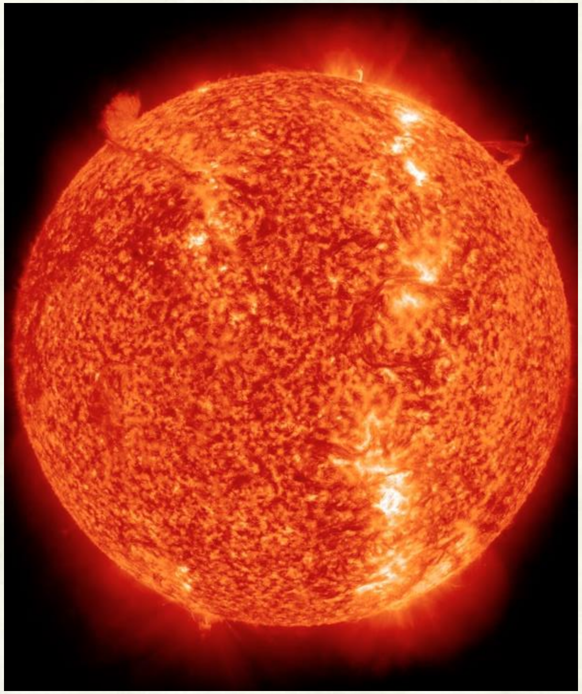
The Sun

ASTR 101
11/14/2018

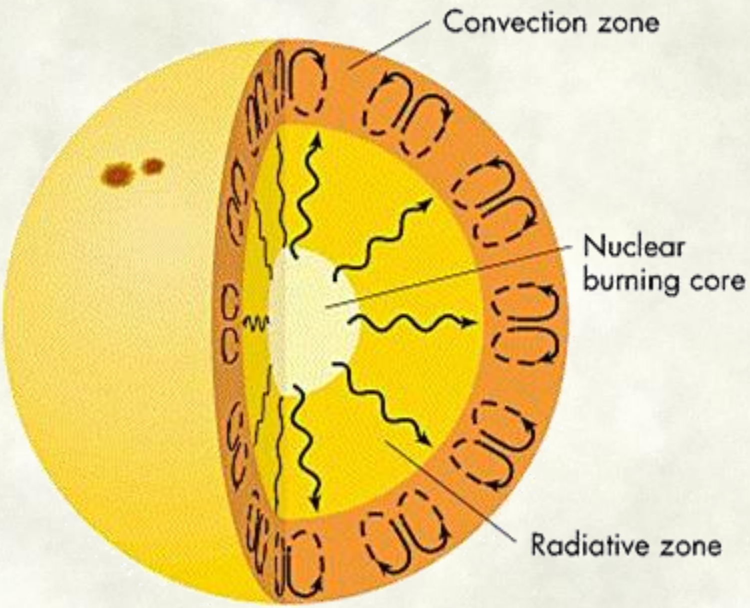
- Radius: 700,000 km (110 $R_{\oplus}$)
- Mass: 2.0×10^{30} kg (330,000 $M_{\oplus}$)
- Density: 1400 kg/m^3
- Rotation: Differential, about 25 days at equator, 30 days at poles.
- Surface temperature: 5800 K
- Total luminosity is about 4×10^{26} W
  - Solar constant—amount of Sun's energy reaching Earth—is 1400 W/m^2 (Solar constant).

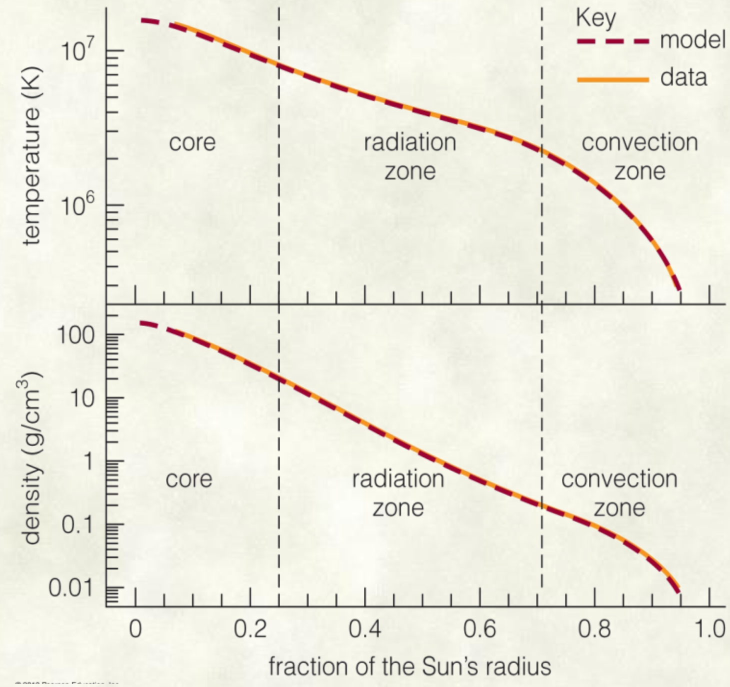
Sun is the nearest star, and is the only star whose surface we can study.

The sun is the source of almost all energy on the earth which life depends on.



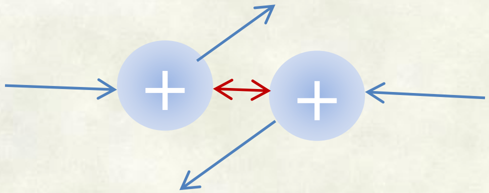
Structure of the Sun



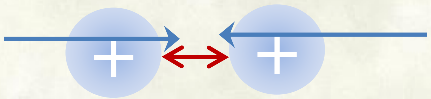


Interior of the Sun can be divided in to several layers:

- **Core:** extending from the Sun's center to about 0.25 solar radius 170,000km.
- Temperature of the core is about 15 million K, well above the temperature needed for hydrogen fusion to take place.



Electrical repulsion between two positively charged hydrogen nuclei keep them apart at lower temperatures.



At temperature above 10 MK, H nuclei have enough thermal energy (speed) to overcome the electrical repulsion and come sufficiently close to each other to undergo nuclear interactions.

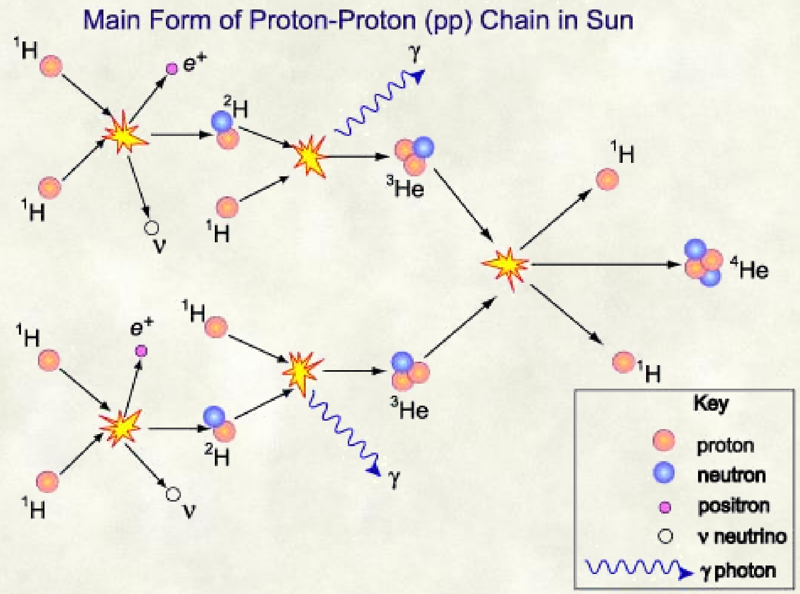
- It becomes hottest near the center (core) where much of the mass is collected.
- When the core temperature is above 10 million K, hydrogen nuclei (protons) are moving fast enough to overcome the electrical repulsion between them and combine together.

$$H + H + H + H \rightarrow He$$

The Proton-Proton Chain

four hydrogen nuclei combine to form a Helium nucleus releasing some energy.

