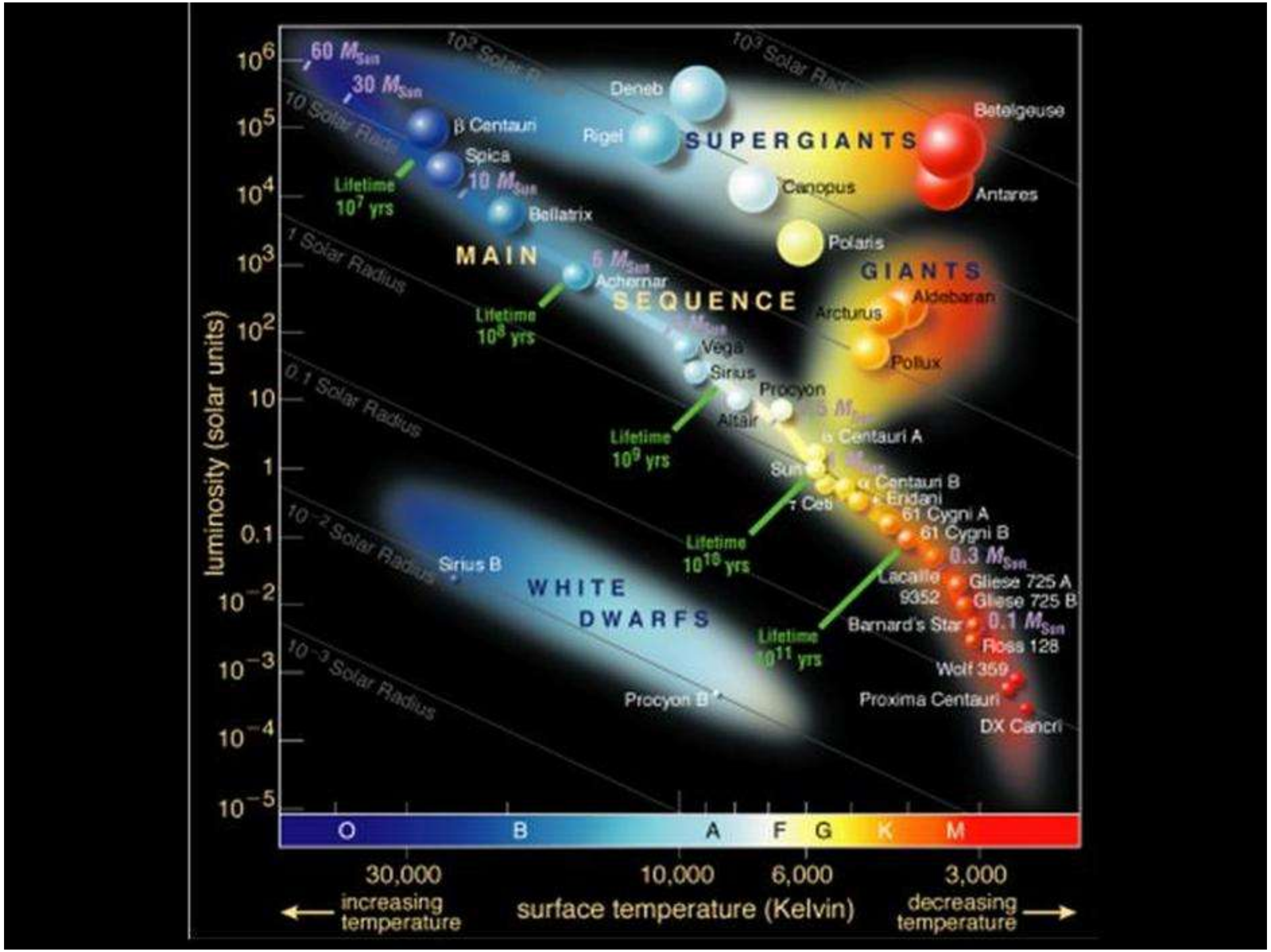
The Sun

Jim Rauf

H-R Diagram



$$L_\odot = 3.8 \times 10^{26}\ \mathrm{W}$$

$$R_c = 70{,}000\ \mathrm{km}$$

Power density of the sun:

$$\frac{L_\odot}{\frac{4\pi}{3} R_c^3} = 300\ \mathrm{W\ m^{-3}}$$

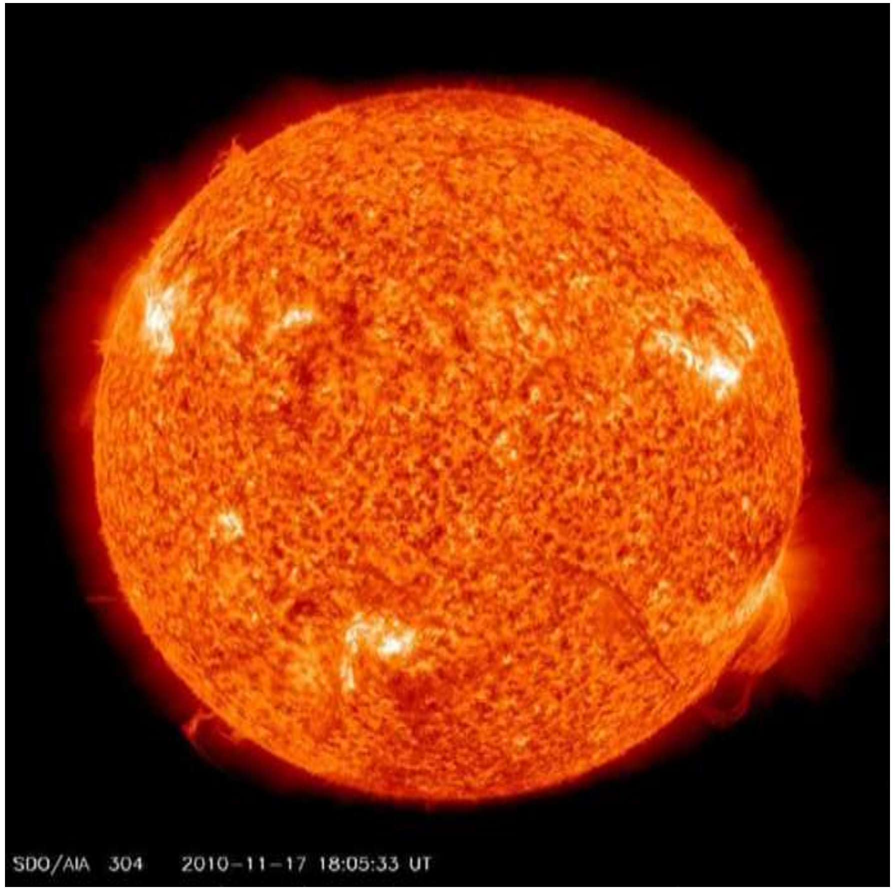
$$T = \frac{2.9 \times 10^{-3}}{\lambda_{max}}$$

$$L = 4\pi R^2 \sigma T_{\mathrm{eff}}^4$$

$$f = \frac{L}{4\pi r^2} \quad (\mathrm{W/m^2})$$

Inverse square law

The Sun



Sun's Physical Characteristics	
Diameter	1.392×10^6 Km
Surface Area	6.0877×10^{12} km^2
Volume	1.412×10^{18} km^3
Mass	1.9891×10^{30} kg
Density	1.408×10^3 kg/cm^3
Escape Velocity	617.7 km/s
Energy Releasing	3.83×10^{26} Joules/second
Temperature at centre	15 million K
Surface Temperature	5800 K

