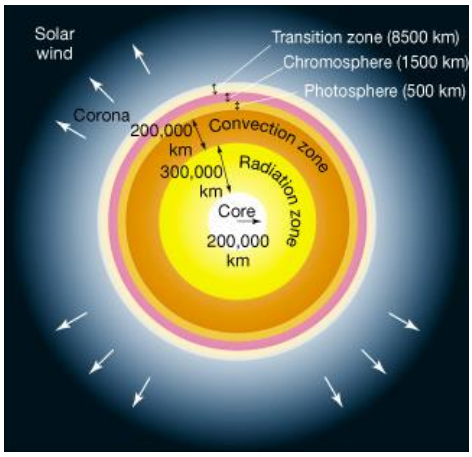
Chapter 09
The Sun
Our Parent Star

9.1 The Sun in Bulk

- The Sun is the closest star to us on Earth
  - A Star is a glowing ball of gas held together by its own gravity and powered by nuclear fusion
- Overall Structure
  - The Photosphere is the surface of the Sun
    - Maybe only 500 km thick which is less than 0.1% of the total radius, which is why it appears to be such a well-defined and sharp edge when being viewed from Earth
  - The Chromosphere is the lower level of the Sun's atmosphere, which is located above the photosphere
  - The Transition Zone is the next level of the atmosphere lying above the chromosphere
  - The Corona is the thin hot upper atmosphere
  - The Solar Wind is the flow of energy and particles past the Corona that extends into the edges of the solar system
  - The Convection Zone is the region below the photosphere
  - The Radiation Zone is the below the convection zone
  - The Core is the center of the Sun

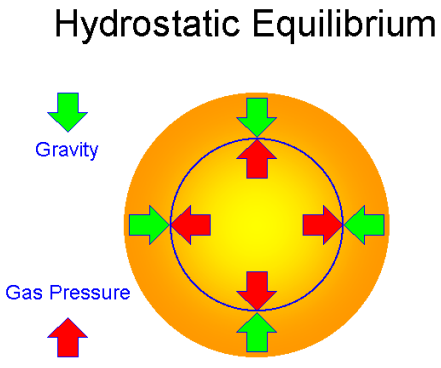


- Luminosity
  - The Sun radiates an enormous amount of energy into space
    - We measure luminosity based on how many watts of power are received per unit area on Earth then multiplied by the surface area of the Sun to get its total luminosity
    - The Sun's luminosity of 3.86×10^{26} W… more than 100 billion nuclear bombs per second!

Radius	Mass	Density	Core Temperature	Surface Temperature
696,000 km	1.99×10^{30} kg	1410 kg/m^3	15 million K	5780 K
Rotation at Equator	**Rotation at 60° Lat.**	**Rotation at Poles**	**Rotation of Interior**	**Luminosity**
25.1 days	30.8 days	36 days	26.9 days	3.86×10^{26} W

9.2 The Solar Interior

- The Sun has been studied very closely for a very long time and many models have been put together to mathematically explain and predict properties of the closest star
  - The Standard Solar Model is the model of stars based on the studies of the Sun
- Modeling the Structure of the Sun
  - Hydrostatic Equilibrium is the balance of the two forces at work within the Sun
    - Nuclear fusion is the force pushing outward
    - Gravity is the force pulling inward
    - These two forces are in a balance so that the Sun remains constantly at its size
    - The surface is more of a liquid than a solid so it has oscillations that create patterns of fluid moving in/out of the core that we can detect using Doppler Effect
  - Helioseismology is the study of the surface and pressure waves of the Sun



- Energy Transport
  - In the core, the temperature is about 15 million Kelvin and the gas is completely ionized, making it basically transparent. The energy created within it radiates outward as there are no electrons bound to atoms that can absorb and re-emit the radiation that is produced
  - In the radiation zone, the heat from the core cools as it expands and it becomes cool enough for electrons to be bound to atoms, so he photons are completely absorbed as they try to escape.
    - Not a single photon from the core makes it out of the radiation zone!

