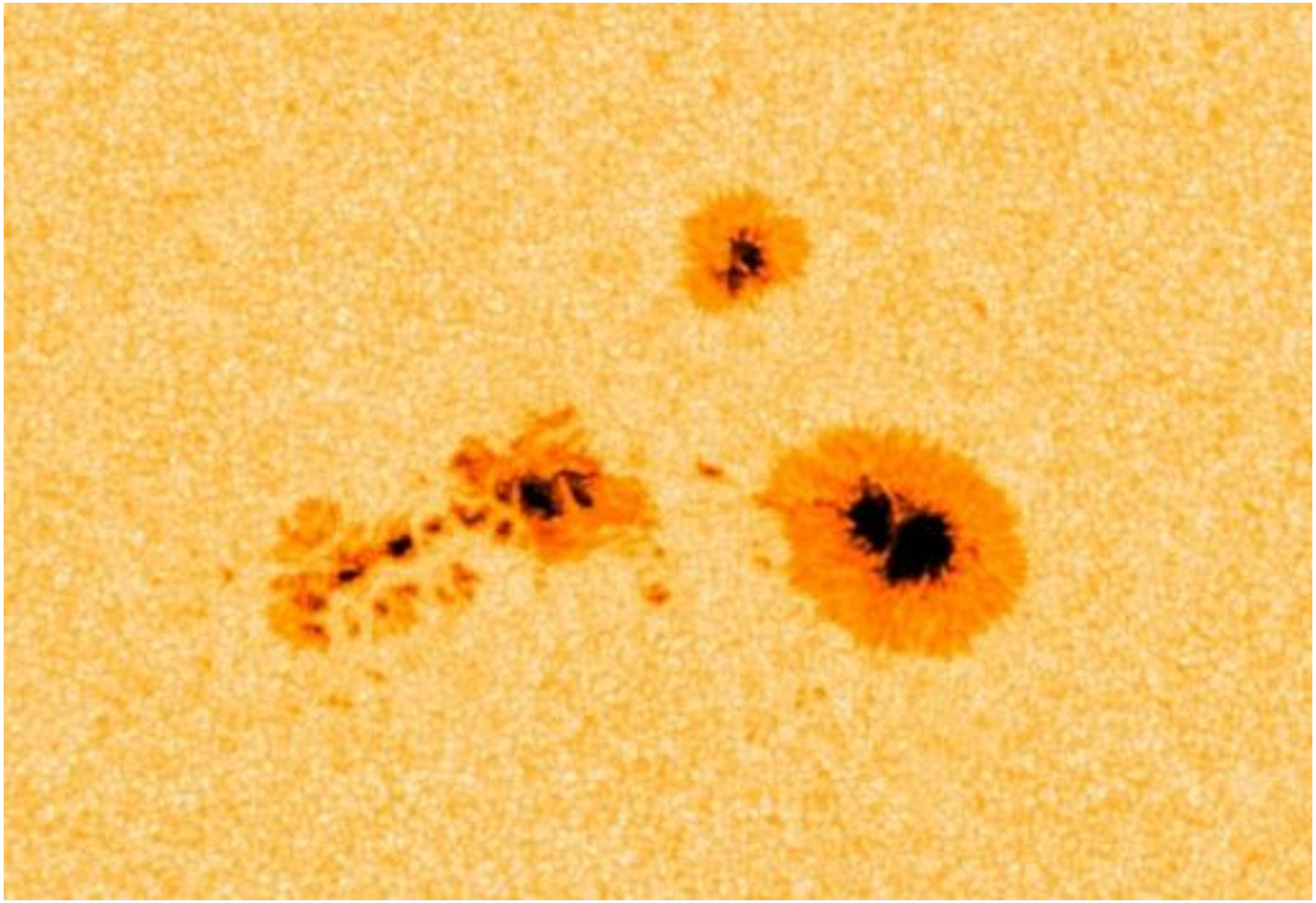
- Comparisson between the chromosphere (left) and the photosphere (right) of the Sun.
- Chromosphere shows prominences/filaments and sunspots.
- Photosphere shows granulation and sunspots.

Granules

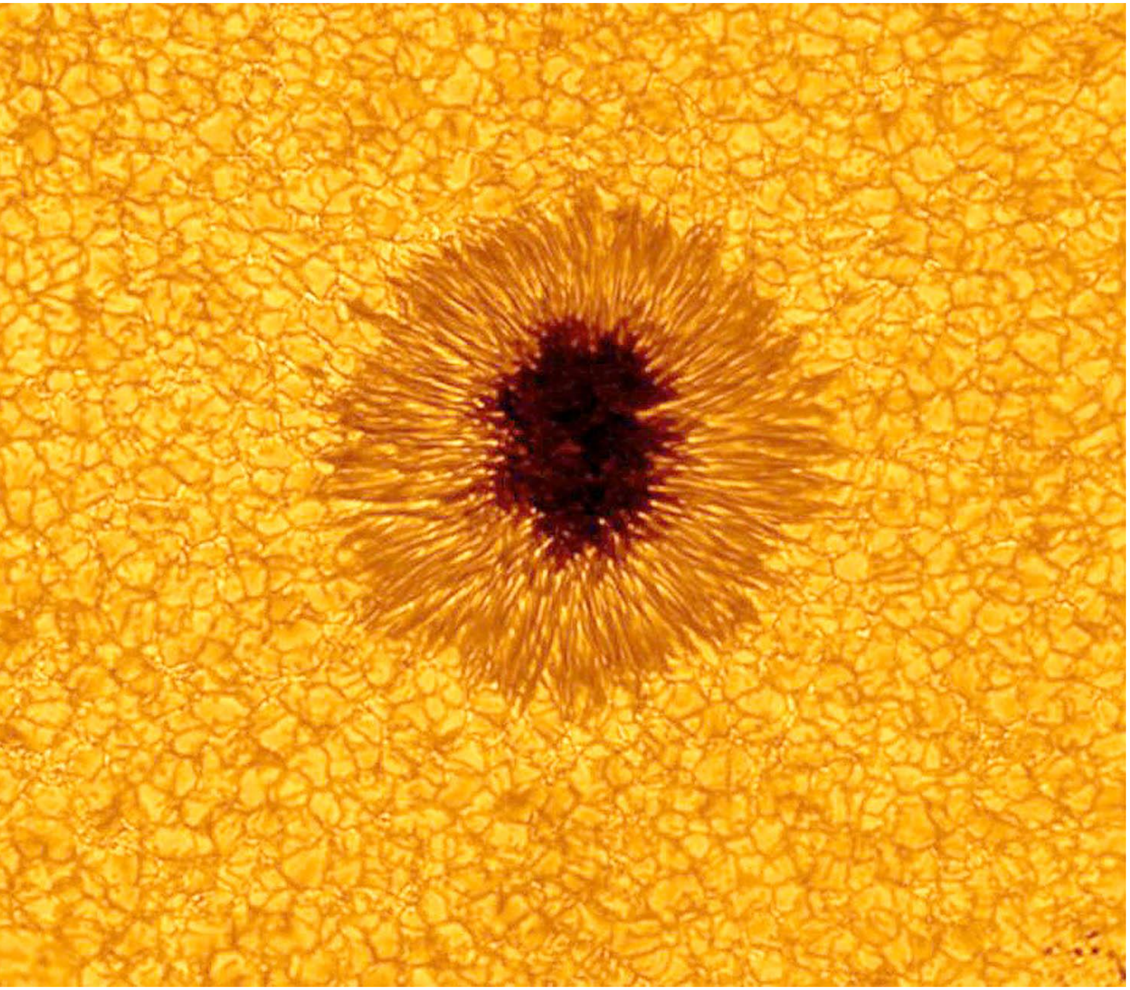


- Granules are about 1000km diameter and last for about 10 minutes.
- Between granules you have the intergranular lanes which are made out of colder plasma, hence they appear darker.
- Inside the granules the plasma rises with about 1 km/s.