The Sun

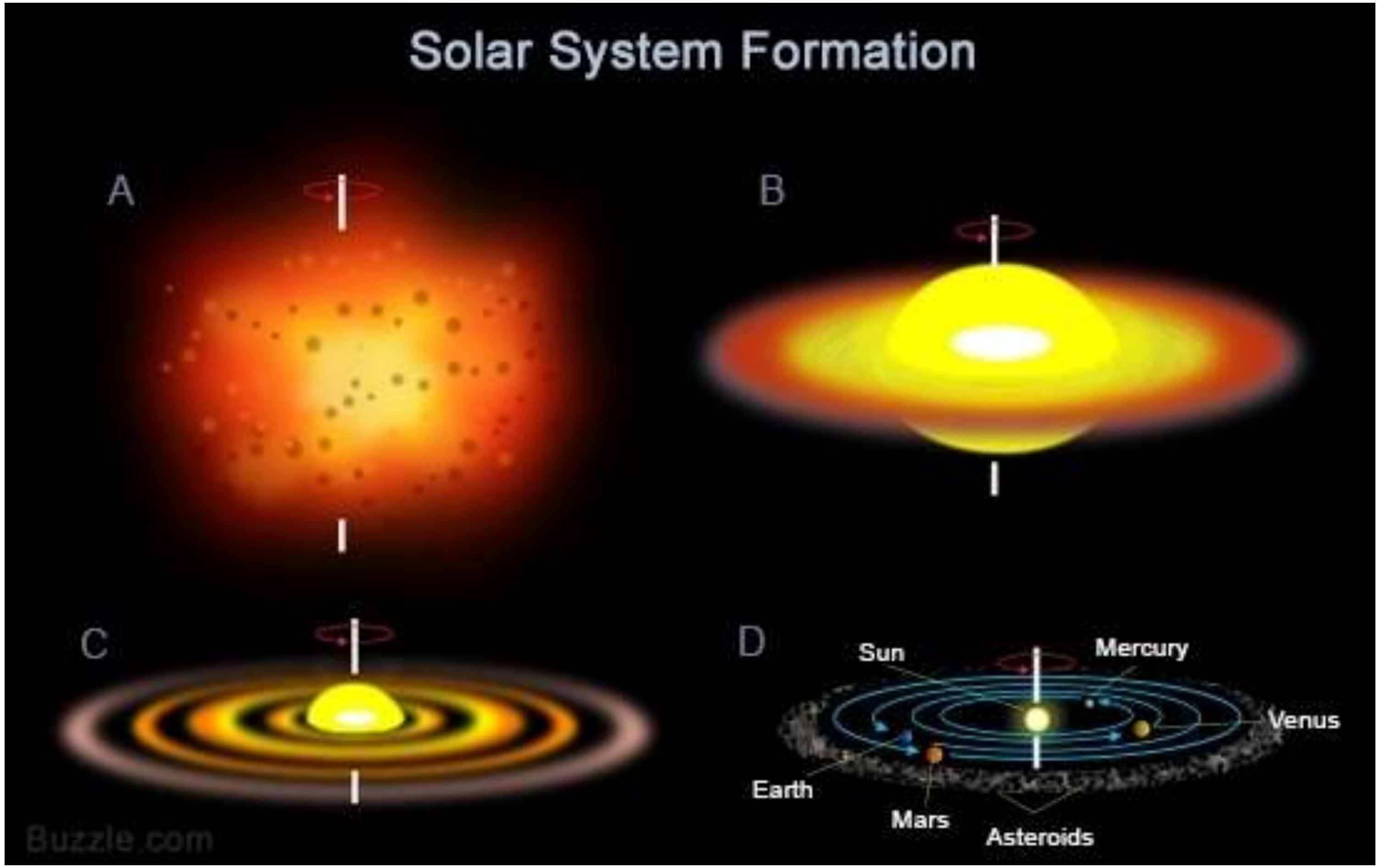
Physical characteristics	
Mean diameter	1.392×10^6 km
Equatorial radius	6.955×10^5 km
Mass	1.9891×10^{30} kg
Average density	1.408×10^3 kg/m^3
Equatorial surface gravity	274.0 m/s^2
Escape velocity	617.7 km/s
Temperature of surface (effective)	5,778 K

Rotation characteristics	
Obliquity	7.25° (to the ecliptic)
Sidereal Rotation period (at 16° latitude)	25.38 days
(at equator)	25.05 days
(at poles)	34.3 days
Rotation velocity (at equator)	7.189×10^3 km/h

Formation

- About 4.5 billion years ago a **solar nebula** of gas and dust collapsed due to gravitational attraction
- The collapsing cloud started to spin and flattened into a disk like structure
- In the center, the material clumped together to form a **protostar** that would eventually become the **Sun**
- A rotating disk around a protostar is a key element in building planets
- It lets the material hang out long enough for the planet formation process
- The disk was made up of elements fused during earlier stars' supernovae explosions
- Gravitational attraction of the material in the disk formed the planets and other bodies in the solar system
- The protostar was a ball of **hydrogen** and **helium**
- Over tens of millions of years, gravity forced the temperature and pressure of the material inside to increase starting the fusion of hydrogen that drives the Sun today
- The Sun required about 50 million years to mature from the beginning of its collapse
- The Sun is about half-way through its life as a mature **class G** star
- The Sun is an average-size star, not too big and not too small
- Its size makes it an excellent star to orbit, as it is neither large and fast-burning nor small and dim