$^1H_1 + {}^1H_1 + {}^1H_1 + {}^1H_1 \rightarrow {}^4He_2$ + energy



$^4He_2$ nucleus is slightly lighter than four $^1H_1$ nuclei

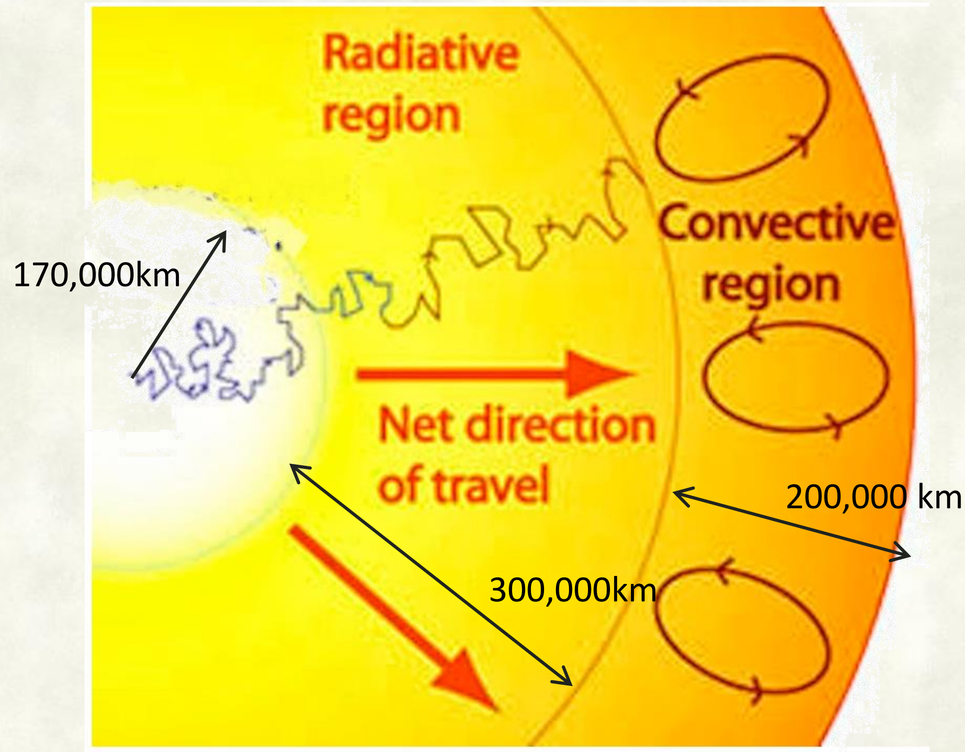
mass of 4 hydrogen nuclei = 6.693×10^{-27} kg,
mass of a Helium (^4He) nucleus = 6.645×10^{-27} kg

Difference in mass = 0.048×10^{-27} kg, 0.7%,

lost mass is converted to energy according to $E=mc^2$

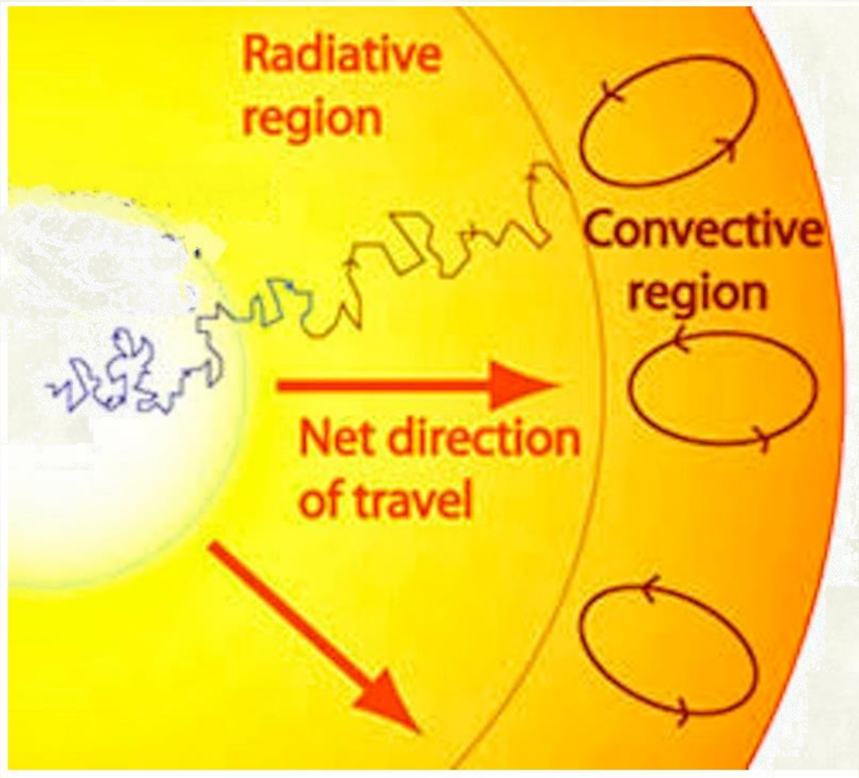
- 600 million tons of hydrogen turn into 596 million tons of helium in the sun's ore. 4 million tons/sec turned into energy, 4×10^{26} W. (.7% of mass becomes energy)

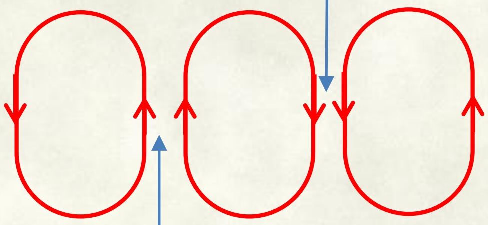
The Radiative Zone



- The core is surrounded by a radiative zone extending to about 0.7 solar radius.
  - In this zone only mechanism energy can travel outward is through radiative diffusion (conditions are not favorable for convection).
  - In the deep interior, the stellar material is very opaque
    - Radiation travels only a small distance before it is absorbed.
    - It is then re-emitted in a random direction
    - and so on until it reaches the surface, which takes about hundred thousand years.

