Review

Last time we

- Explored the solar atmosphere.
- Defined characteristics of the photosphere, chromosphere, and corona.
- Discussed how we can probe the interior of the Sun using helioseismology.
- Discussed sunspots and the solar magnetic cycle.
Fusion: Energy of the Stars

So we understand why there are solar cycles, what the surface of the Sun looks like, and how we know about the interior. So what makes the Sun so hot?

Fusion
What is Fusion?

Fusion is the combining of two atoms to create a single atom of a different element.

- Fusion combines light nuclei into heavier nuclei.
- Fusion releases energy contained in the strong force which binds atomic nuclei together.
- Hydrogen atoms are fused into Helium in the core of the Sun.
Hydrogen Fusion in the Sun

Atomic nuclei are positively charged and tend to repel each other using electromagnetic forces.

- To get hydrogen nuclei to collide takes a large temperature, so they move fast enough to overcome this repulsive Coulomb barrier. Requires at least 10,000,000 kelvins.
- To get hydrogen nuclei to collide takes a large density, so there are a lot of nuclei around.
- The Sun fuses hydrogen into helium using a process known as the proton-proton chain.
The Proton-Proton Chain

The Proton-Proton Chain consists of 3 reactions which occur in the hot, dense core of the Sun:

\[ ^1\text{H} + ^1\text{H} \rightarrow ^2\text{H} + \text{e}^\pm + \nu_e \]
\[ ^2\text{H} + ^1\text{H} \rightarrow ^3\text{He} + \gamma \]
\[ ^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + ^1\text{H} + ^1\text{H} \]

Each of the first two reactions has to happen twice in order to generate the two \(^3\text{He}\) atoms that fuse into \(^4\text{He}\). This series of reactions produces \(4.3 \times 10^{-12}\) Joules of energy. 1 Joule is the amount of energy required to lift an apple waist high. If one kilogram of hydrogen were all to fuse into Helium, \(6.4 \times 10^{14}\) Joules would be produced.
How Long Will the Sun Shine?

At this point we have enough information to figure out how long the Sun will shine. We measure that the Sun’s energy output $4 \times 10^{26}$ watts, and we know that the Sun has a mass of $2 \times 10^{30}$ kg. Over the lifetime of the Sun, the entire mass of hydrogen in the core (about 10% of the Sun’s mass) will be converted into Helium, producing $1.28 \times 10^{44}$ Joules. The lifetime of the Sun can then be calculated as

$$\frac{\text{total energy}}{\text{energy output per second}}$$

This yields

$$\frac{1.28 \times 10^{44} \text{ J}}{4 \times 10^{26} \text{ W}} = 3 \times 10^{17} \text{ s} = 10 \text{ billion years}$$
Solar Neutrinos

Most of what we detect from space is radiation, but we also know about are able to detect a particle emitted from objects in space. The neutrino

- is very low mass. A neutrino is almost without mass.
- is neutrally charged.
- almost never interacts with other matter.
- travels at nearly the speed of light.

So how do we detect these solar neutrinos? Do we detect the right amount according to our proton-proton chain theory?
The Solar Neutrino Problem

After these detectors were built, we ended up detecting only about 50% of the neutrinos we expected. This is the solar neutrino problem. A new theory, neutrino oscillation theory developed to explain this discrepancy.

- Neutrinos must have some minute mass.
- Neutrinos can change into other types of neutrinos when they move.

Newer neutrino detectors have detected the other type of neutrino predicted under the neutrino oscillation theory.
Hydrostatic Equilibrium

What holds the Sun up?

• The theory of stellar structure posits that at every position in the Sun the force of gravity is exactly balanced by outward pressure.

• This exact balance is called *hydrostatic equilibrium*.

• Should pressure or gravity begin to dominate somewhere in the Sun, then the Sun would expand or collapse to maintain equilibrium.
Energy Transport

Fusion takes place in the core of the Sun, but that energy needs to make its way to the surface.

- In the deep interior of the Sun, photons carry the energy to the surface. The interior is almost transparent to photons because the atoms and electrons are floating freely. Without energy levels to excite, the photons are unimpeded.

- As the density of gas drops, the photons have a tough time moving. Convection becomes the most efficient way to transport energy, and the convection zones of the Sun begin.