<u>Solar Energy Production</u>

We're now ready to address the very important question:

What makes the Sun shine?

Why is this such an important topic in astronomy?

- As humans, we see in the visible part of the spectrum, so the light provided mostly by stars is what we see with our eyes when look out at the Universe.
- Without the energy provided by the Sun, life on Earth or anywhere else in the solar system would be impossible – *(except maybe Europa, why?).*
- Without the process of fusion inside stars, the Universe would be a dark and sterile place composed only of hydrogen and helium.
- Furthermore without fusion, there wouldn't even be any stars because stars achieve an equilibrium against gravity by producing high pressures provided by the energy released from fusion. All of the clouds of gas that form stars would just collapse into white dwarfs, neutron stars, and ultimately black holes!

Solar Energy Production: Some History

The answer to the question, “What makes the stars shine,” wasn’t found until the **1930’s** – **which is not that long ago**. Why did it take so long? **Consider one number.** By the late nineteenth century, astronomers could calculate:

$$\text{Solar Luminosity}, L_{\odot} = 4 \times 10^{26} \text{ Watts}$$

The total energy emitted by the Sun in radiation (i.e. light) at all wavelengths in one second
(*what do you buy that’s measured in Watts?* (LC))

The problem of solar energy production can be stated as:

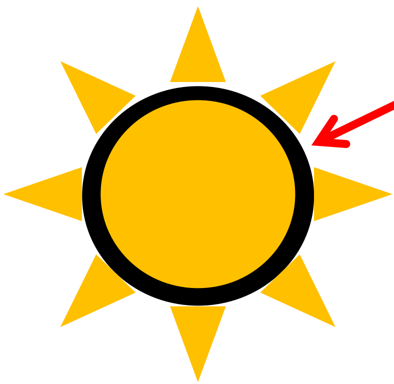
How can the Sun produce so much energy and be able to do so for such a long period of time?

In the early 20th century, astronomers had no idea what powered the Sun. No known mechanism could produce the Solar Luminosity for the estimated age of the Sun – which, at that time, was believed to be about 1 billion years.

Solar Energy Production: Some History

Could the Sun be powered by Chemical Reactions?

More to show that the idea doesn't work, Hermann Helmholtz calculated how much coal would have to be completely burned on the surface of the Sun to produce the 4 X 10^{26} Watts, i.e. the Solar Luminosity:



1500 pounds of coal on every square foot every hour!

Consume 1 Solar Mass of coal in ~5000 years!

So, the Sun can't be Powered By chemical reactions

Could Kelvin Helmholtz Contraction (adiabatic compression) power the Sun?

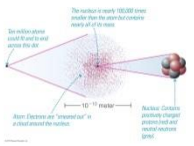
- If the Sun is contracting under gravity, the gas would be compressed, heated, and emit radiation.
- A contracting Sun can produce 4 X 10^{26} Watts, but it can only do so for a few million years.
- Also, in the not too distant past, Mercury, Venus, and the Earth would have had to be inside the Sun!

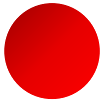
So, what can power the Sun for so long?

The Answer: Nuclear Reactions

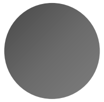
By the 1930's:

- Physicists had come to an understanding of the atom, and how the electrons in the atom determine its chemical properties (see Light and Matter lecture).
- Previously, all that we said about the atomic nucleus is that it provides the positive charge to bind the electrons to the nucleus.
- By the 1930's, it was realized that **the nucleus also has a structure:**



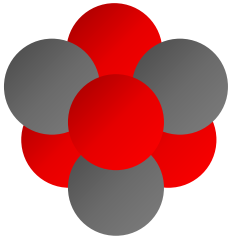


Positively charged Proton (about 2000 times more massive than electron)



Neutral Neutron (about the same mass as the proton)

The Nucleus is protons



and neutrons bound by
The Strong Nuclear Force.