The Convection zone

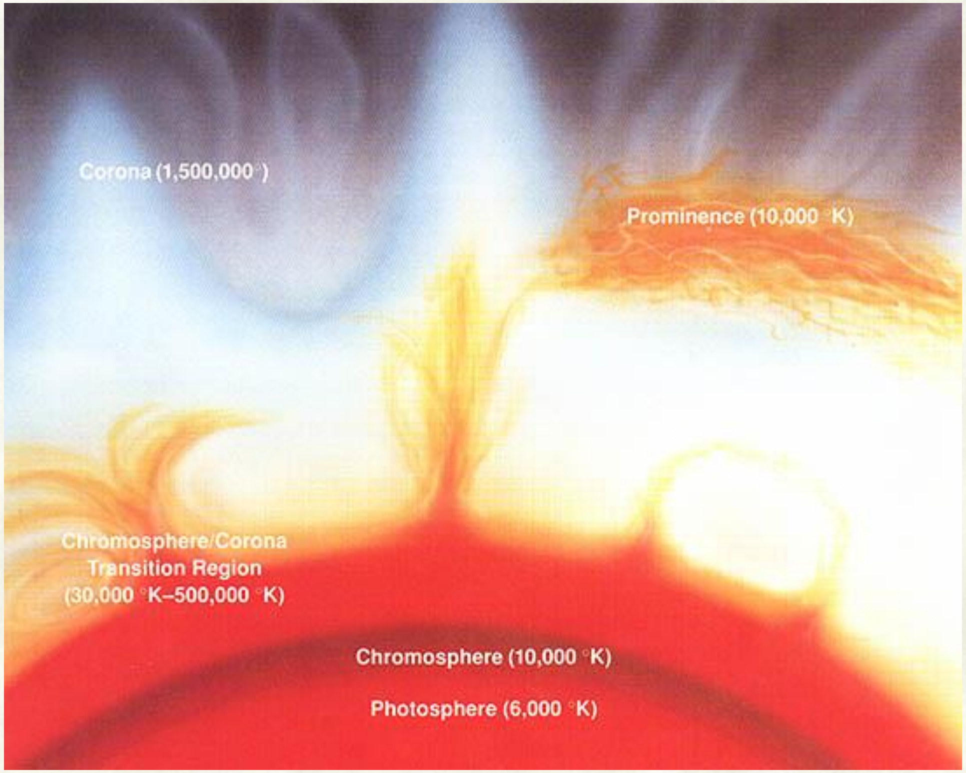


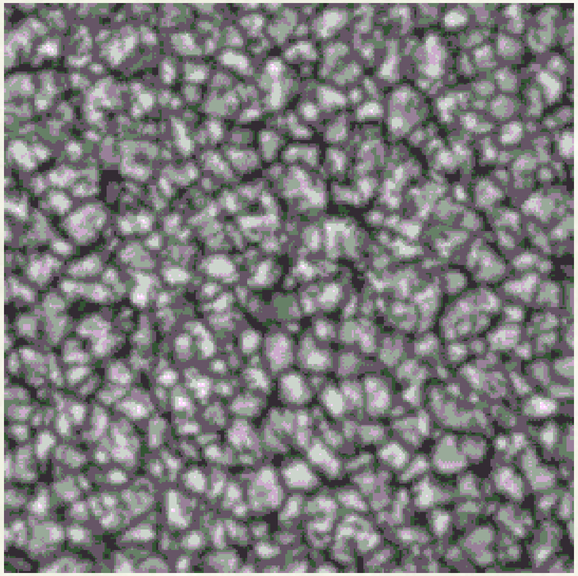


The radiative zone is surrounded by a rather opaque convective zone

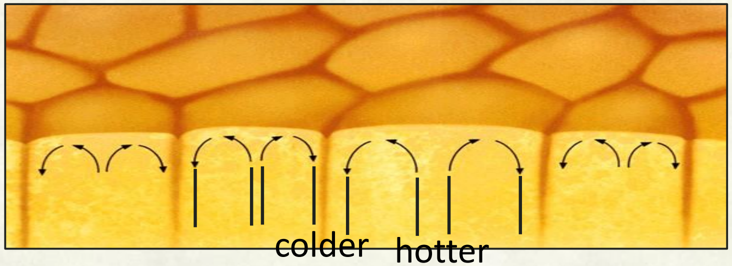
- gas at relatively low temperature and pressure.
- In this zone, conditions are favorable for convection, so energy travels outward primarily through convection.

Solar Atmosphere





A fast motion image of the photosphere

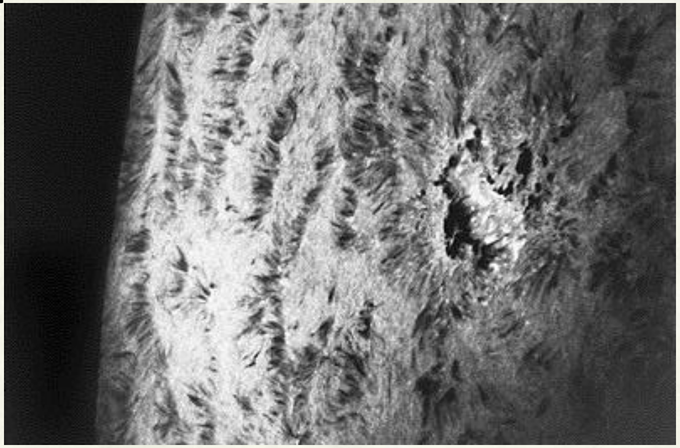


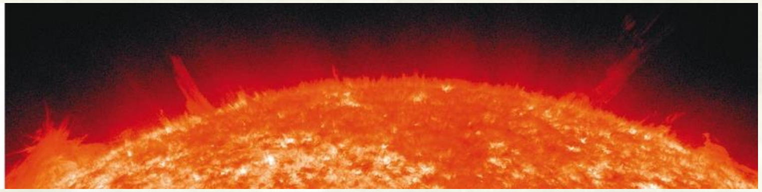
- The Sun's atmosphere has three main layers
- **Photosphere:**
  - The lowest layer in the solar atmosphere, just above the convection zone.
  - It is transparent, so light can escape without further absorption and scattering.

Photosphere is the visible surface of the Sun.

  - Photosphere appears granular, due to the convection cells in the photosphere(1000-2000 km in size).
  - Areas of upwelling hot material looks brighter, they are surrounded by areas of sinking colder darker looking material.