Formation



Solar System Formation
A
B
C
D
Sun
Mercury
Venus
Earth
Mars
Asteroids
Buzzle.com

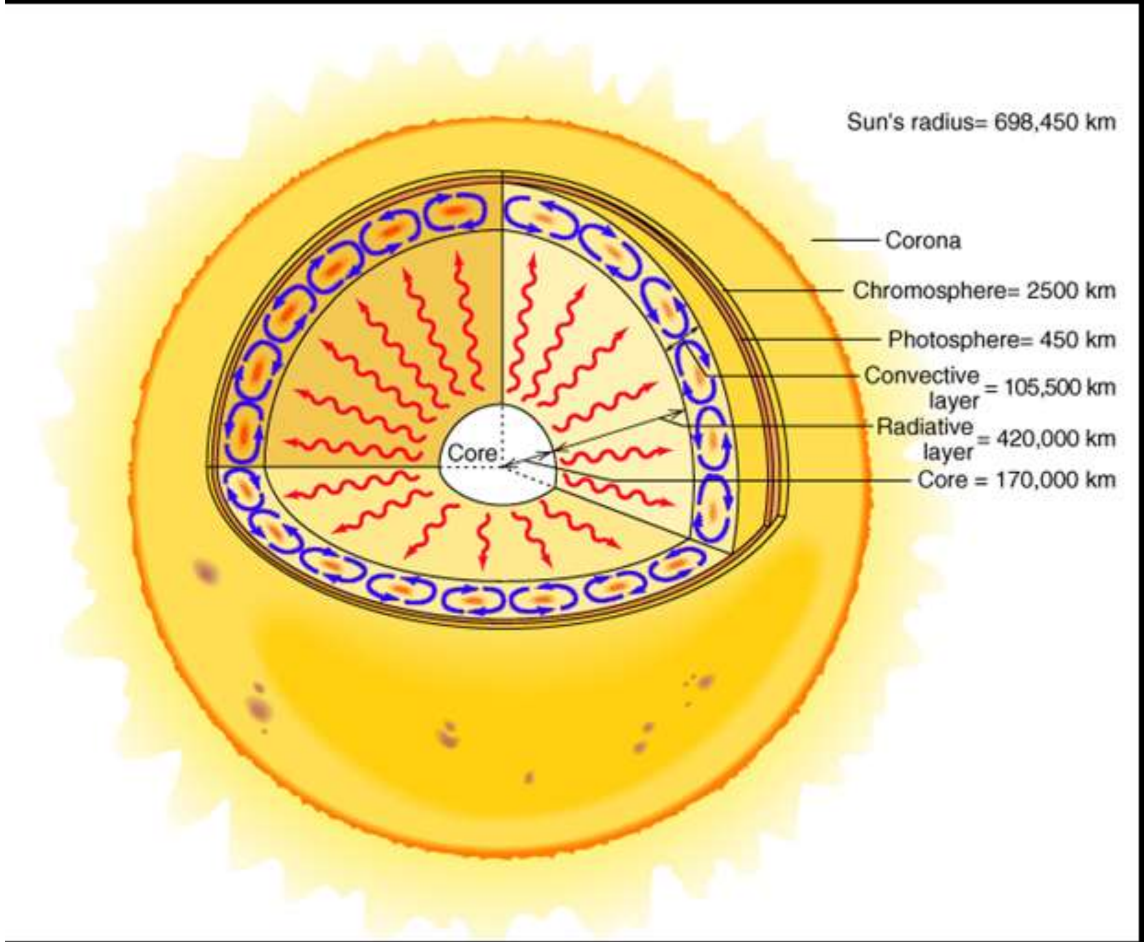
Observations

- Scientists began studying the **Sun** from Earth and Earth orbit for some time
- **NASA** launched a series of eight orbiting observatories known as the **Orbiting Solar Observatory** between 1962 and 1971
- Seven were successful, collecting data at ultraviolet and X-ray wavelengths and photographing the super-hot corona
- In 1990, **NASA** and **the European Space Agency (EASA)** launched the **Ulysses** probe to make the first observations of the sun's polar regions
- In 2004, **NASA's Genesis** spacecraft returned samples of the solar wind to Earth for study
- In 2007, **NASA's** double-spacecraft **Solar Terrestrial Relations Observatory (STEREO)** mission returned the first three-dimensional images of the sun
- In 1995 the joint **NASA-ESA Solar & Heliospheric Observatory (SOHO)** was launched to study the solar wind, as well as the sun's outer layers and interior structure
- In 2010, **NASA's Solar Dynamics Observatory (SDO)**, to study how solar activity is created and drives space weather by measuring the Sun's interior, atmosphere, magnetic field, and energy output
- **NASA's Parker Solar Probe** was launched in 2018 travels directly through the Sun's atmosphere -- ultimately to a distance of about 6.5 million km(4 million miles) from the surface
- There are other ESA and NASA missions planned to observe the sun in the next few years

Observations

- The radius of the **Sun**, $R_{\odot}$, is 109 times that of Earth
- Its distance from Earth is 215 $R_{\odot}$
- It subtends an angle of $^1/_2$° in the sky, roughly the same as that of the **Moon**
- The Sun has *no fixed surface*
- The temperature is so high that no solid or liquid can exist there
- The constituent materials are predominantly gaseous **atoms**, with a very small number of **molecules**
- The surface viewed from Earth, called the **photosphere**, is the layer from which most of the radiation reaches us
- The radiation from below is absorbed and reradiated
- The Sun is so far from Earth that this slightly fuzzy *surface* cannot be resolved, and so the limb (the visible edge) appears sharp
- The mass of the Sun, $M_{\odot}$, is 743 times the total mass of **all** the planets in the solar system and 330,000 times that of Earth
- Under the force of gravity, the great mass of the Sun presses inward, and to keep the star from collapsing, the central pressure outward must be great enough to support its weight
- The density at the Sun's core is about 100 times that of water
- The temperature is at least 15 million K, so the central pressure is at least 3.5×10^{11} atm (5.145×10^{12} psia)

Structure of the Sun



Diameter of the Sun = Diameter of 56 Earths!

Layers of the Sun

1. Core

   the core of the sun alone is the size of 13 Earths!