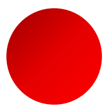
- **What is the nature of this Strong Force?**

It is a force of attraction between all nucleons (protons and neutrons).
It is very strong (***how do we know this? LC***), but very short range.

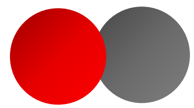
Nuclear Structure

What are Nuclear Isotopes?

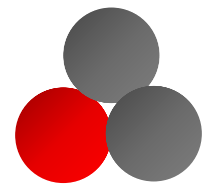
- The number of protons in a nucleus determines the element:
  e.g. 1 = hydrogen, 2 = helium, 3 = lithium, etc.
- Isotopes are nuclei of the same chemical element (so they have the same number of protons) that have different numbers of neutrons, **e.g. Hydrogen:**



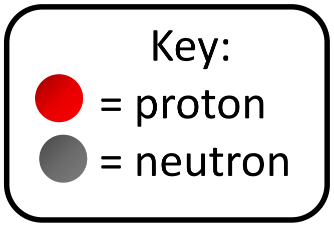
^{1}H
(normal hydrogen)
Mass number, A =1



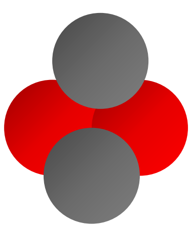
^{2}H, Deuterium
Mass number, A =2



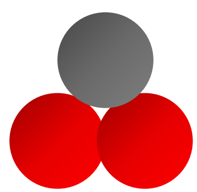
^{3}H, Tritium
Mass number, A = 3



or for Helium:



^{4}He
(normal helium)
Mass number, A = 4



^{3}He
(helium-3)
Mass number, A = 3

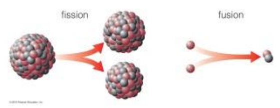
Mass Number, A = number of protons and neutrons

Nuclear Structure

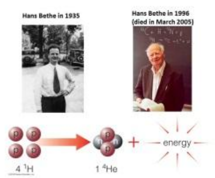
- Not all nuclear isotopes are stable, i.e. some spontaneously decay into something more stable. **The most stable nucleus is:**

^{56}Fe (Iron-56) which has 26 protons and 30 neutrons, A = 56

- Therefore, reactions between nuclei (i.e. when they combine or break apart to form different nuclei) **release energy** (exothermic) if:
  1. They combine nuclei with A < 56 into something closer to 56: **Fusion reactions**
  2. Break apart nuclei with A > 56 into pieces with A closer to 56: **Fission reactions**

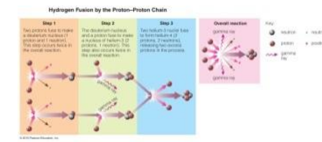


- In the 1930's, **Hans Bethe** proposed that the simplest fusion reaction that combines four hydrogen nuclei into one helium nucleus plus a release of energy could be what powers the Sun.



- **Now, picture the plasma inside the Sun:**
  Is it likely that four protons will simultaneously come together at the same time and fuse into one ^{4}He nucleus?
  Not really, two body interactions would be much more common.
  Bethe proposed that one possible sequence is the proton-proton chain.

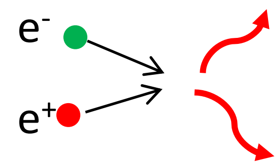
The Proton – Proton Chain



sweeping a minor detail under the rug

- **The proton – proton chain is a sequence of two – body reactions that produces the net reaction: $4\ {}^{1}H \longrightarrow {}^{4}He$**

- To understand the proton – proton chain, we need to discuss **two more particles:**
  - **The Positron (e^{+}):** anti-particle of the electron; the same as an electron in every way except it has a positive charge. When an electron and positron meet, they annihilate into two gamma-ray photons:



  - **The Neutrino** (ν): a very elusive and low-mass particle, present anytime protons turn into neutrons and vice versa. Would pass through light-years of solid lead and rarely interact.