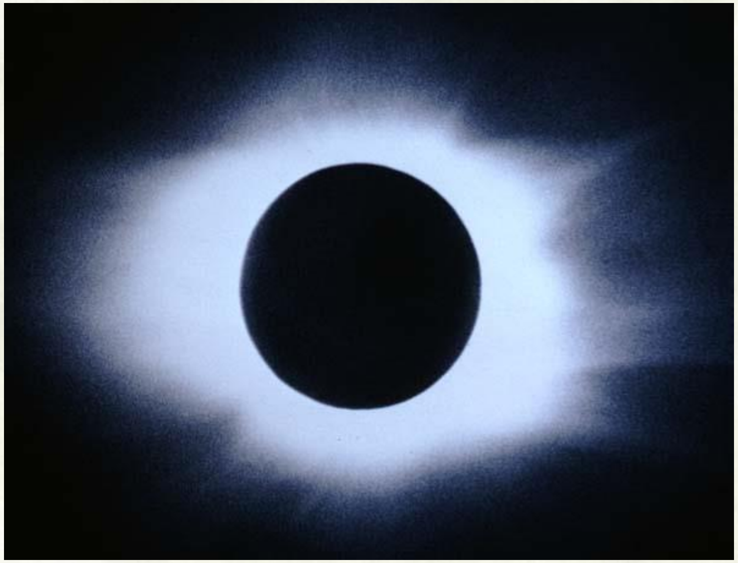
The Chromosphere

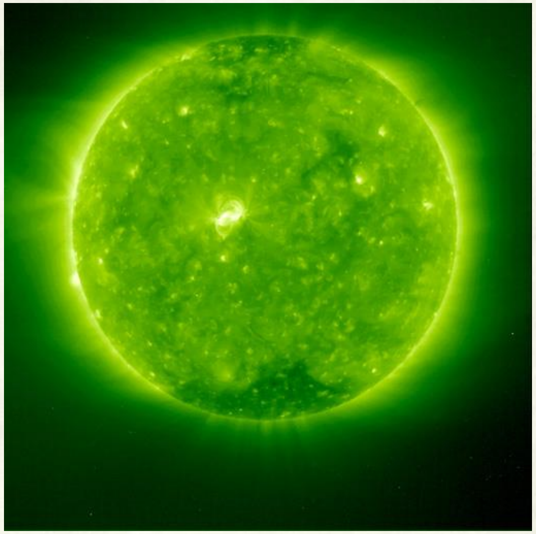




- Above the photosphere is a layer of less dense but higher temperature gases called the chromosphere. Spicules extend upward from the photosphere
- The chromosphere is 2000-3000 km thick.
  - It glows faintly relative to the photosphere, so difficult to see directly,
  - Visible during a solar eclipse.
  - Small solar storms in the chromosphere emits spikes of gas called *spicules,* that rise through it.

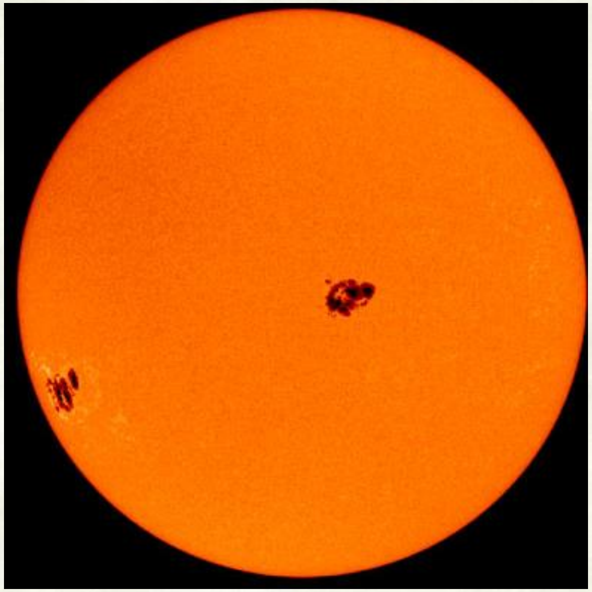
The Corona

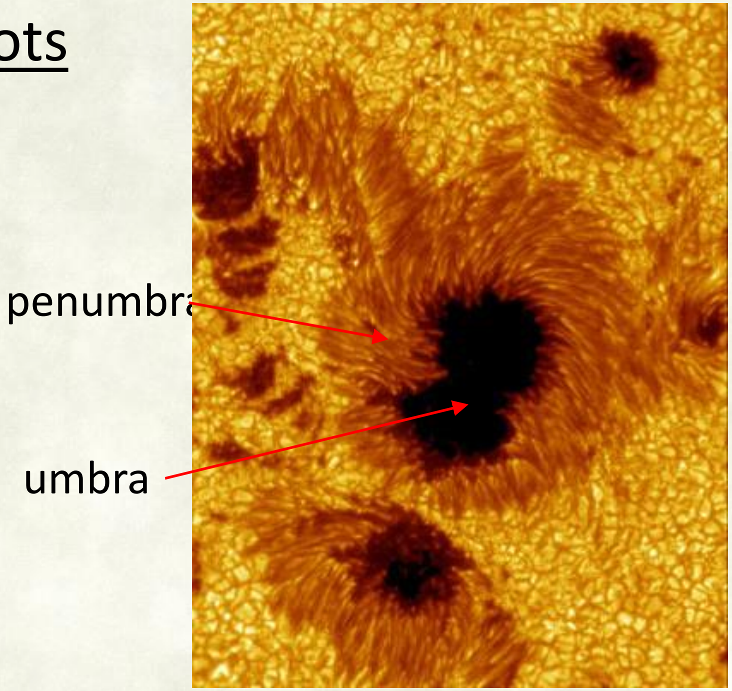


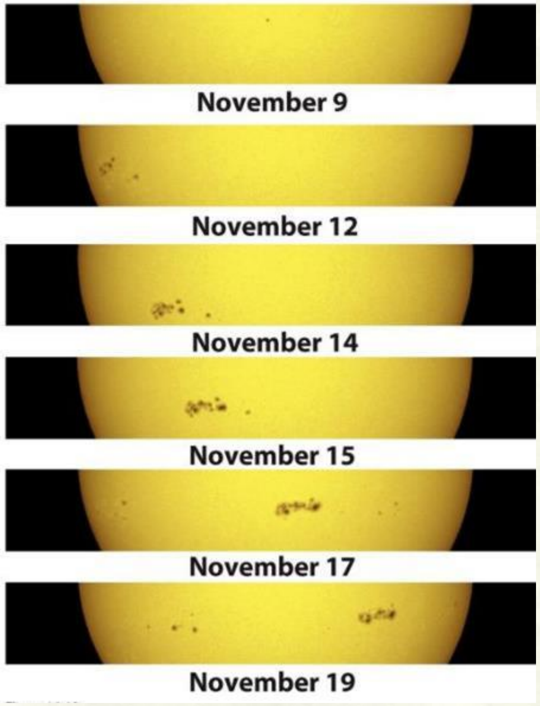


- The outermost layer of the solar atmosphere, the corona, is made of very high-temperature gases at extremely low density.
- It is faint, directly visible only during eclipses.
- Its temperature is very high 1- million K. So most of the elements in the corona is highly ionized.
- Fast-moving ions can escape the Sun's gravitational attraction.
  - Moving outward at hundreds of kilometers/second,
  - Those charged ions escaping the sun and travel outward are called the **solar wind**.
  - They travel to the farthest reaches of the solar system