2. Radiative Zone

   energy from the core radiates through this part of the Sun

3. Convective Layer

   convection cells move energy through this part of the Sun

4. Photosphere

   This is the part of the sun we see

5. Chromosphere

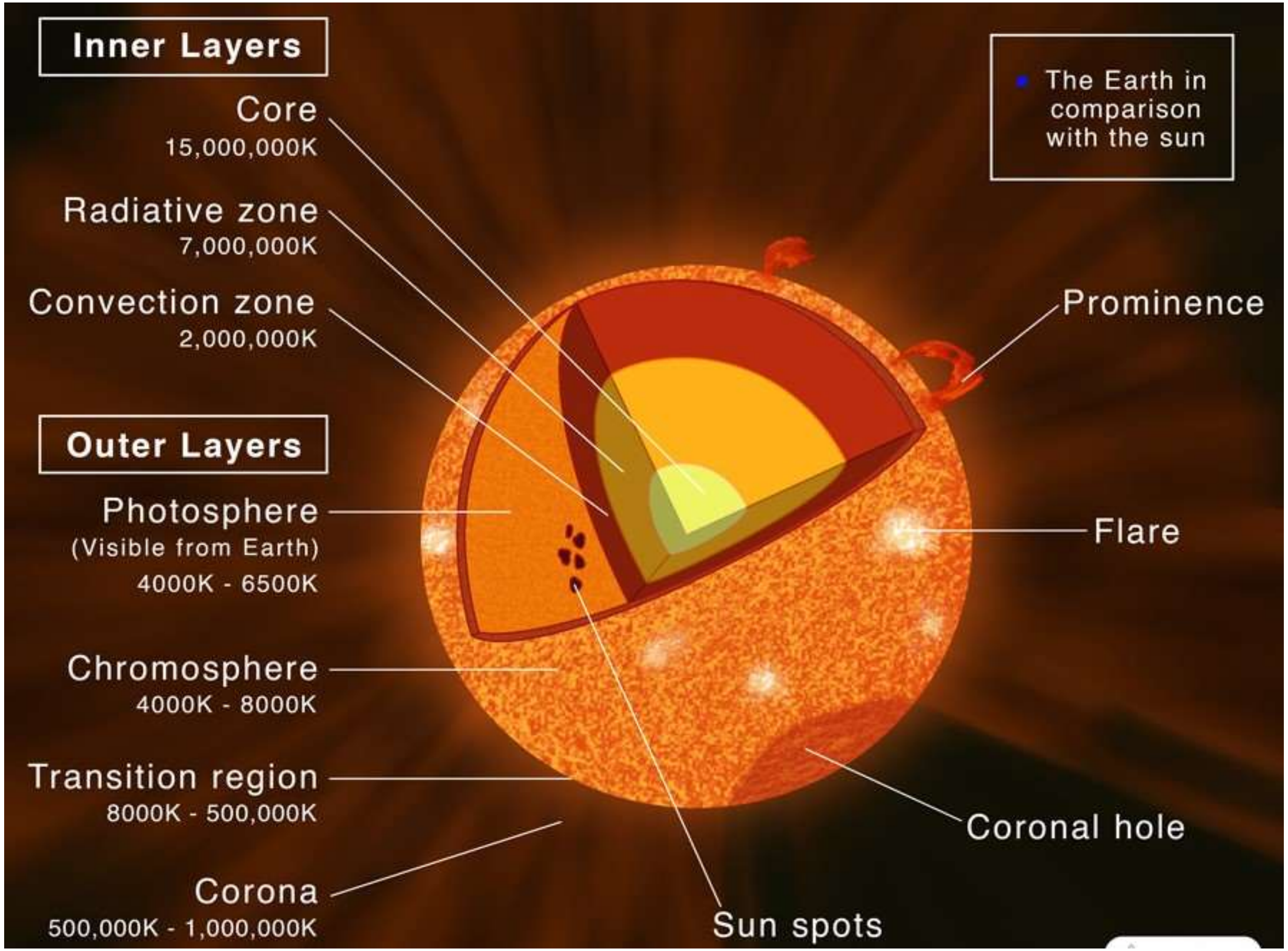
   a part of the Sun's atmosphere

6. Corona

   This is a bright halo around the Sun

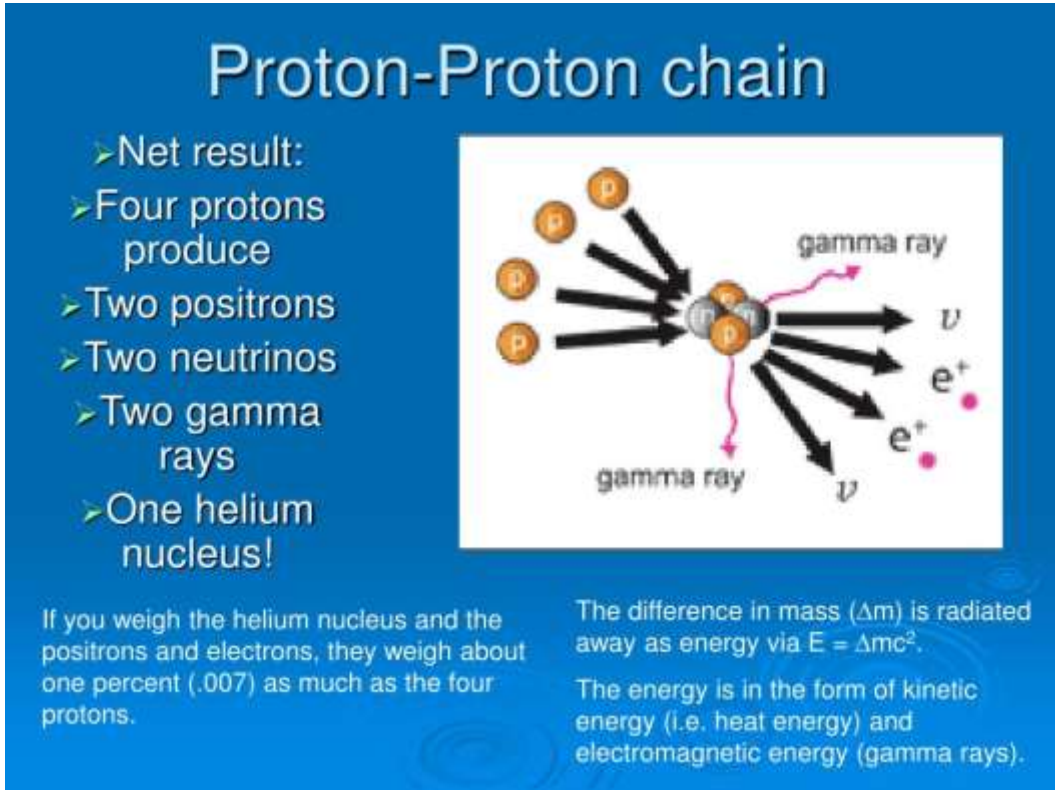
Transition Zone

Structure of the Sun



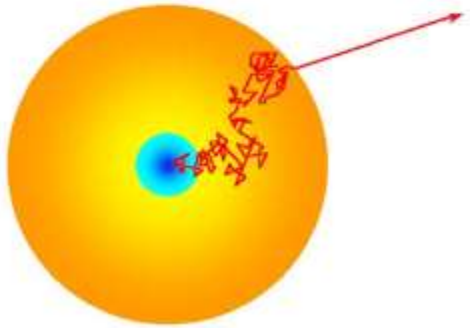
Structure of the Sun-Core

- The energy radiated by the **Sun** is produced in its **core** by nuclear fusion at ~15 million K
- The conversion of **hydrogen (H)** nuclei to **helium (He)** nuclei
- The Sun is at least 90 percent hydrogen by number of atoms
- One hydrogen atom weighs 1.0078 atomic mass units
- One helium atom weighs 4.0026 amu
- Conversion of four hydrogen atoms to one helium atom yields 0.0286 mass unit, which is converted to energy (***E = mc²***) 6.8 million electron volts (MeV), in the form of **gamma (γ) rays** or the **kinetic energy** of the products
- During most of its life the Sun produces energy by nuclear fusion of hydrogen nuclei into helium nuclei