Sunspots

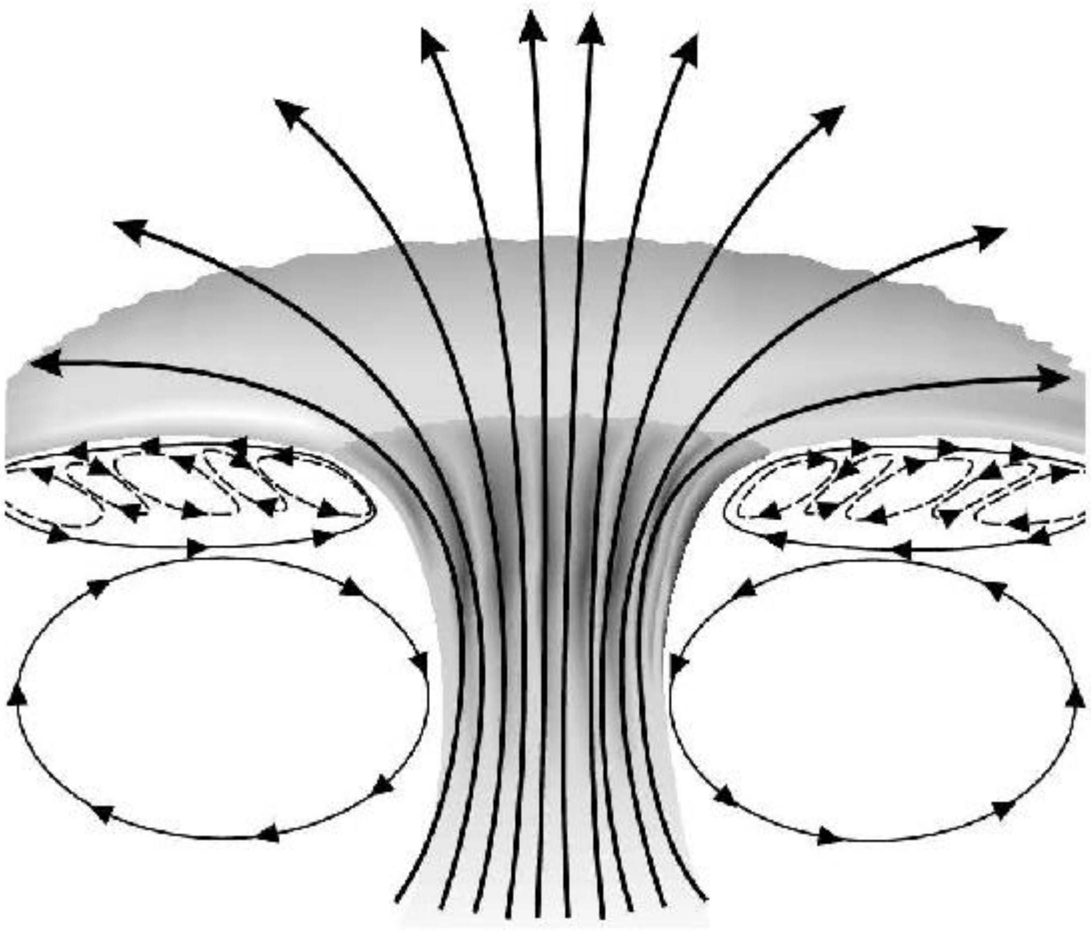


Sunspot



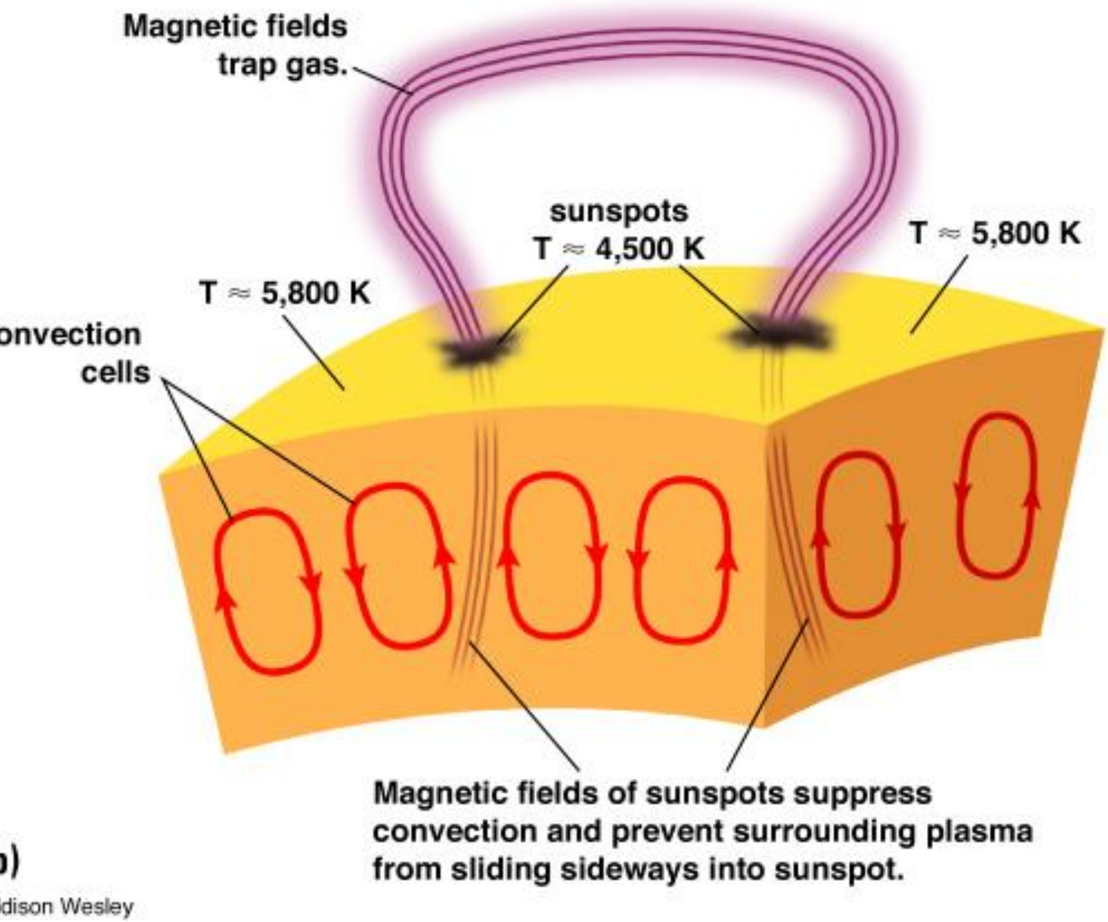
- Sunspots have two regions, the dark, inner region called umbra and the only slightly darker region called the penumbra.
- The umbra is characterized by relatively cold plasma of about 4000K, and strong magnetic fields (about 1000 times the normal photospheric field)
- Typical life times are several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