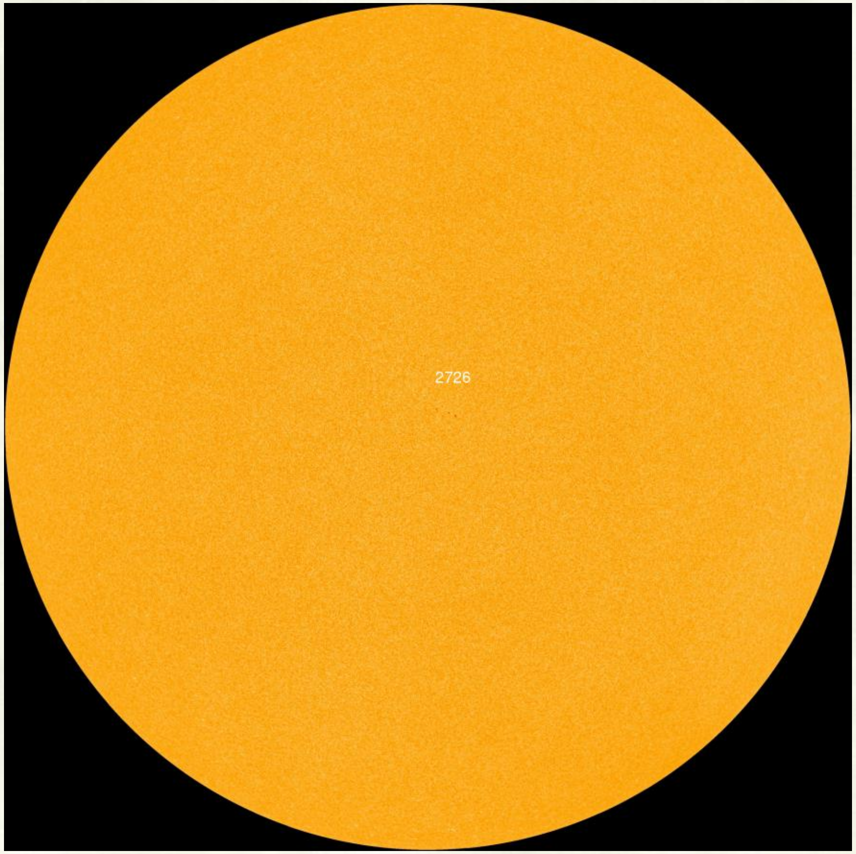
Sun Spots





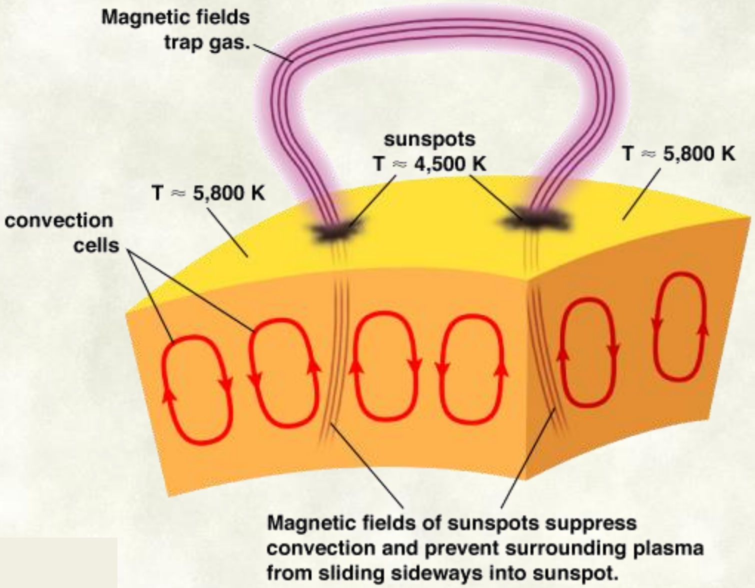


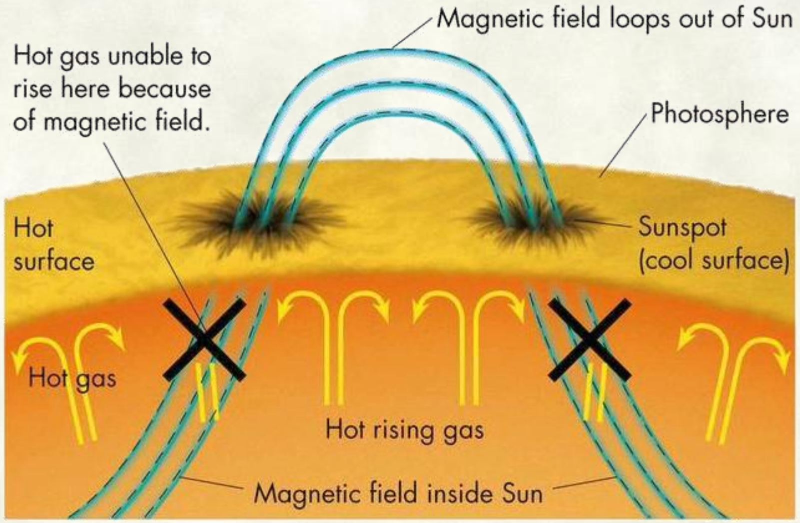
- Dark features on the sun’s photosphere.
  - They appear dark because slightly cooler than the surroundings. (4000 K, compared with 5700 K for the surroundings).
- Sun spots can be as large as 50,000 km, and often appear as groups.
  - They develop and persist for periods ranging from hours to months, and are carried around the surface of the Sun by its rotation .
- A typical sunspot consists of a dark central region called the *umbra* and somewhat lighter surrounding region called the *penumbra*



The Sun today (11/14)

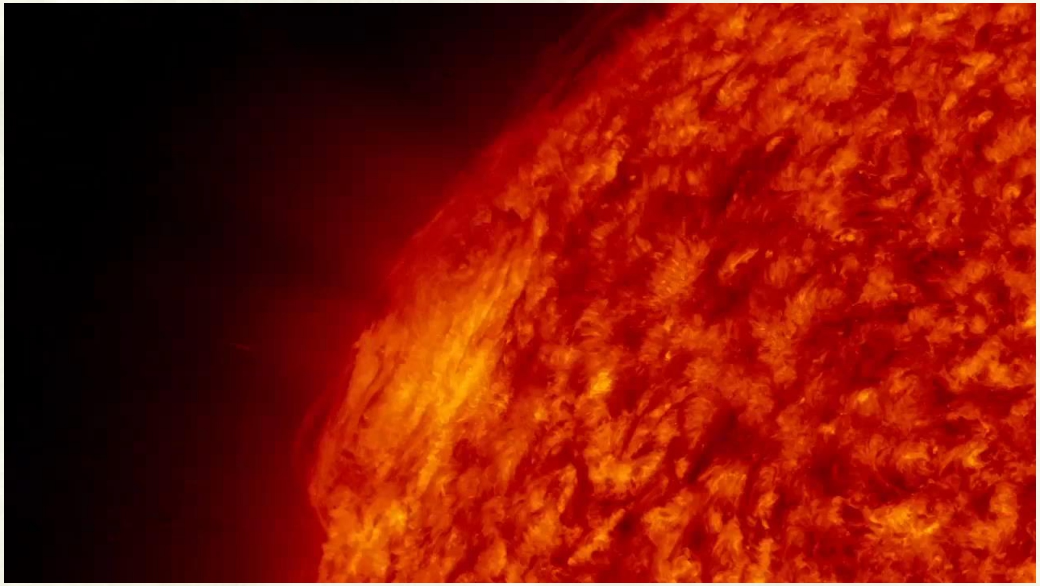
from: http://www.spaceweather.com





- Sunspots are produced by local concentrations of the Sun's magnetic field, in the form of loops.
  - Since solar material is highly ionized plasma, the magnetic fields exert forces on them.
  - This influence the convective motion beneath the photosphere.
  - That hinder the convection of heat to the surface by making it harder for the hot gases to rise.
  - Thus, the region where there are strong magnetic fields tends to be cooler than the surrounding region and thus appears darker than the surrounding regions at higher temperature.
- Because sunspots are magnetic, they occur in pairs where one is a north pole while the other is a south pole.