Structure of the Sun-Core

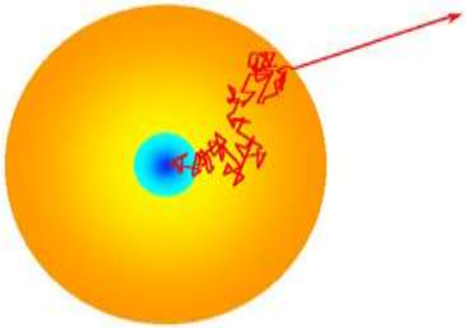
- About 2% of the energy is carried away as **neutrinos**
- **Kinetic energy** of product particles, which heats the gases in the core
- **Gamma-ray photons** until they are absorbed and reradiated by the local atoms
- The density is so high that the photons travel only a few millimeters before they are scattered
- Farther out the nuclei have electrons attached, so they can absorb and reemit the photons, but the effect is the same
- The photons take a so-called **random walk** outward until they escape from the Sun
- Radiant energy emitted- about 49% Infrared, 43% Visible light, 7 % Ultraviolet and 1% X-rays, gamma rays and radio waves
- Because the **nuclei** at the core are completely **ionized**, or stripped of their electrons, the photons are simply scattered there into different paths

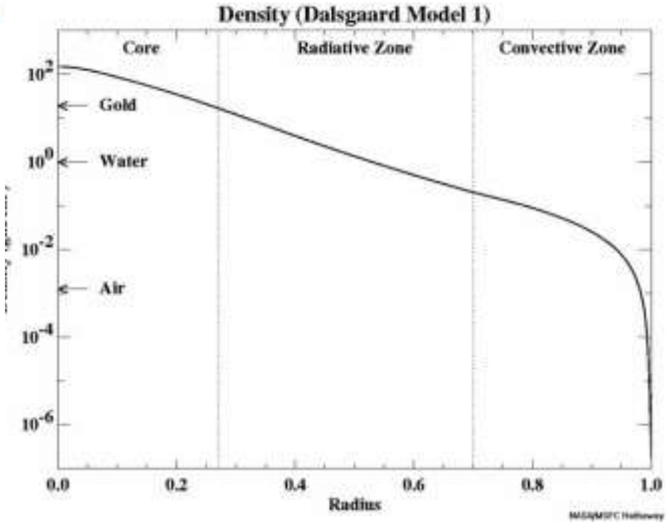


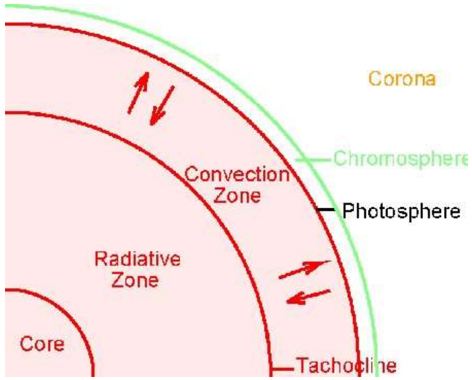
- The distance covered in a random walk is the average distance traveled between collisions (**mean free path**) multiplied by the square root of the number of steps(interval between successive collisions)
- Average mean free path in the Sun is about 10 centimeters , a photon must take 5×10^{19} steps to travel 7×10^{10} centimeters (radius of the sun)
- At the speed of light this process takes ~ 10,000 to 170,000 years to reach the "surface"
- Photon takes ~8 minutes to reach Earth
  - 1.496x10E8 km/(3x10E8 km/sec x60 sec/min)

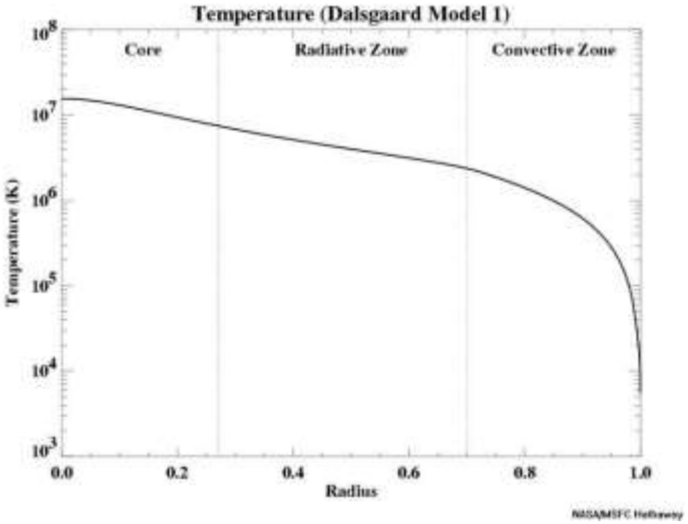
Structure of the Sun-Radiative Zone

- The **radiative zone** extends outward from the outer edge of the core to the **interface layer** at the base of the **convection zone** (from 25% of the distance to the surface to 70% of that distance)
  - It makes up 32 percent of the sun's volume and 48 percent of its mass
- Energy generated in the core is carried by light (**photons**) that bounces from particle to particle through the radiative zone
- Although the photons travel at the speed of light, the random indirect path that they follow takes them a long time to finally reach the interface layer
- The density drops from 20 g/cm³ (about the density of gold) down to only 0.2 g/cm³ (less than the density of water) from the bottom to the top of the radiative zone
- The temperature falls from 7 million K to about 2 million K over the same distance



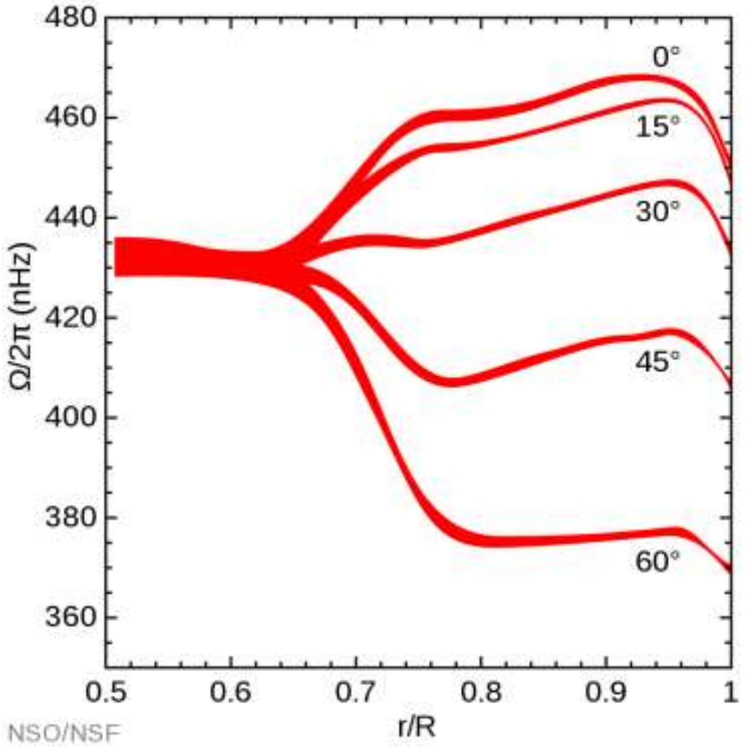






Structure of the Sun-The Interface Layer

- The **interface layer** lies between the radiative zone and the convective zone
- The fluid motions found in the convection zone slowly disappear from the top of this layer to its bottom where the conditions match those of the calm radiative zone
- It is believed that the Sun's **magnetic field** is generated by a magnetic dynamo in this layer due to convective motion and differential rotation
- The changes in fluid flow velocities across the layer (shear flows) can stretch magnetic field lines of force and make them stronger
- There also appears to be sudden changes in chemical composition across this layer
- The Sun is a self-sustaining dynamo that converts within the Sun to electric-magnetic energy