Convection associated with sunspot



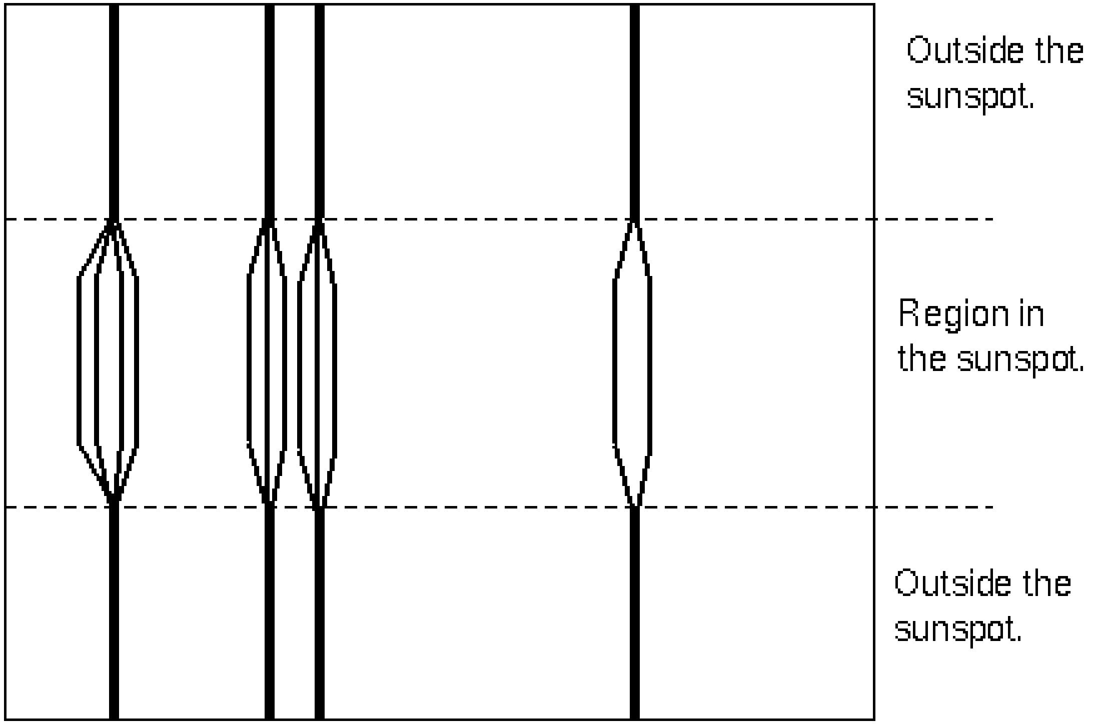
- At the center of teh sunspot (umbra), the magnetic field is nearly vertical.
- The plasma is frozen to the magnetic field, so it cannot moves sideways at the surface but just sits there and cools.
- The magnetic field is more inclined in the penumbra, allowing some convection movement, hence it is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

The inside of a sunspot



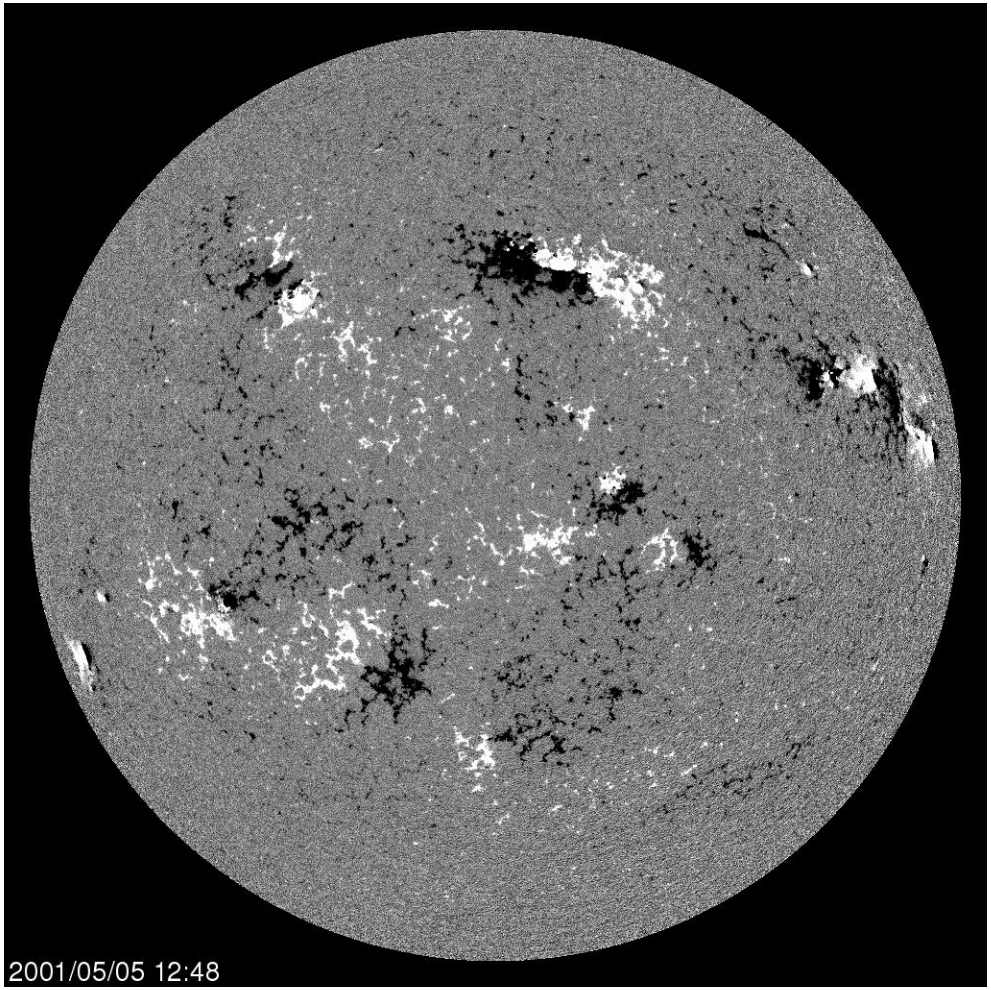
- Sunspots usually appear in pairs with opposite magnetic polarity.
- With the help of spectroscopy you can measure the magnetic field inside the sunspot.