- At the edge of the radiation zone the gas is very hot still, while the gas extending to the edge of the convection zone is very cool. Just like on Earth, the cool gas will sink as the hot gas rises creating a section of the Sun known as the convection zone.
  - Once the gas reaches the edge of the convection zone, it has decreased in density enough to escape into space through radiation
- The region that emits radiation out into space is the photosphere which emits the photonsthat make it to the surface and we can see from Earth as our "sunlight"

- Evidence for Solar Convection
  - High resolution photographs of the solar surface show that the surface is highly mottled with regions of bright and dark gas known as *granules*.
    - Granulation is the process by which granules are created and move up or down
      - Granules will measure about 1000 km across
    - Supergranulation is the same as granulation but the size of the granules is more than 30,000 km across

9.3 The Solar Atmosphere

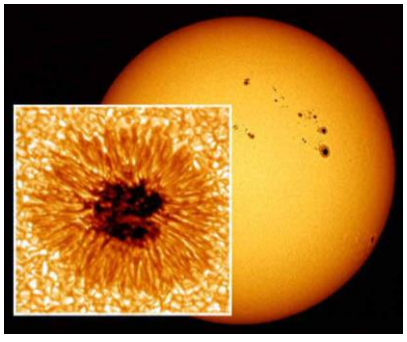
- The absorption spectra is analyzed to determine the composition of the solar atmosphere:

Element	% of Atoms	% of Mass
Hydrogen	91.2	71.0
Helium	8.7	27.1
Oxygen	0.078	0.97
Carbon	0.043	0.40
Nitrogen	0.0088	0.096
Silicon	0.0045	0.099
Magnesium	0.0038	0.076
Neon	0.0035	0.058
Iron	0.0030	0.14
Sulfur	0.0015	0.040

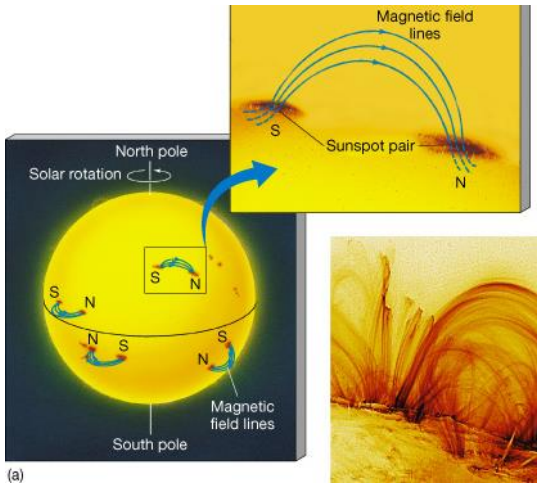
- The Chromosphere
  - Chromosphere is much less dense than the photosphere and can only be seen during total eclipse
- The Transition Zone and Corona
  - Both are more ionized than the photosphere or chromosphere indicating that their temperature is much higher, similar to the Earth's upper atmosphere being hotter than the lower levels
- The Solar Wind
  - At the edge of the Corona, the gas is moving fast enough to escape the gravity of the Sun which escapes into space as the Solar Wind
    - The high energy EM Radiation and fast moving charged particles (protons and electrons) escape from the photosphere at the speed of light, taking 8 minutes to reach the Earth
    - Basically, the Sun evaporating just like a puddle of water does on Earth is the Solar Wind