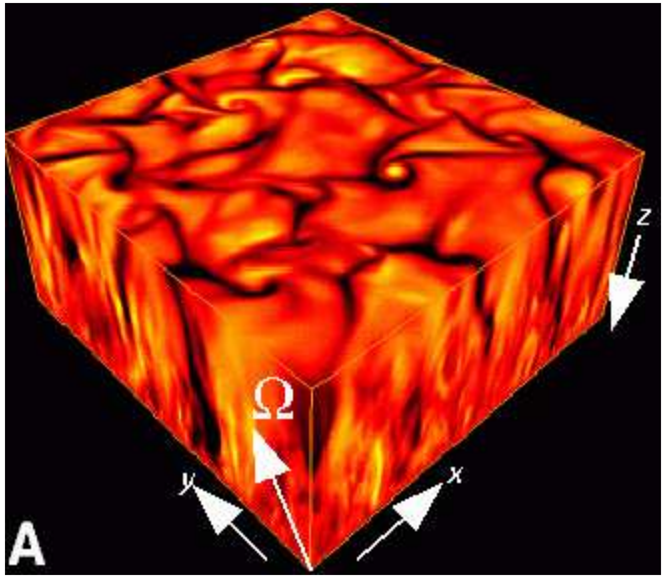
- Differential rotation in the outer convective region and almost uniform rotation in the central radiative region
- The transition between these regions is the interface layer

Structure of the Sun-The Convection Zone

- The convection zone is the outer-most layer of the solar interior
- It extends from a depth of about 200,000 km right up to the visible surface
- At the base of the convection zone the temperature is about 2,million K
- This is "cool" enough for the heavier ions (such as carbon, nitrogen, oxygen, calcium, and iron) to hold onto some of their electrons
- This makes the material more opaque so that it is harder for radiation to get through
- This traps heat that ultimately makes the fluid unstable and it starts to "boil" or convect
- Convection is the transfer of thermal energy by the movement of a liquid or gas
- Convection works when a liquid or gas is unevenly heated
- Hot liquids (and gases) are less dense and rise, causing convection currents
- The warmer section of the material will rise while the cooler part sinks
- Where this occurs a volume of material moved upward will be warmer than its surroundings and will continue to rise further
- These convective motions carry heat quite rapidly to the surface-high gravitational force
- The fluid expands and cools as it rises
- At the visible surface the temperature has dropped to 5,700 K and the density is only 0.0000002 gm/cm³ (about 1/10,000th the density of air at sea level)
- The convective motions themselves are visible at the surface as **granules** and super gr**anules**

Structure of the Sun-The Convection Zone

- The bottom of the convection zone is heated by the radiations coming out of the radiative zone
- The temperature at the bottom of the convection zone is 2 million K
- The top of the convection zone (surface of the Sun) is being cooled by the creation of light
- The temperature at the surface is only about 5800 K
- There is a large temperature difference between the base and the surface of the convection zone
- This difference in the temperature results in convection (along with gravity)
- These bubbles are very similar to the cells observed at the surface of the Sun

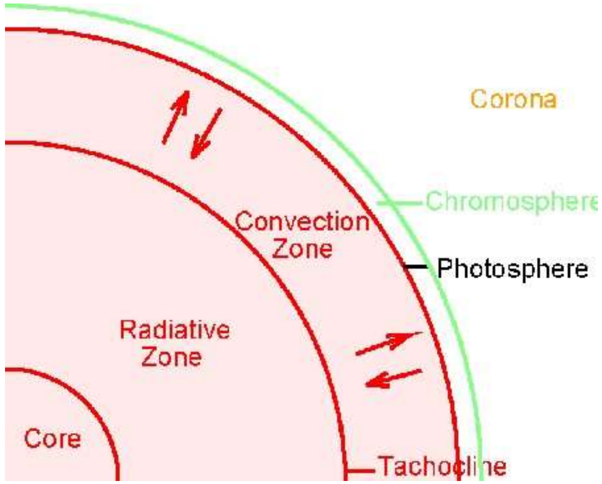


- Computer generated graphic representing the temperatures in a small slice of the convection zone
- Red is hot and black is cold
- The complicated patterns give you an idea of how turbulent the flow is

Structure of the Sun-The Photosphere

- The **photosphere is** deepest part of the Sun that can be observed with visible light
- The Sun is a gaseous object, it does not have a clearly defined surface
- Its visible parts are usually divided into a '**photosphere**' and '**atmosphere**'.
- The **photosphere** is the visible “surface” of the Sun
- It is not a solid surface but is actually a layer about 100 km thick (very thin compared to the 700,000 km radius of the Sun)
- When we look at the center of the disk of the Sun we look straight in and see somewhat hotter and brighter regions
- When we look at the **limb**, or edge, of the solar disk we see light that has taken a slanting path through this layer and we only see through the upper, cooler and dimmer regions
- This explains the "limb darkening" that appears as a darkening of the solar disk near the limb

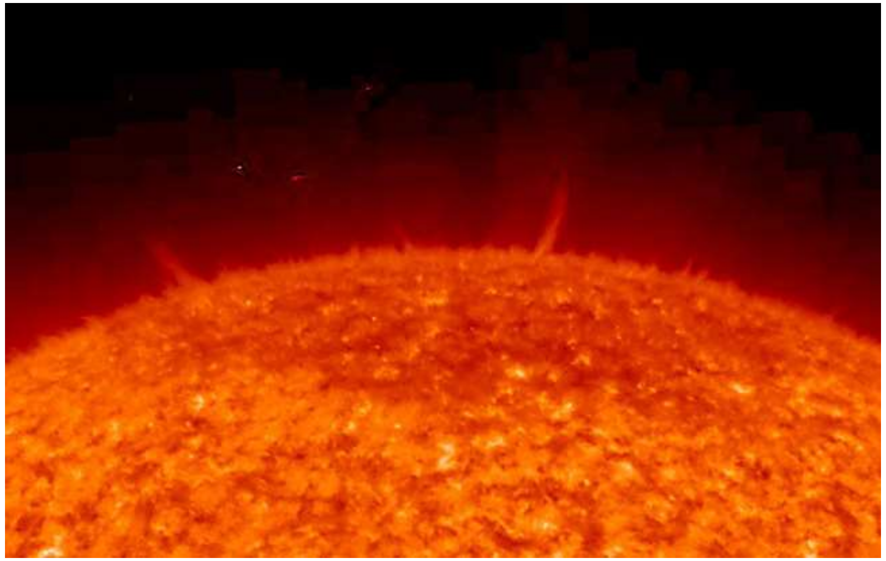
- A number of features can be observed in the photosphere with a simple telescope
- These features include the dark **sunspots**, the bright **faculae**, and **granules**
- We can also measure the flow of material in the photosphere using the Doppler effect
- These measurements reveal additional features such as **super granules** as well as **large scale flows** and a pattern of **waves and oscillations**