Zeeman effect

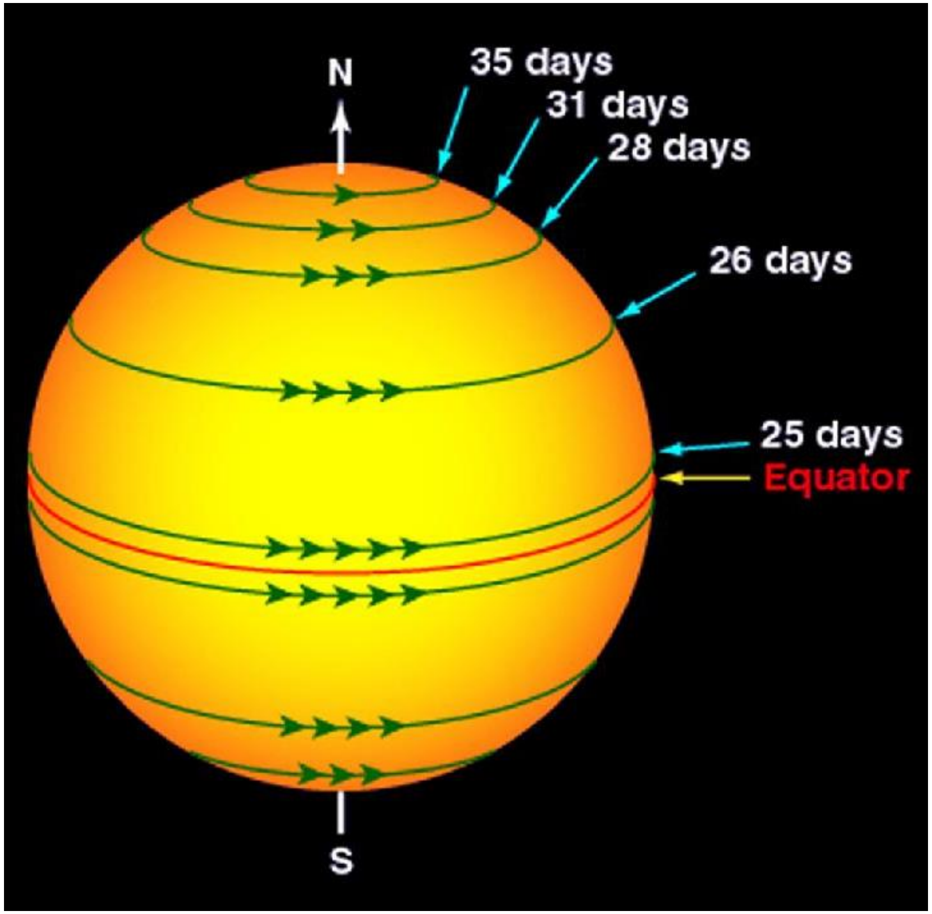


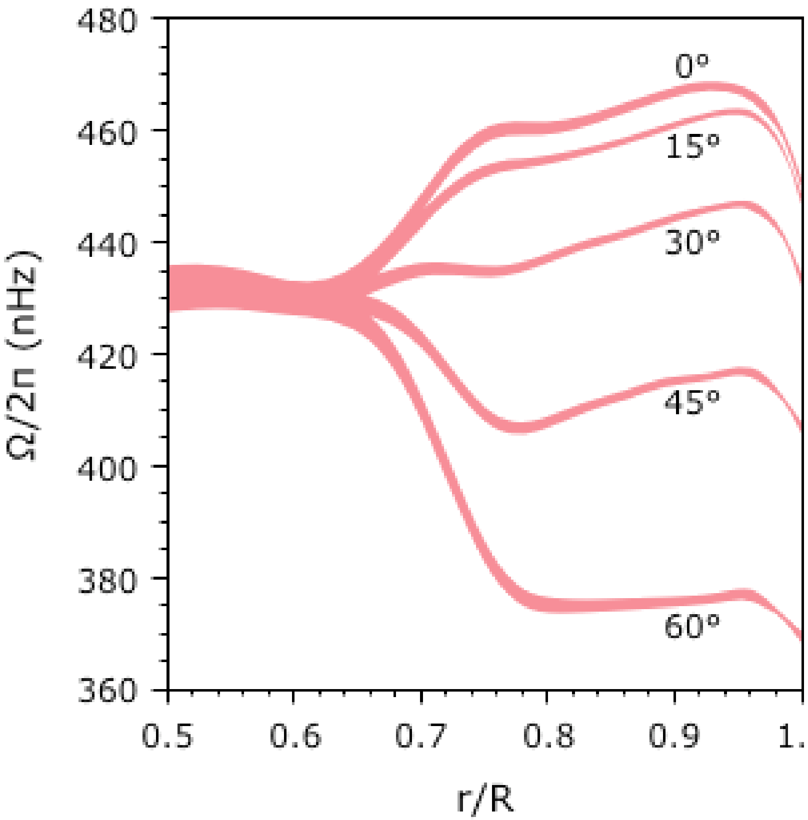
The Zeeman effect: a strong magnetic field splits the spectral lines into two or more components. The strength of the magnetic field can be measured from the amount of separation of the components. Sunspots are regions of strong magnetic fields.