9.4 The Active Sun

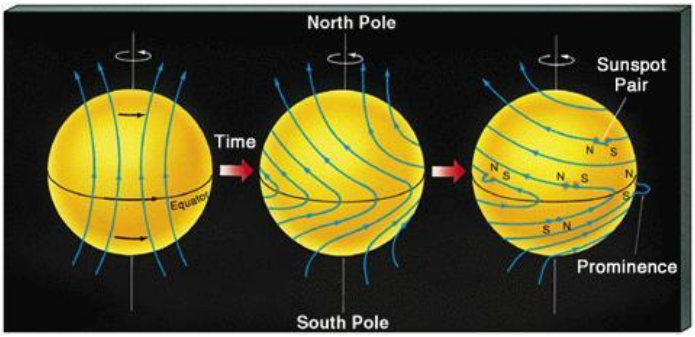
- Most of the Sun's luminosity results from the continuous emission from the photosphere. There are other events that we know of that can affect a stars output that are much more irregular in nature
  - Solar Activity is the irregular activity of the surface of the Sun that does not contribute much to the total luminosity but can affect it slightly.
- Sunspots
  - Sunspots are dark regions of on the surface of the Sun that can measure up to 10,000 km across and are cooler than the 6000 K surface temperature of the Sun.
    - Dark, coolest, inner region called the Umbra
      - Temperature about 4500 K
    - Light, cool, outer region called the Penumbra
      - Temperature about 5500 K



- Solar Magnetism
  - Spectroscopy shows that the magnetic field in a sunspot is about 1000 times greater than the field in the surrounding photosphere.
    - This has led to the understanding that sunspots usually come in pairs and are linked by their polarity. One is "north" and one the "south"
      - North is when the magnetic field points into the center of the Sun
      - South is when the magnetic field points away from the center of the Sun

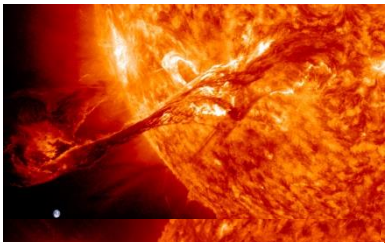


- The Solar Cycle
  - There is a pattern to all of the irregular surface disturbances of the Sun.
    - The Sunspot Cycle is the 11 year period where sunspots go from almost 0, and increases to a large amount, then comes back down to almost 0 again
    - The Solar Cycle is the 22 year period where the sunspot cycle and the magnetic field repeat themselves.

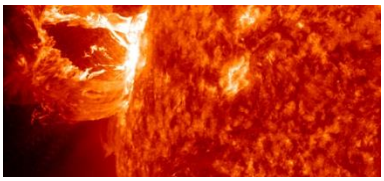


Magnetic Field Cycle

- Active Regions
  - Active Regions are the areas surrounding sunspots that tend to erupt violently from time to time
    - Prominences are loops or sheets of glowing gas that were trapped, but then are ejected from an active region on the solar surface.
      - They are brought back down to the surface by the magnetic field
    - Flares are much more violent than prominences and can be as hot as reach 100 million K, which is 6 times hotter than the core
      - So powerful, they are not able to be pulled back down by the magnetic field
    - Coronal Mass Ejections are a giant magnetic bubble of ionized gas that separates from the rest of the atmosphere and escape into space
      - These bubbles can interact with the Earth's magnetic field and cause disruptions with all of our communications and power on the planet.



Prominence



Solar Flare

Coronal Mass Ejection

- The Sun in X-Rays
  - X-Ray images of the Sun show regions where the gas does not have enough energy to emit X-Rays due to having such a low density compared to the rest of the Corona
    - Coronal Holes are these X-Ray "holes" in the Corona
- The Changing Solar Corona
  - The Corona seems to change with the sunspot cycle as well as the magnetic field cycle.
  - It is basically a "magnetic carpet" that surrounds the surface of the Sun and is prone to the strong magnetic fields produced by the Sun

9.5 The Heart of the Sun

- Nuclear Fusion
  - Nuclear Fusion is the process of combining the nuclei of small mass to create nuclei of larger mass

$$nucleus1 + nucleus2 \rightarrow nucleus3 + energy$$

  - During nuclear reactions, there is always a little bit of mass lost during the reaction which is what produces the energy from the reaction in accordance with Einstein's famous equation relating energy (E) to the mass (m) and the speed of light (c):