Structure of the Sun-Chromosphere

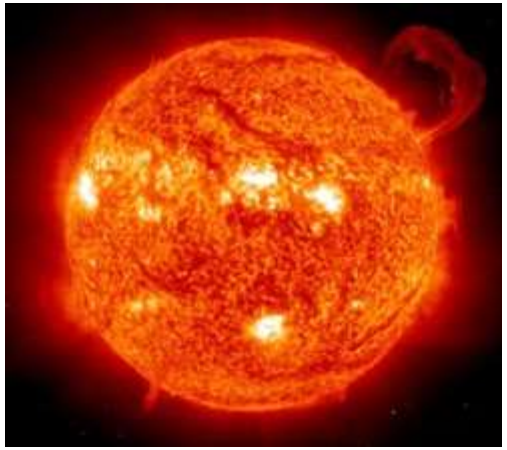
- **Chromosphere** ,is the lowest layer of the Sun's atmosphere, several thousand kilometers thick
- It is located above the bright photosphere and below the corona
- The lower chromosphere is more or less homogeneous
- The upper contains comparatively cool columns of ascending gas known as **spicules**, having between them hotter gas much like that of the corona, into which the upper chromosphere merges gradually
- Spicules occur at the edges of the chromosphere's magnetic network, which traces areas of enhanced field strength
- Temperatures in the chromosphere range from about 4,500 to 100,000 K, increasing with altitude
- The mean temperature is about 6,000K-8000 K

- **Spicules** extend up to 10,000 kilometers above the surface of the Sun



Structure of the Sun-Chromosphere

- A **prominence** is a large, bright, gaseous feature extending outward from the Sun's surface, often in a loop shape
- They are anchored to the Sun's surface in the photosphere, and extend outwards into the solar **corona**
- While the corona consists of extremely hot ionized gases (plasma), which do not emit much visible light, prominences contain much cooler plasma, similar in composition to that of the chromosphere
- A prominence forms over timescales of about a day and may persist in the corona for several weeks or months, looping hundreds of thousands of kilometers into space
- Some prominences break apart and may then give rise to coronal mass ejections
- The red-glowing looped material is plasma



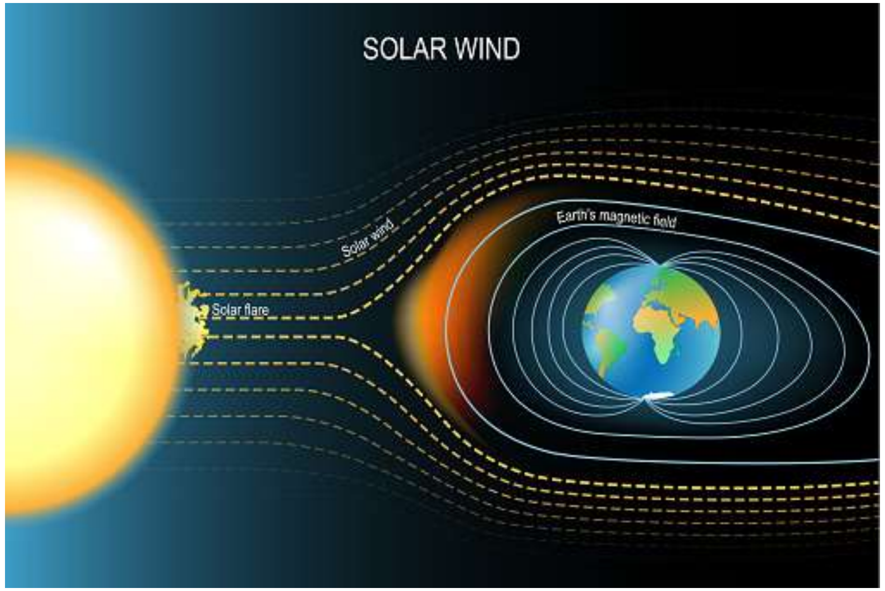
- The prominence plasma flows along a tangled and twisted structure of magnetic fields generated by the Sun's internal dynamo
- An erupting prominence occurs when the structure becomes unstable bursting outward, releasing the plasma
- A typical prominence extends over many thousands of kilometer
- The largest on record was estimated at over 800,000 km long, roughly a solar radius

Structure of the Sun-Corona

- A **corona** is an aura of plasma that surrounds the Sun
- It extends millions of kilometers into outer space and is most easily seen during a total solar eclipse
- Spectroscopy measurements indicate strong ionization in the corona and a plasma temperature in excess of I million K, much hotter than the surface of the Sun
- The **corona** is separated from the **photosphere** by the relatively shallow **chromosphere**
- The exact mechanism by which the corona is heated is not understood
- Possibilities include induction by the Sun's magnetic field and magnetohydrodynamic waves from below
- The outer edges of the Sun's corona are constantly being transported away due to open magnetic flux, generating the **solar wind**

Structure of the Sun-The Solar Wind

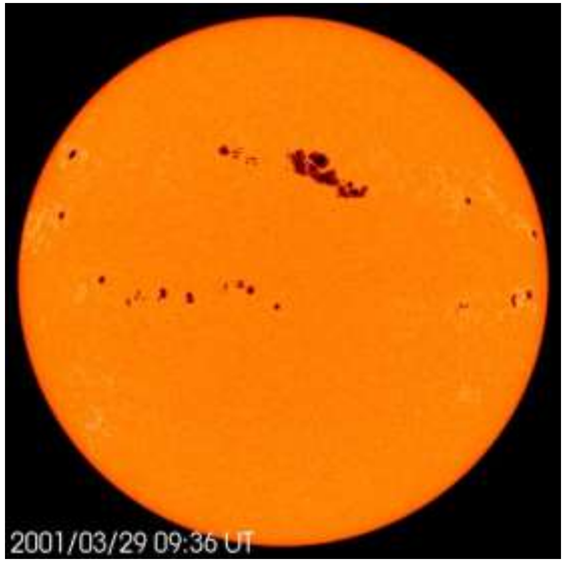
- **Solar wind** is a stream of charged particles released from the upper atmosphere of the Sun, called the **corona**
- This plasma mostly consists of electrons, protons and alpha particles with kinetic energy between 0.5 and 10 keV
- The solar wind streams off the Sun in all directions at speeds of 300 km/s to 800 km/s
- It varies in density, temperature and speed over time and over solar latitude and longitude
- Its particles can escape the Sun's gravity because of their high energy resulting from the high temperature of the corona, which in turn is a result of the coronal magnetic field
- The solar wind is mostly deflected by Earth's magnetic field, but when intense, some of it can get through