Solar magnetogram

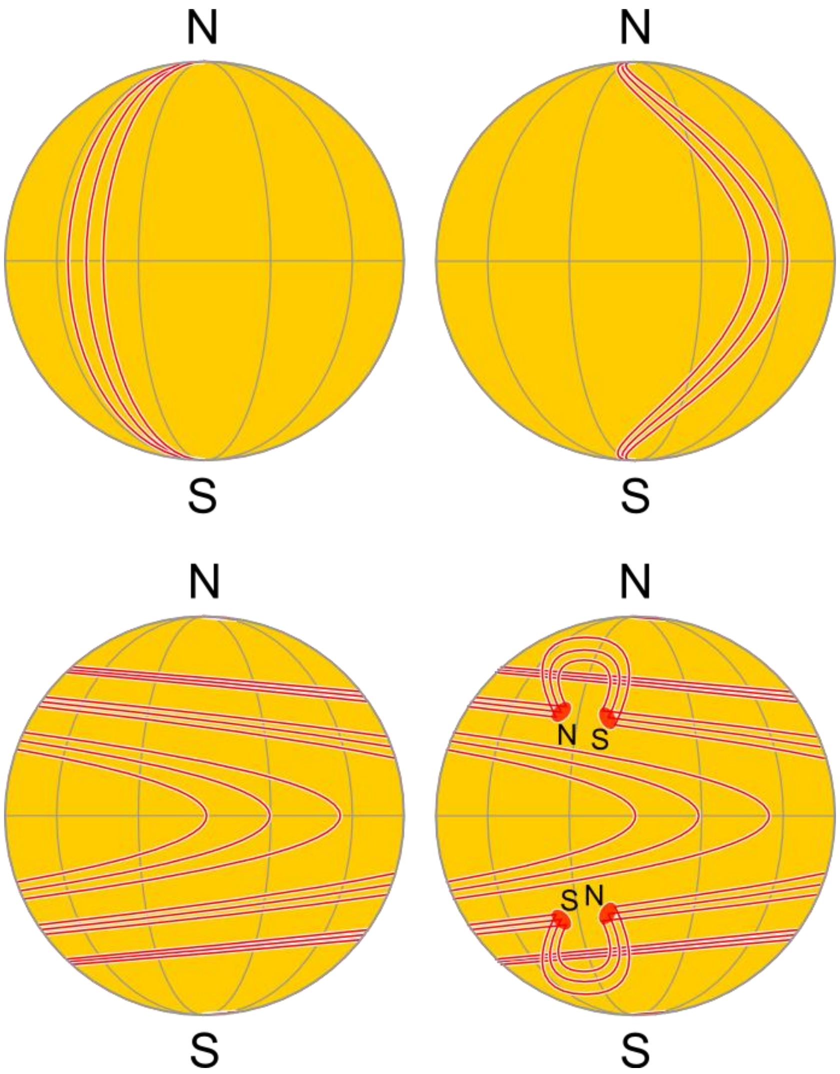


Differential rotation



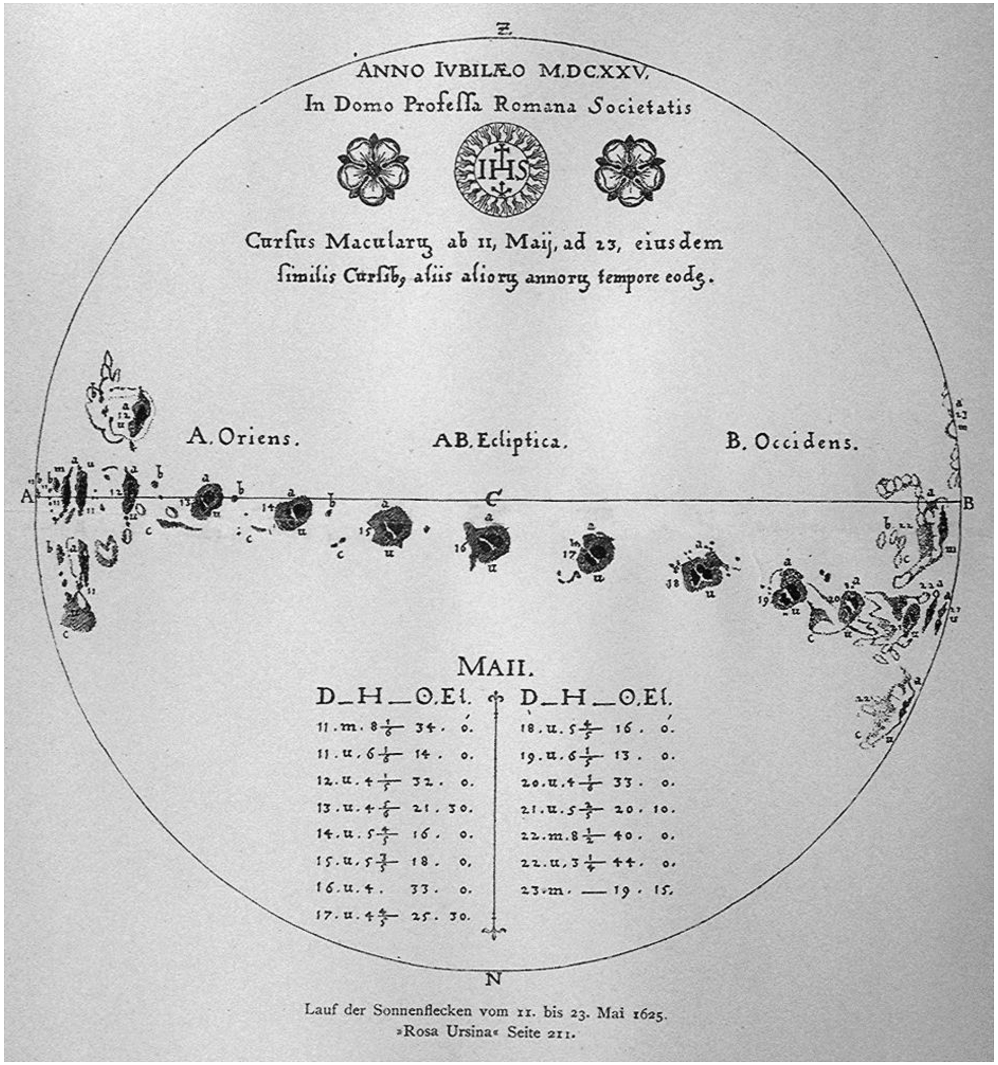


Formation of sunspots



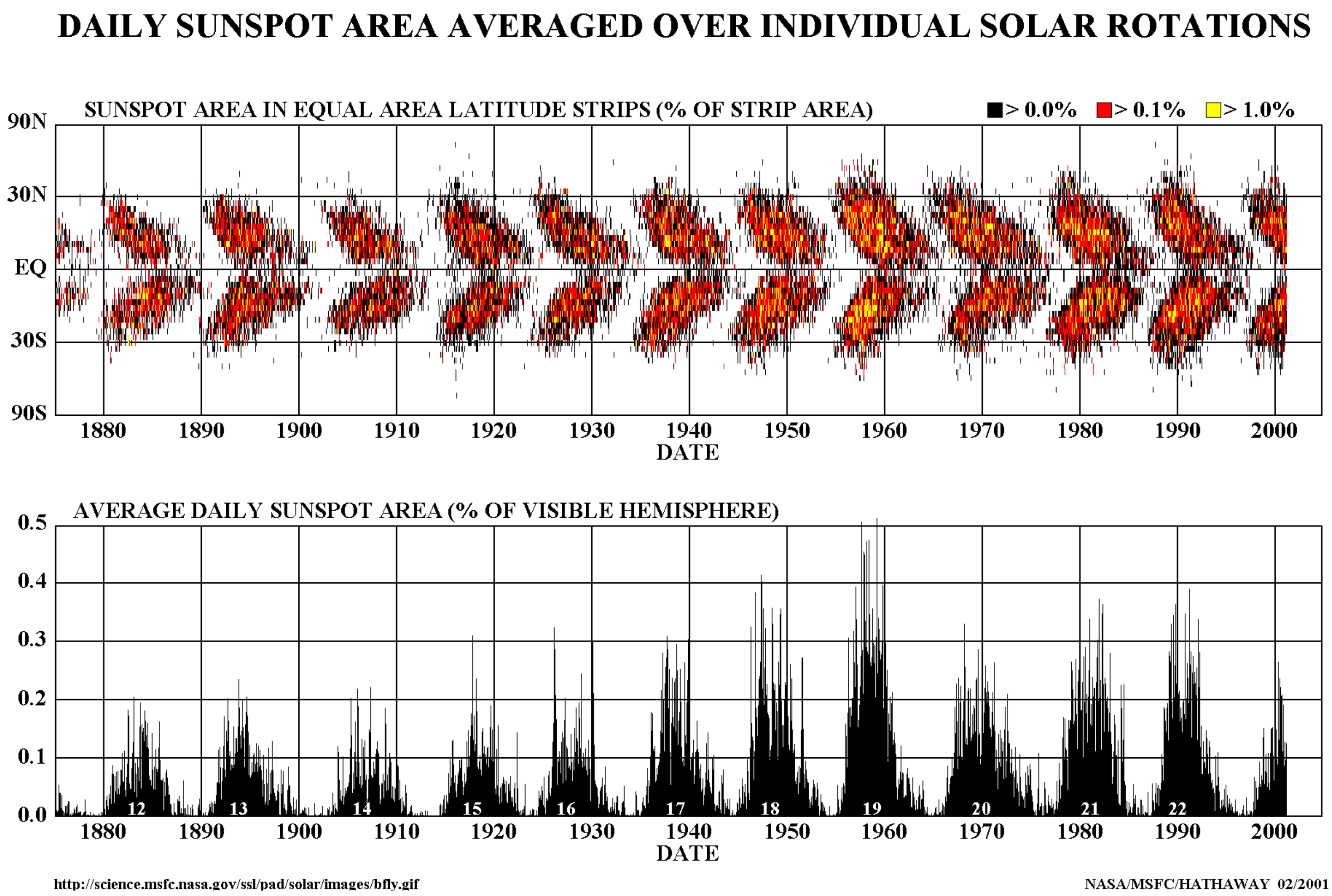
- The velocity shear at the radiative zone/convection zone boundary creates the solar magnetic field.
- The differential rotation of the convection zone «winds up» the magnetic field lines over time.
- At some point, the magnetic field rises through the convection zone (it bubbles up) and breaks through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