Solar prominences

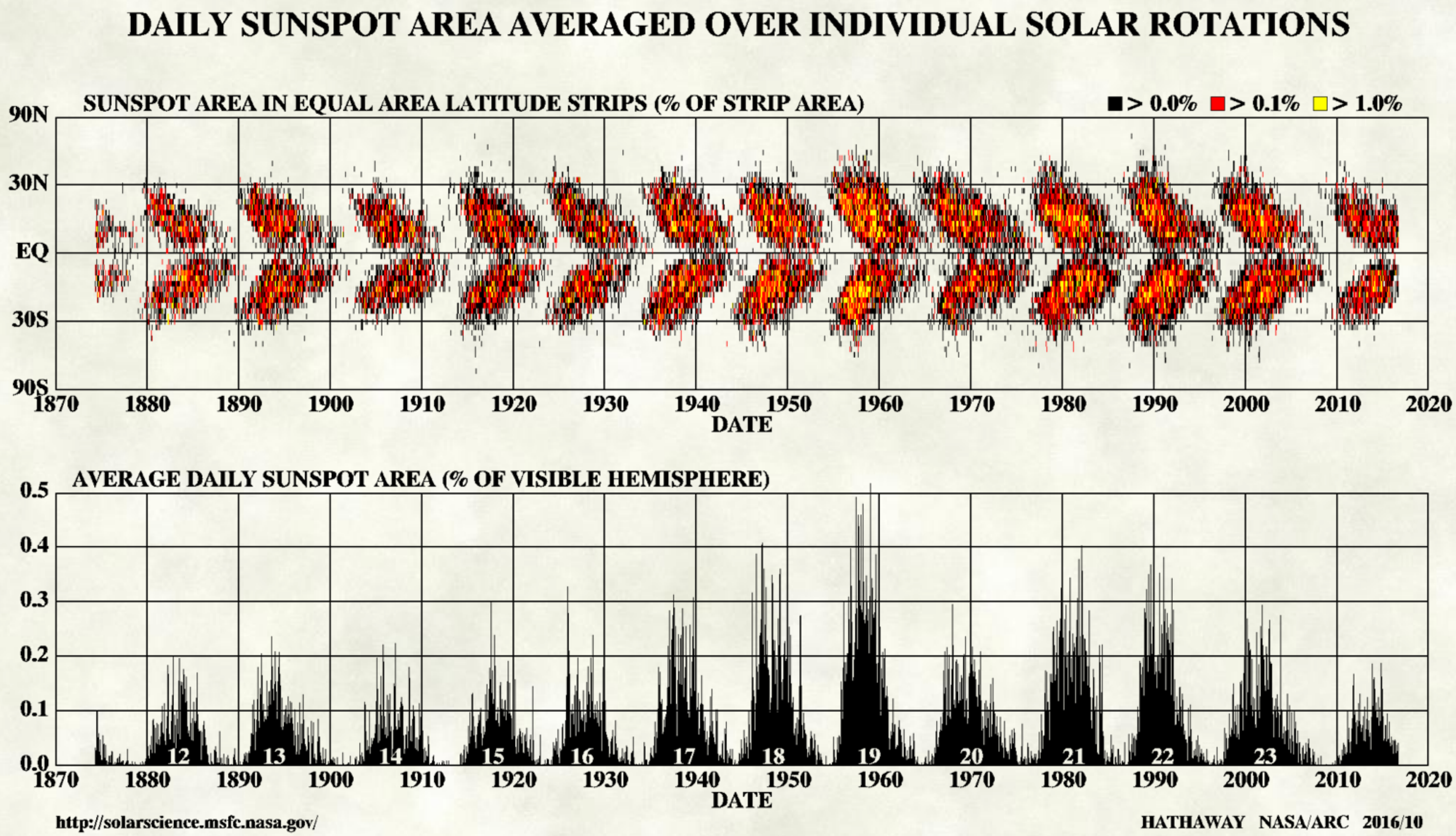
http://science.nasa.gov/science-news/science-at-nasa/2010/21apr_firstlight

- Areas around sunspots are active, large eruptions may occur in photosphere
- prominences are clouds of gas that erupt from disturbed regions near sunspots, extending outward from the Sun's surface, often in a loop shape.
- The sun's magnetic field can hold them in place for days.

The Solar Cycle

Latitude of sunspots

number of sunspots



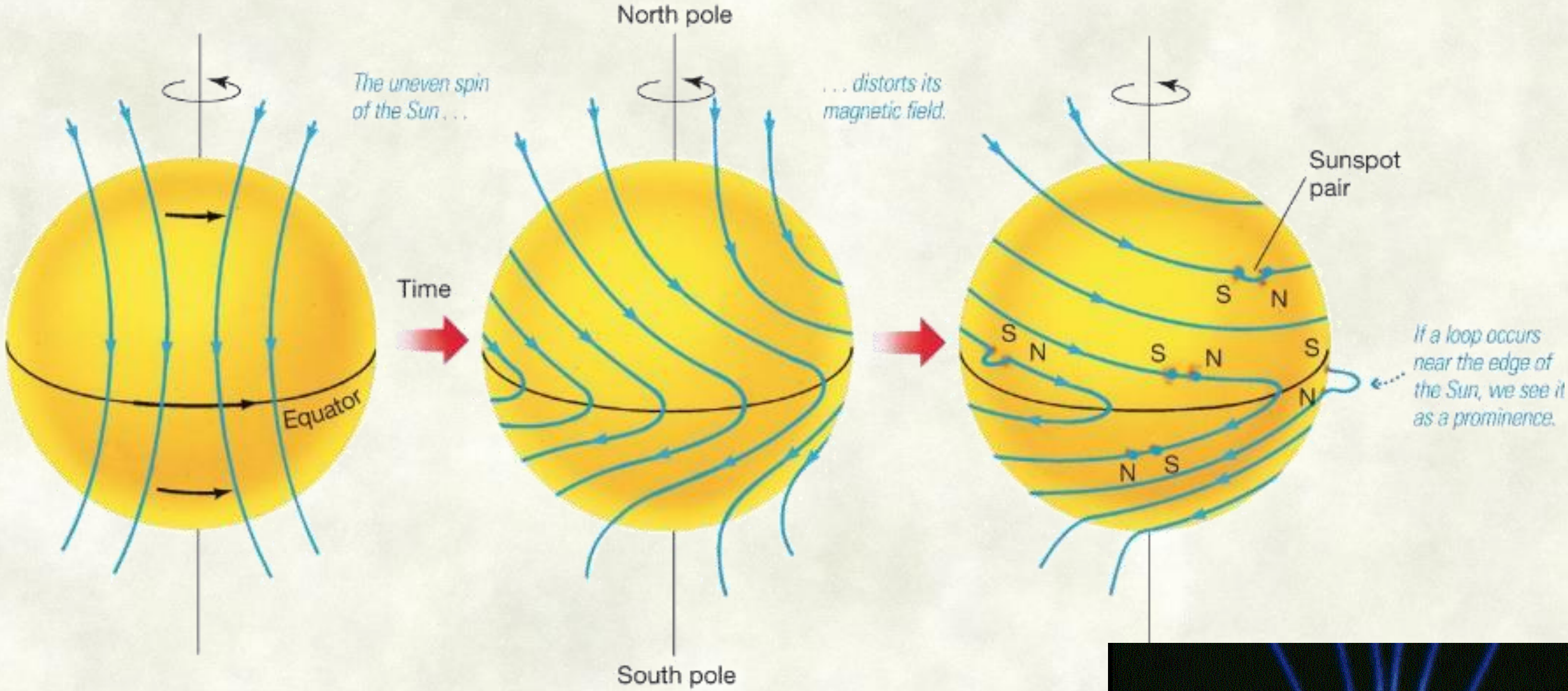
Butterfly diagram.