- Study your author's figure of the proton – proton chain, and remember it's a sequence of two – body reactions that produces a simple net reaction.

The Proton – Proton Chain

In the proton – proton chain (or any nuclear reaction), where does the energy come from?

- Note: the answer isn't in the gamma-ray photons or in the neutrinos or positrons – that's where the energy produced by the reaction ends up, not where it comes from.

- Consider some numbers:

  Mass of 1 Hydrogen = 1.007826 u (atomic mass units)

  Mass of 1 Helium = 4.002680 u

  The numbers aren't important, but **do you notice anything odd?**

  Mass of 1 He < 4 X Mass of 1 H

  (the whole is less than the sum of the parts)

  The lost mass, m, has been converted to energy, E, according to Einstein's famous equation:

$$E = mc^2 \quad \text{where} \quad c = \text{speed of light}$$

Or in Einstein's own words. *Also, we will see this in the video on Albert Einstein's life and science.*

The Conditions for Fusion

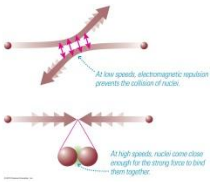
- **How much energy can we get from fusion?**

  Consider fusing 1 kilogram of Hydrogen into Helium in 1 second:
  (we could get that much hydrogen from a bucket of water)

  Releases ~ 6 X 10^{14} Watts (~140 kilotons of TNT)

- **Why won't any old hydrogen fuse into helium?**

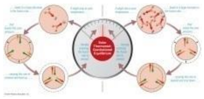
  Consider the first step in the proton – proton chain: two protons have to get close enough for one to turn into a neutron and then fuse together into a deuterium nucleus.
  How do you achieve high enough speeds? (LC)
  High Temperatures.
  Also, we want the particles to encounter each other frequently.
  This means **High Density**.



- **Therefore, the necessary conditions for Fusion are high temperature and high density – just the conditions in the core of the Sun.**

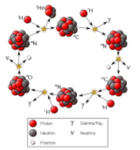
More on Fusion

- The rate of fusion in the Sun is regulated by what your author calls the **Solar Thermostat.** (The rate of fusion in the core is very sensitive to the temperature (T), *e.g. the rate goes as T^4 for the proton-proton chain and as $T^{19.6}$ for the CNO cycle – see below*)

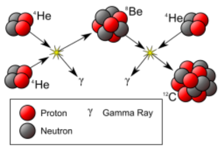


- **Are other fusion reactions possible?** Yes, two that we will consider:

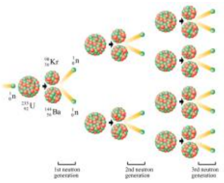
  - **The Carbon-Nitrogen-Oxygen (CNO) Cycle:**
    Net reaction is still 4 hydrogens fusing into one helium; the carbon, nitrogen, and oxygen act as a nuclear catalyst.
    PP-chain dominates in low mass stars, CNO dominates in higher mass stars



  - **Triple – Alpha Process:**
    Fuses 3 Heliums into one Carbon; occurs at very high temperatures and is important at the end of a star's life.



More on Fusion



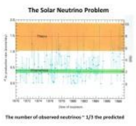
Can we generate nuclear reactions on Earth? Yes:

- **Fission of Uranium or Plutonium:**
  Used in the first nuclear weapons during the second world war and in a controlled manner in nuclear power plants.

- **Fusion of Hydrogen:**
  Used in weapons, but, even after more than 60 years of research, and many different designs, a commercially viable fusion reactor has yet to be built.

But, you may live to see it . .

The Solar Neutrino Problem:



- Although difficult to do, neutrinos from the Sun can be detected. This caused some concerns in the 1970's, 80's and 90's since only about 1/3 of the expected neutrinos were seen.
- **Poll: What's the solution of the Solar Neutrino Problem? (LC)**
  The solution is that there are three types of neutrinos that have a small, but nonzero mass, thus the types can change into one another. Early experiments could only see one kind of neutrino.