First sunspot observations

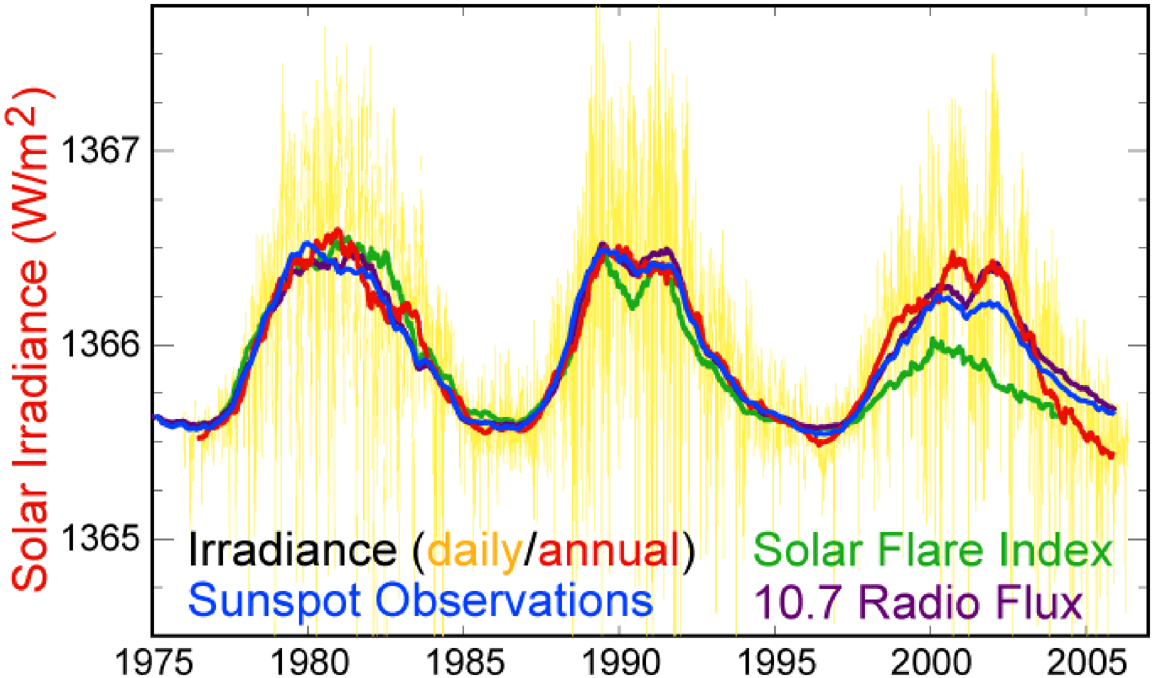


- In 1610, shortly after viewing the sun with his new telescope, Galileo Galilei (or was it Thomas Harriot?) made the first European observations of Sunspots.
- Christoph Scheiner (1573-1650), a Jesuit mathematician began his study of spots in 1611
- Scheiner, wished to preserve the perfection of the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