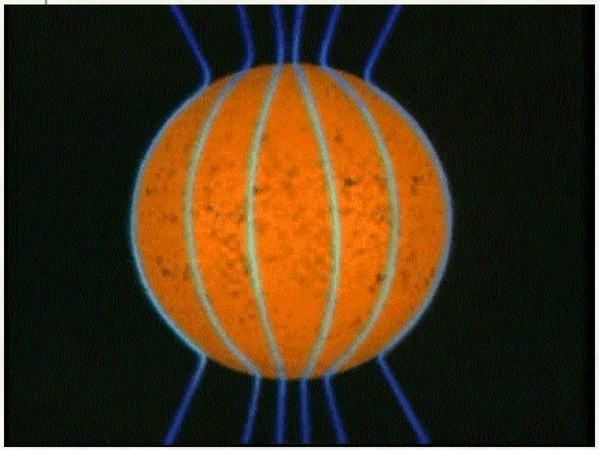
- The number of sunspots varies over an 11-year period.
  - Number of sunspots rises from ‘solar minimum’ to ‘solar maximum’, the numbers of flares and prominences also rise.
  - Sunspots tend to emerge over a range of higher latitudes after a solar minimum and later as the cycle progress, toward the solar equator.

Formation of magnetic loops and the solar cycle

slower

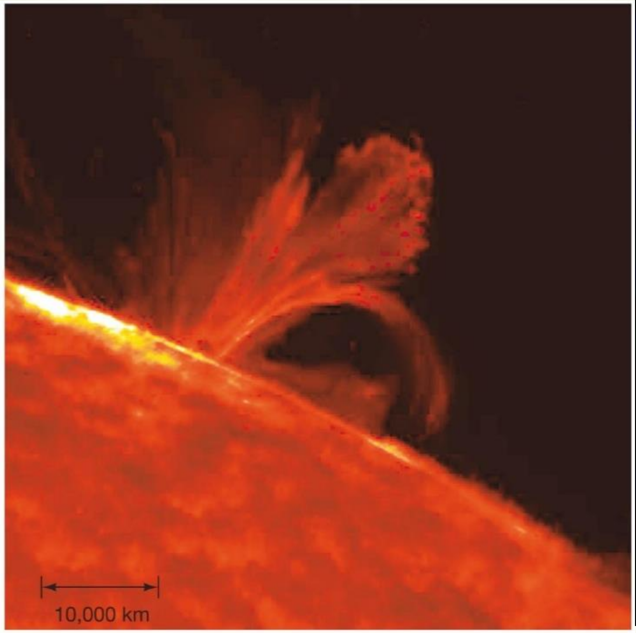
faster

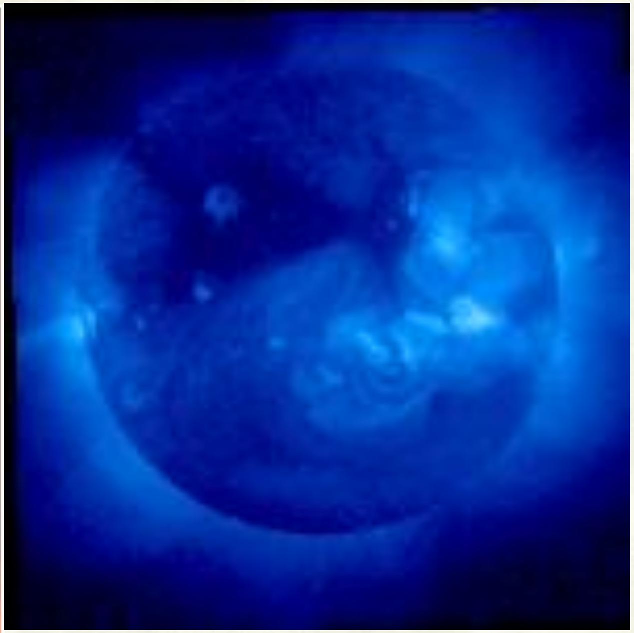


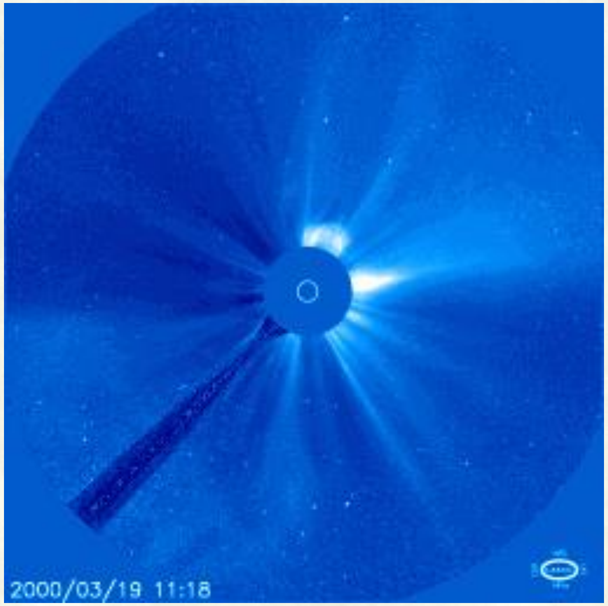


- Magnetic loops on the sun surface which create sunspots are formed when the Sun's differential rotation wraps and distorts the solar magnetic field.
- Occasionally, the field lines burst out of the surface and loop through the lower atmosphere, thereby creating a sunspot pair.