$$E = mc^2$$

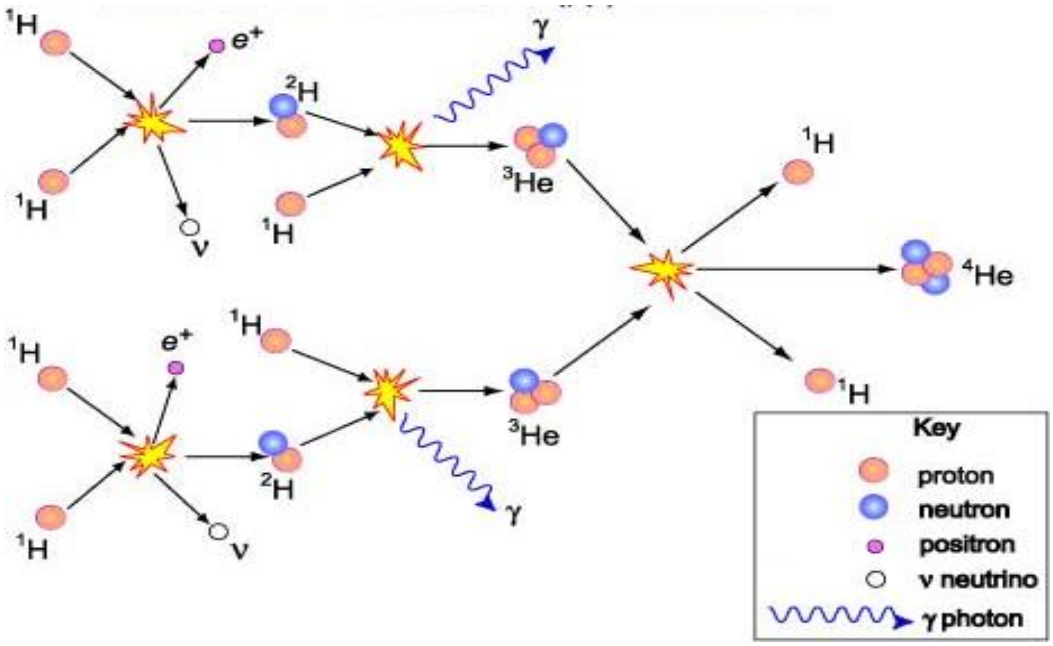
  - The Law of Conservation of Mass and Energy states that the sum of the mass and energy must always remain constant in any physical process:

$$mass_{before} + energy_{before} = mass_{after} + energy_{after}$$

- The Proton-Proton Chain
  - The Strong Nuclear Force is the strongest fundamental force in the universe
    - It works on a very short distance (10^{-15} m) and can keep the positively charged protons bound together in the nucleus if they collide with enough speed to get close enough
  - Definitions of some particles involved in nuclear processes
    - Hydrogen Nuclei are single protons without an electron bound to them
    - Deuteron is a hydrogen nuclei with one neutron giving it an atomic mass of 2
    - Positron is the antimatter version of an electron that has same properties except – charge
    - Neutrinos are chargeless and almost massless particles that obey the weak nuclear force
  - The overall nuclear reaction that converts the hydrogen nuclei into helium is:

$$4\,{}^1_1H \rightarrow {}^4_2He + 2v + 2\gamma$$

  - The Proton-Proton Chain is a sequence of events that eventually leads to the production of Helium through the fusion of Hydrogen within a star



    - Step 1 = Two groups of two protons combine, each forming one deuteron, while releasing a positron and a neutrino.

$$4\,{}^1_1p^+ \rightarrow 2\,{}^2_1H^+ + 2\,{}^0_1e^+ + 2v)$$

    - Step 2 = The two deuterons combine with another proton to create an unstable version of Helium called Helium-3 (only has 1 neutron), while the positron annihilates with an electron, producing gamma rays. The neutrino escapes into space.

$$2\,{}^2_1H^+ + {}^1_1p^+ \rightarrow {}^3_2He^{+2}$$
$$2\,{}^0_1e^+ + 2\,{}^0_{-1}e^- \rightarrow \gamma$$

    - Step 3 = Two Helium-3 nuclei combine to form Helium-4 and two protons

$$2\,{}^3_2He^{+2} \rightarrow {}^4_2He^{+2} + 2\,{}^1_1p^+$$