Butterfly diagram

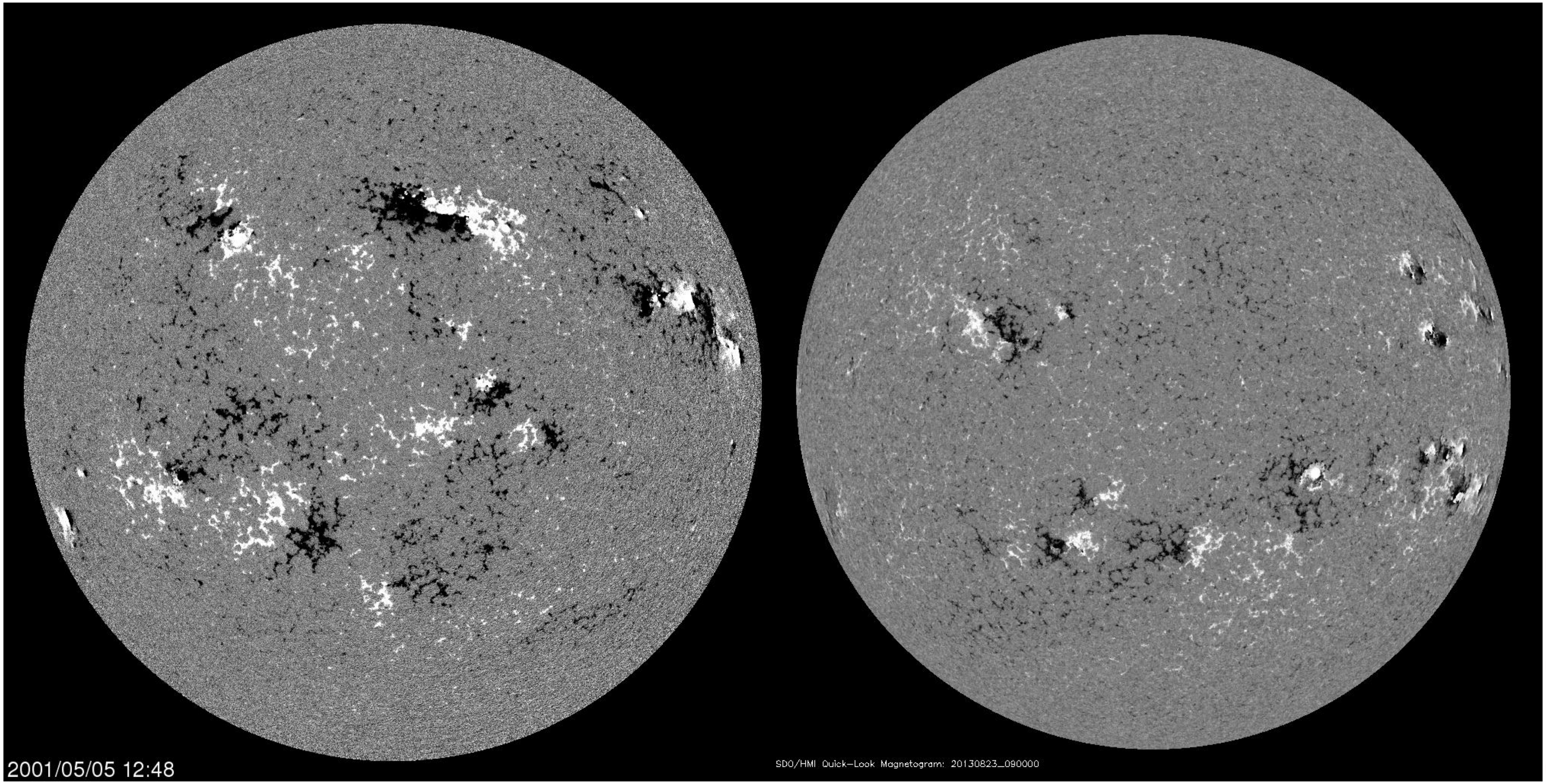


Solar cycle variations

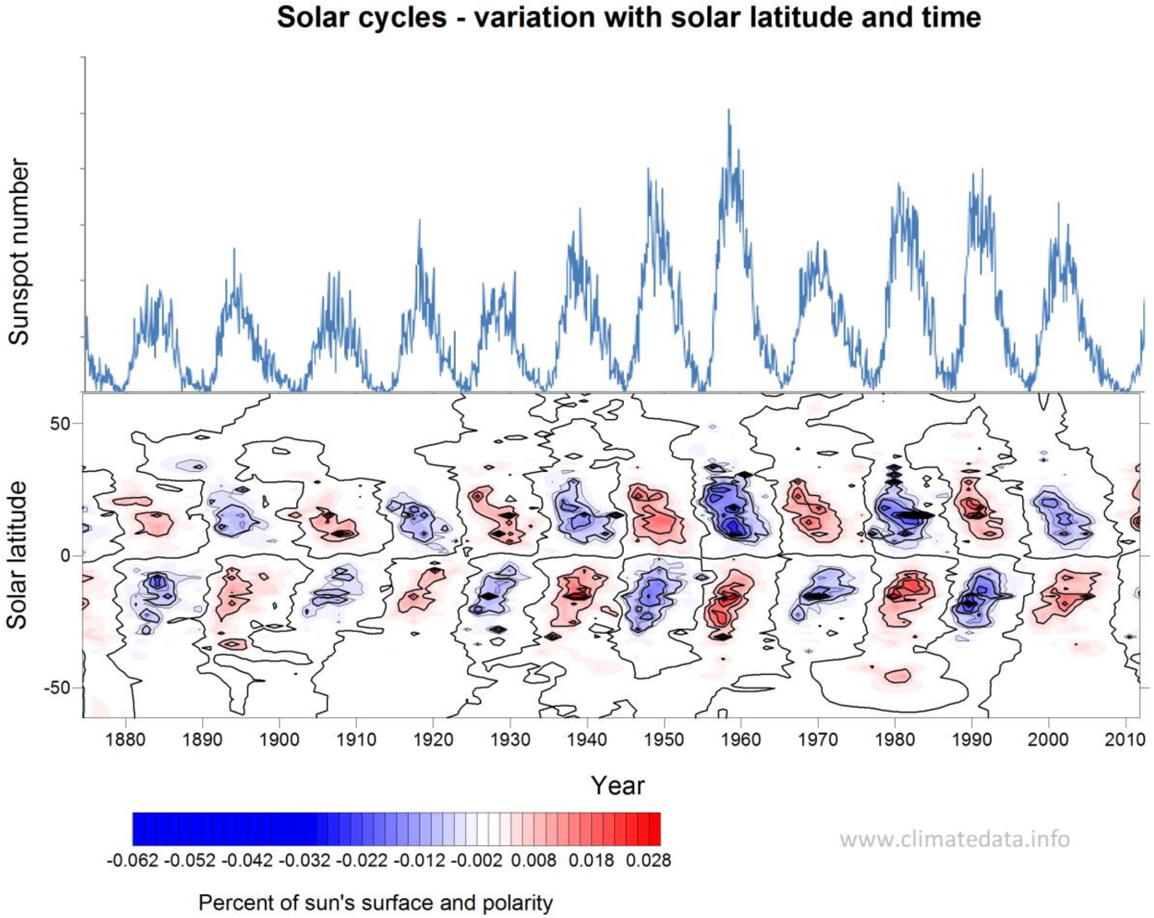


- Not only the number of sunspots varies, but also other solar parameters like
  - The total irradiance («solar constant»)
  - The number of flares
  - The amount of electromagnetic radiation emitted in the UHF radio band (at 2800 MHz)

Leading sunspot polarity

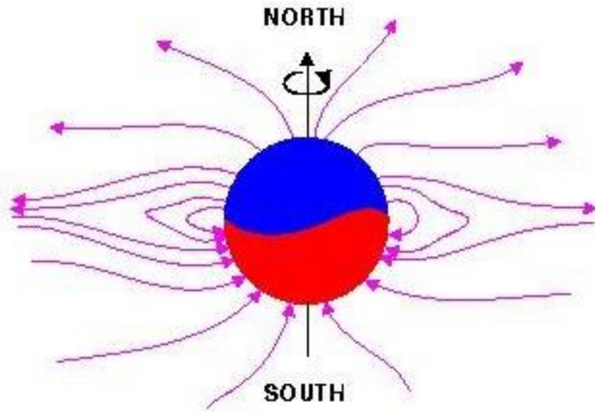


22-year cycle

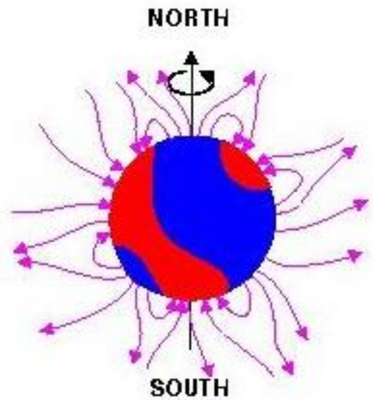


- The leading polarity of sunspot pairs changes between solar cycles – known as Hale’s Polarity Law.
- The change occurs during solar minimum.
- The polar magnetic field of the Sun changes at solar maximum, is hence out of phase with the sunspot magnetic fields.