Solar Flares

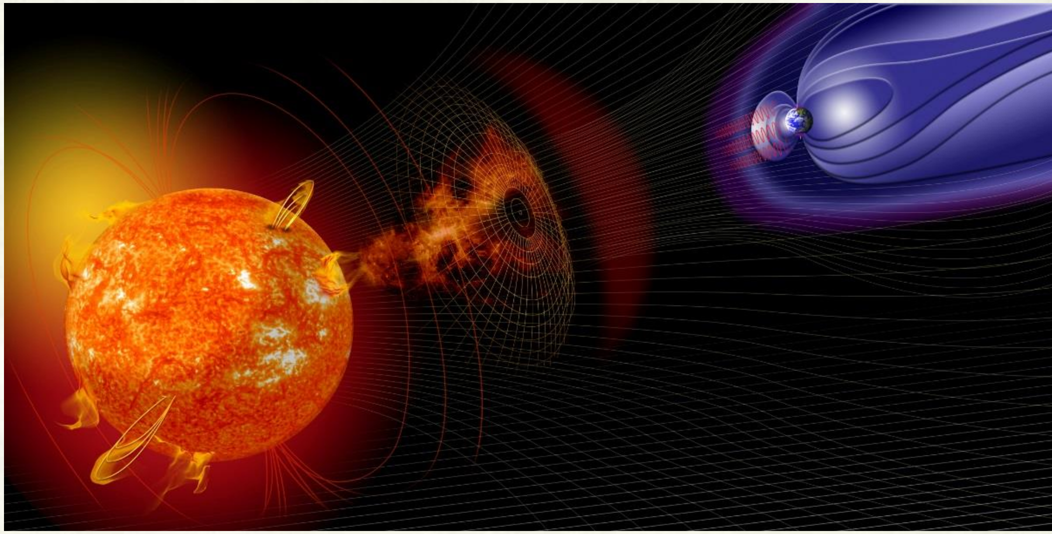






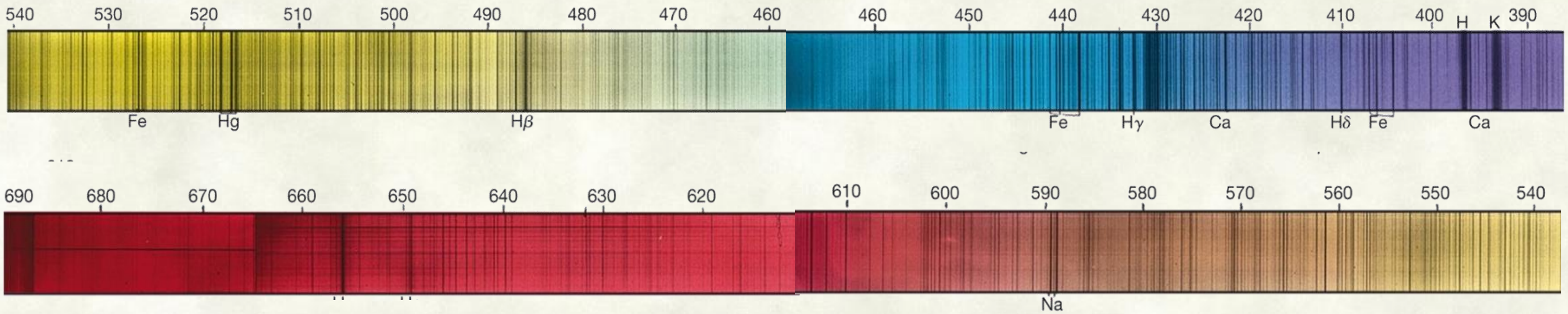
Sun in X-ray

- Solar flare is a large explosion on Sun’s surface, comparable in size to a prominence, but shorter in duration, seconds or minutes rather than days.
- A coronal mass ejection is a much larger eruption that involves immense amounts of gas from the corona.



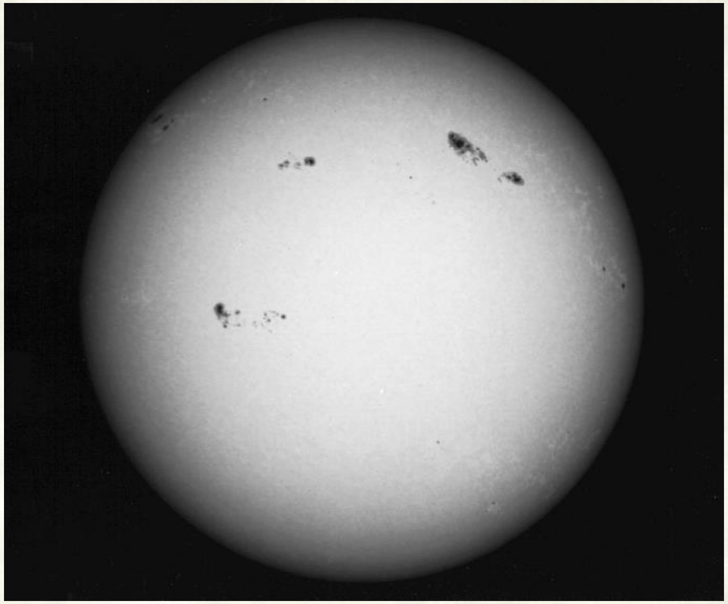
- solar wind shock waves from Solar flares and coronal mass ejections disturbs the Earth’s magnetosphere and ionosphereand create geomagnetic storms.
  - disrupting radio communication, electronics and endangering satellites and astronauts, even electrical power plants.

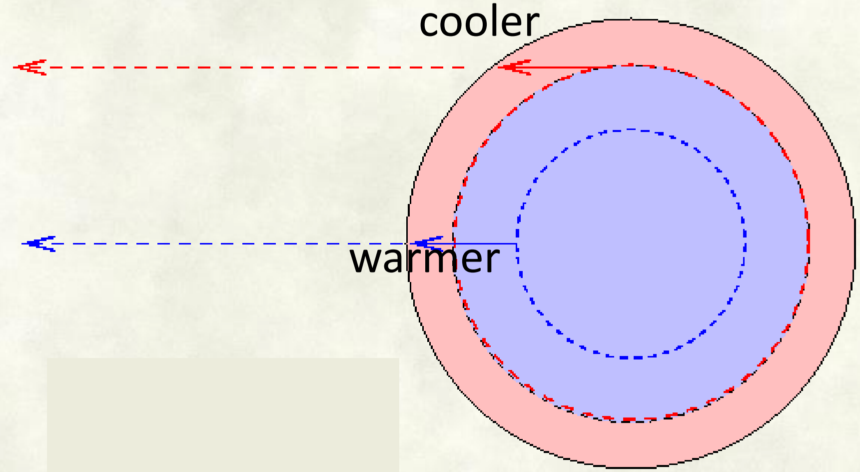
The Solar spectrum



- The solar spectrum consists of a continuum with thousands of dark absorption lines superposed.
- The lines are called the Frauenhofer lines after Joseph Frauenhofer who discovered them in 1814.
- Spectral classification of the Sun is G2
- These lines are produced primarily in the photosphere, by hydrogen and other elements.
  - **Helium was first discovered on the Sun from its spectral lines.**

Limb darkening





- Limb darkening is the gradual decrease in brightness of the disk of the Sun as observed from its center to its edge (called limb, it also becomes redder).
- Two factors contribute to the limb darkening.
  - The density of the solar photosphere decreases as the distance from the center increases
  - The temperature of the photosphere decreases as the distance from the center increases.
- At the center of the solar disk, an observer sees the deepest and warmest layers that emit the most light.
- At the limb, only the upper, cooler layers that produce less light can be seen.
- Observations of solar limb darkening are used to determine the temperature structure of the Sun's atmosphere.

Review Questions

- How old is the Sun?
- How long will sun stay as a main sequence star burning hydrogen?
- How does the Sun produce energy?
- How much hydrogen is converted in to helium in the sun in a second?
- What are the most abundant elements in the sun?
- What is the "surface" of the sun that we normally see in visible light is called?
- Why isn't the solar corona normally visible to us?
- What are the sunspots?
- Why do sunspots appear dark?
- What is solar wind?
- What is the difference between solar prominences and solar flares?
- What is limb darkening? What is causing that?
- What are the Frauenhofer lines?