Lecture 12: Making the Sun Shine
Readings: Sections 18-1, 18-4 and Box 18-1

Key Ideas
- Stars shine because they are hot—need an internal energy source to stay hot
- Kelvin-Helmholtz Mechanism
  - Energy from Gravitational Contraction
  - Doesn't work in the Sun now, but is important during the early stages of a star's life
- Nuclear Fusion Energy
  - Energy from fusion of 4 hydrogen atoms into 1 helium atom
  - Proton-proton nuclear reaction chain
  - CNO nuclear reaction chain

Why do stars shine?
Stars shine because they are hot
- Emit light with a roughly thermal (blackbody) spectrum
- Internal heat "leaks" out of their surfaces

Luminosity=rate of energy loss

To stay hot, stars must make up for the lost energy, otherwise they would cool and eventually fade out.

Case Study: The Sun
<u>Question</u>
- How long can the Sun shine?

<u>Need two numbers</u>
- How much internal heat is there in the Sun?
- How fast this heat is lost (Luminosity)

$$\text{Lifetime} = \frac{\text{Internal Heat}}{\text{Luminosity}}$$

Sources of Energy

In the 19th century, two energy sources were known:

Chemical Energy
- Burning of oil or wood by oxidation
- Chemical explosives

Gravitational Energy
- Water running downhill to power a mill
- Heat from meteorite impacts

The Age Crisis: Part 1

The most powerful chemical reactions could work for only a few thousand years

Meteorites could work for about 1 million years

But: Geologists estimated that the Earth was at least a few 10s to a 100s of million years old

<u>Logical Inconsistency:</u>

How can the Earth be older than the Sun?

Kelvin-Helmholtz Mechanism

Energy from Gravitational Contraction of the Sun

As gas contracts, its temperature rises as energy stored as gravitational potential energy is released

This energy is radiated into space, cooling the star. Gravity keeps contracting the star, more and more energy is radiated away. When the star has completely collapsed, you've gotten all the energy you can from the Kelvin-Helmholtz mechanism.

Predicts that the Sun's size will change with time (though really slowly).

The Age Crisis: Part II

Late 1800s:

Kelvin estimated the Sun could shine for about 30 million years

Geologists estimated that the Earth is at least 2 billion years old, based on measuring the amount of uranium that had decayed to lead in rocks.

In an interesting twist, the phenomenon of radioactivity, which sealed the rejection of the Kelvin-Helmholtz mechanism, also started providing the clues that pointed out the real answer.

Nuclear Energy

1896 Röntgen & Becquerel discover radioactivity

1905 Einstein demonstrates equivalence of Mass & Energy. Conservation says that the sum of matter and energy does not change.

1920s Eddington noted that 4 protons have 0.7% more mass than 1 Helium nucleus (2p+2n)

If 4 protons fuse into 1 Helium nucleus, the remaining 0.7% of mass is converted to energy.

Payne-Gaposhkin showed that the Sun's atmosphere was mostly H.

Fusion Energy

Fuse 1 gram of hydrogen into 0.993 grams of helium

Leftover 0.007 grams is converted into energy

$$E = mc^2 = 6.3 \times 10^{18} \text{ergs}$$

Enough energy to lift 64,000 Tons of rock to height of 1 km.

The Age Crisis: Averted

Luminosity of the Sun is about 4×10^{33} erg/sec (4×10^{26} watts)

Must fuse about 600 million tons of H into He each second

Converts about 4 million tons of matter into energy each second

Sun contains about 10^{21} million tons of H, but only 10% is hot enough for fusion

Fusion Lifetime is about 10 billion years. The Earth is 4.5 billion years old, so the Sun has enough energy to keep going for about 5 billion years. Phew!

Nuclear Fusion 101

Gravity unimportant, the forces that are important are the strong nuclear, the electromagnetic, and the weak nuclear force. Weak force at work when neutrons change into protons and vice versa.

Nuclear particles

Proton (positively charged)

Neutron (neutrally charged)

^{4}He and bigger particles
Not all possible combinations of neutrons and protons exist

- ^{5}He doesn't
- ^{2}He doesn't
- and many others

Fusion==combining *positively charged* nuclei together

Electromagnetic Force

- Like charges repel
- Opposite charges attract

So trying to put protons together is difficult. Proton with ^{4}He is even tougher.