Change of polar solar magnetic field

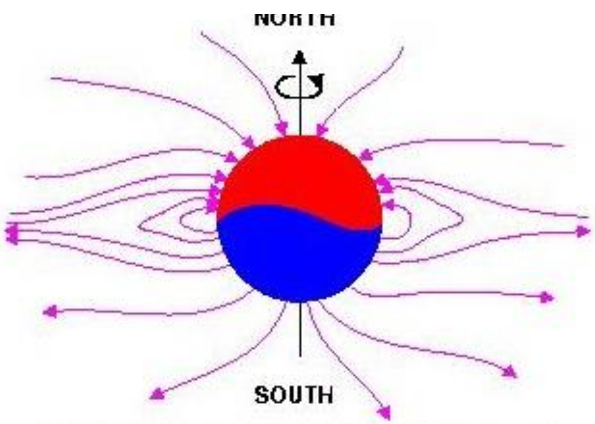


CORONAL MAGNETIC FIELD LINES AT SOLAR MINIMUM ACTIVITY



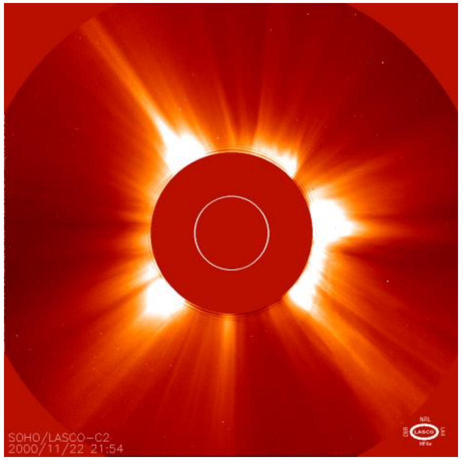
CORONAL MAGNETIC FIELD LINES AT SOLAR MAXIMUM ACTIVITY

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



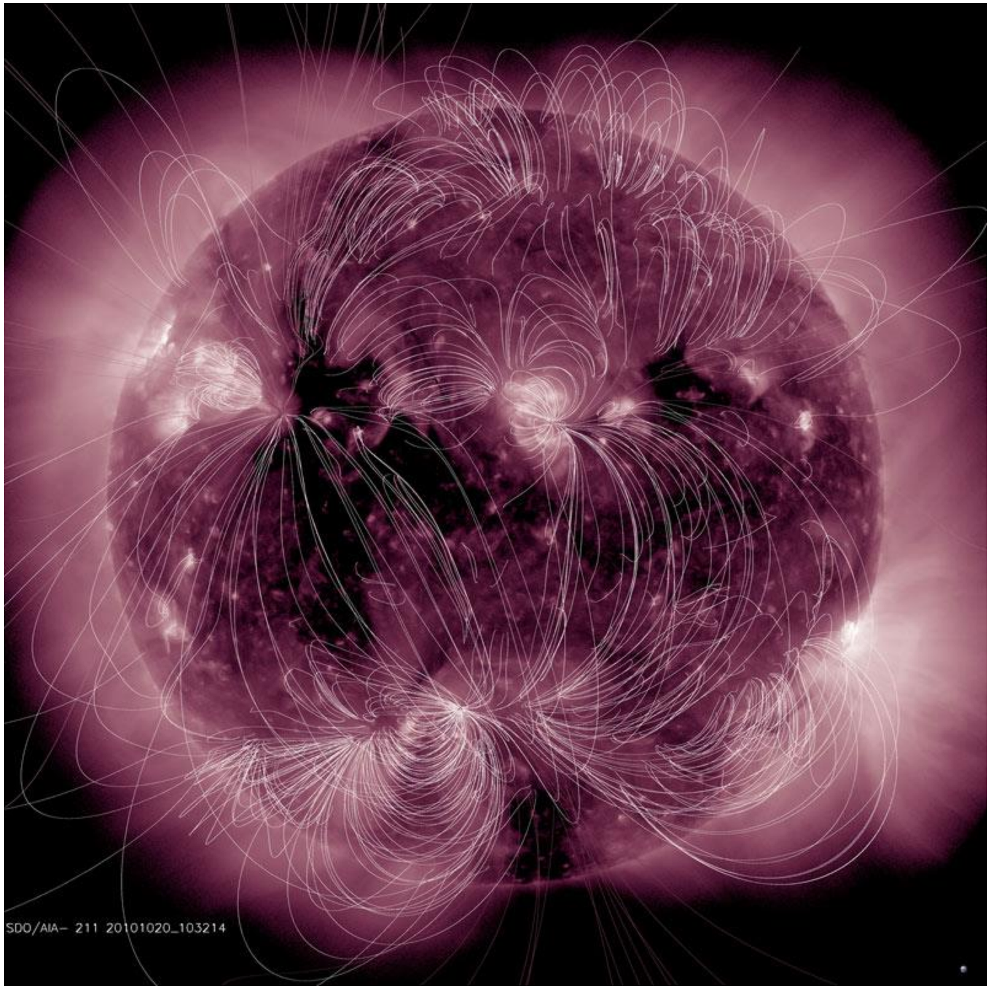
CORONAL MAGNETIC FIELD LINES AT NEXT SOLAR MINIMUM

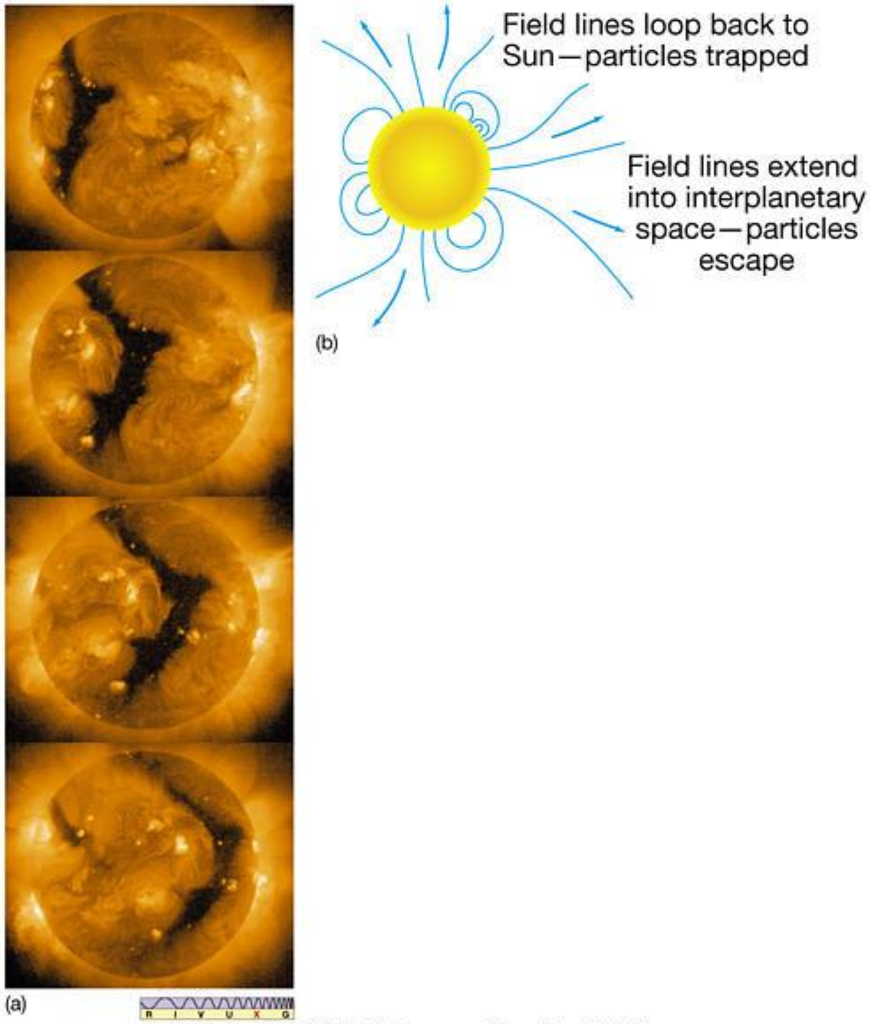
1995

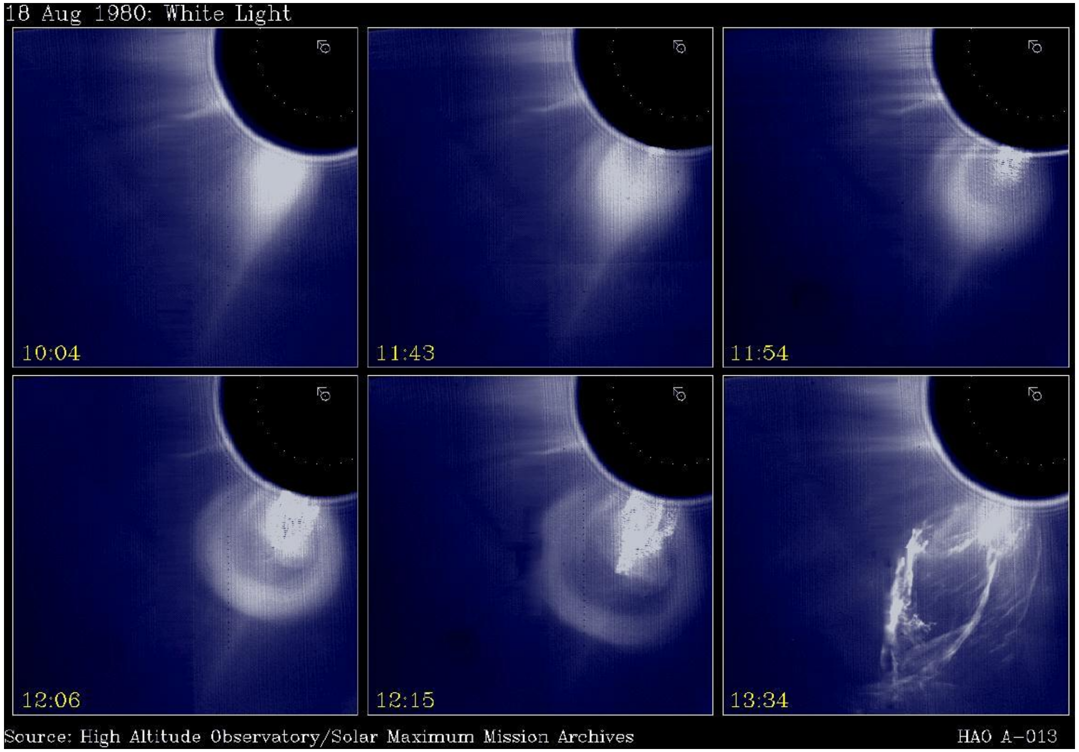


2000

Coronal holes







- 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

Current solar cycle