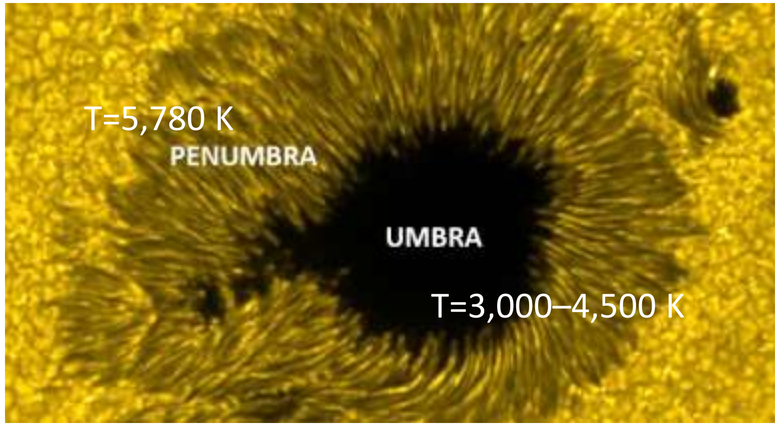


- Once in near-Earth space, the particles can trigger **aurora** near the poles
- The ionization and excitation of atmospheric constituents emit light of varying color and complexity

Structure of the Sun-Sunspots

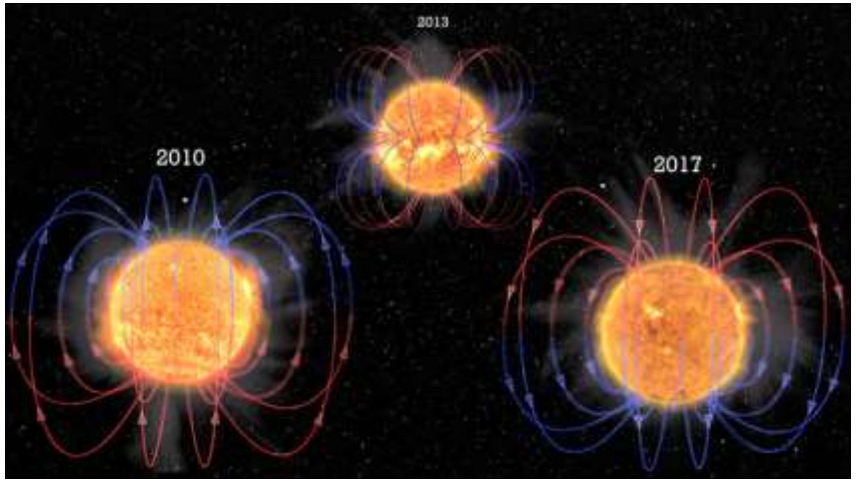
- **Sunspots** are temporary phenomena on the photosphere that appear as spots darker than the surrounding areas
- They are regions of reduced "surface" temperature caused by concentrations of magnetic field flux that inhibit convection
- They have two parts:
- The **umbra**, the darkest part, where the magnetic field is approximately vertical to the Sun's "surface"
- The **penumbra**, which is lighter, where the magnetic field is more inclined to the Sun's "surface"
- Individual sunspots or groups of sunspots may last anywhere from a few days to a few months

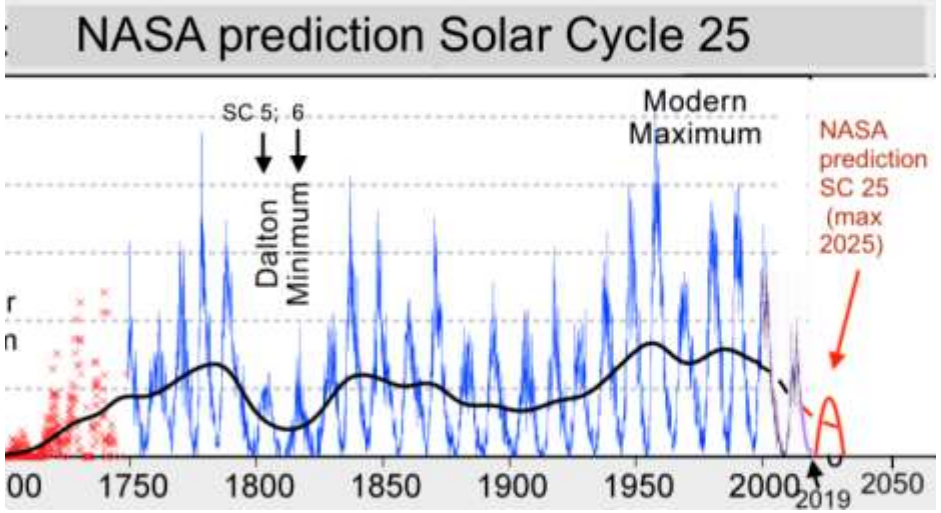




Structure of the Sun-Magnetic Fields

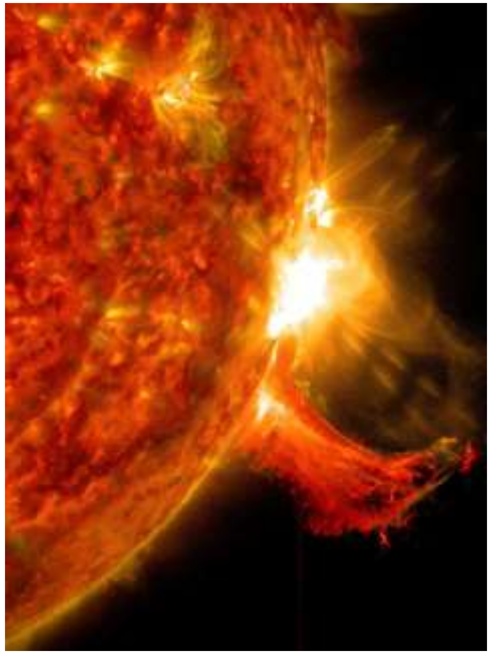
- The Sun's **magnetic fields** originate in its turbulent outer layers (interface ?) and have a complex dependency upon how quickly the Sun is rotating
- Magnetic fields are generated by moving charged particles (plasma), involving their rotation and convection (rising and falling of plasma in the Sun's interior)
- During what is known as the **solar cycle**, the magnetic field of the Sun has reversed every 11 years over the past centuries
- Follows the sunspot cycle
- The south magnetic pole switches to north and vice versa, occurring during the peak of each solar cycle





Structure of the Sun-Solar Flares

- A **solar flare** is a sudden flash of increased brightness on the **Sun**, usually observed near its surface and in close proximity to a sunspot group
- Powerful flares are often, but not always, accompanied by a coronal mass ejection
- They are barely detectable in the total solar irradiance ("solar constant”)
- Flares are closely associated with the ejection of plasmas and particles through the Sun's corona into outer space
- Flares also emit radio waves
- If the ejection is in the direction of the Earth, particles associated with this disturbance can penetrate into the upper atmosphere (the ionosphere) and cause bright auroras
- They a may even disrupt long range radio communication



- It usually takes days for the solar plasma ejecta to reach Earth
- Particles ejected by solar flares may travel at ~7 million km/hr
- They can disrupt earth communications

Next Session

- Fate of the Sun
- Summary