BUT strong force, which binds protons and neutrons together, is stronger than electromagnetic repulsion.

BUT strong force is short range ($<10^{-15}$ meters), so the protons need to get really close together before they will stick

BUT protons don't like to get close together. They need to be traveling fast enough so the repulsive force can't stop them. Remember that temperature measures the speed of particles in a gas. Therefore what we need is a high temperature.

<u>Rate of nuclear fusion depends on temperature</u>

Proton-Proton Chain

$$p + p \rightarrow {}^2H + e^+ + \nu_e \text{ (twice)}$$

$$^2H + p \rightarrow {}^3He + \gamma \text{ (twice)}$$

$$^3He + {}^3He \rightarrow He + p + p$$

note that the atoms are all completely ionized. I've dropped the $^+$ for convenience.

<u>The Bottom Line</u>
Fuse 4 protons (^{1}H) into one ^{4}He nucleus plus the following reaction by-products

- 2 photons = Energy
- 2 positrons (positive electrons, will annihilate and produce more energy)
- 2 neutrinos (ν_e) that leave the Sun carrying energy

Additional Details:

Protons do not just collide with protons in the center of the Sun. There are other nuclei floating about and protons can collide with these. These lead to the pp-II and pp-III chains. These reactions also release neutrinos, neutrinos that have higher energy than neutrinos from the pp-I chain.

Test: Solar Neutrinos

Question: How do we know that fusion is occurring in the core of the Sun?

Answer: Look for the neutrinos created by the p-p chain

What are Neutrinos?

Weakly interacting neutral subatomic particles

- Very nearly massless
- Travel very near the speed of light
- Interact with matter via the weak nuclear force
- Can pass through lead 1 parsec thick!

Neutrinos created by nuclear fusion in the Sun's core would stream out of the Sun, not interacting with the protons, electrons, helium atoms, etc. in the Sun. This is good! They also only rarely interact with detectors on Earth. This is bad!

The Sun emits about 10^{33} neutrinos/sec

(FYI, humans emit about 3×10^8 neutrinos/day from the decay of radioactive potassium)

Every second we have many neutrinos pass through our bodies: 400,000 billion from the Sun, 50 billion from the Earth and 100 billion from nuclear power plants. This is not dangerous, because the neutrinos do not interact.

Detection of neutrinos is hard

- Need massive detectors
- Work deep underground to shield out other radiation

Homestake Mine experiment

- 100,000 gallons of tetrachloroethylene, a common cleaning fluid.

Very rarely, a solar neutrino will change a ^{37}Cl into a ^{37}Ar atom.
Set up your tank, wait a few months, then find the few dozen ^{37}Ar atoms in your tank that has 10^{30} atoms in it.
Calculate the solar neutrino flux!

Results:
We detect neutrinos from fusion in the Sun, with the expected energies, in all of the experiments to date.

The CNO cycle

In stars with central temperatures hotter than the Sun's, H is fused into He using carbon, nitrogen and oxygen nuclei as catalysts. The hotter temperatures mean that the large repulsion between the 6-8 protons and the proton can be overcome. And there is no more annoying step where you need to proton to change into a neutron as the moment the two protons are interacting.

$^{12}\mathrm{C} + \mathrm{p} \rightarrow {}^{13}\mathrm{N} + \gamma$

$^{13}\mathrm{N} \rightarrow {}^{13}\mathrm{C} + \mathrm{e}^{+} + \nu_e$

$^{13}\mathrm{C} + \mathrm{p} \rightarrow {}^{14}\mathrm{N} + \gamma$

$^{14}\mathrm{N} + \mathrm{p} \rightarrow {}^{15}\mathrm{N} + \mathrm{e}^{+} + \nu_e$

$^{15}\mathrm{N} + \mathrm{p} \rightarrow {}^{12}\mathrm{C} + {}^{4}\mathrm{He}$

Note that you start with ^{12}C, add 4 protons, and end up with a ^{12}C and a ^{4}He.

<u>These reactions happen at higher temperatures because the repulsive force increases as the number of protons in the nuclei increases, and the nuclei have to be moving faster to overcome the repulsion.</u>

We will discuss other stages of nuclear fusion (such as helium fusing into carbon) later in the course.