Forces and Nuclear Processes

To understand how stars generate the enormous amounts of light they produce will require us to delve into a wee bit of physics. First we will examine the forces that act at large, and small, distances. Next we will learn about nuclear energy. Finally we will study a few of the processes that power stars.

1.1 The Forces in Nature

There are four forces that act in nature: Gravity, Electromagnetic, Strong, and Weak. The range of each force and what they act on are listed below.

Force	**Acts On**	**Range**
Gravity	Mass	Long
Electromagnetic	Electric Charge	Long
Strong	Protons and Neutrons	Short
Weak	Everything	Short

Long Range Forces

Gravity is the force that keeps you from floating away, keeps the Moon in its orbit around the Earth, keeps the Earth in its orbit around the Sun, and on and on. Gravity is an attractive force between objects that have mass. Gravity is a long range force. Even though Pluto is very far away from the Earth, and its mass is quite small compared to the Earth, it still influences the orbit of the Earth around the Sun.

The Electromagnetic force is responsible for electricity, magnetism and light. Therefore it governs all of chemistry and biology! The electromagnetic force acts on electric charges: opposite sign charges attract, same sign charges repel. So protons and electrons are attracted to one another and protons repel other protons. The electromagnetic force also is a long range force - light can travel all the way across the galaxy and beyond. The electromagnetic force is much stronger than the force of gravity.

Everyone has experience with these long range forces. Most people do not have experience with the short range forces. The short range forces are sometimes referred to as the nuclear forces.

Short Range Forces

The Strong force is an unbelievably strong force - it is many times stronger than than the electromagnetic force - but only acts over distances smaller than the nucleus of an atom. The strong force acts like glue to hold the protons and neutrons close together in the nucleus of an atom. Over very short distances the strong force is stronger than the electromagnetic force of repulsion between protons. At longer distances the electromagnetic repulsive force can overwhelm the strong force.

The Weak force acts on everything (protons, neutrons, electrons, etc.) This force is responsible for some types of radioactivity and allows some strange things to happen (like changing a proton into a neutron plus an anti-electron and a neutrino!).

1.2 Nuclear Energy

The energy released in nuclear reactions is millions of times the energy released in chemical reactions. The energy released comes from mass being converted into energy. The famous equation from Einstein shows how much energy you can get out of an amount of mass.

Energy from Mass

$$E = mc^2$$

Example
How much energy can be released from 1.00 kg of mass?

$$\begin{aligned} E &= mc^2 \\ E &= (1.00)\,(3.00\,\mathrm{x}\,10^8)^2 \\ E &= 9.00\,\mathrm{x}\,10^{16}\,\mathrm{J} \end{aligned}$$

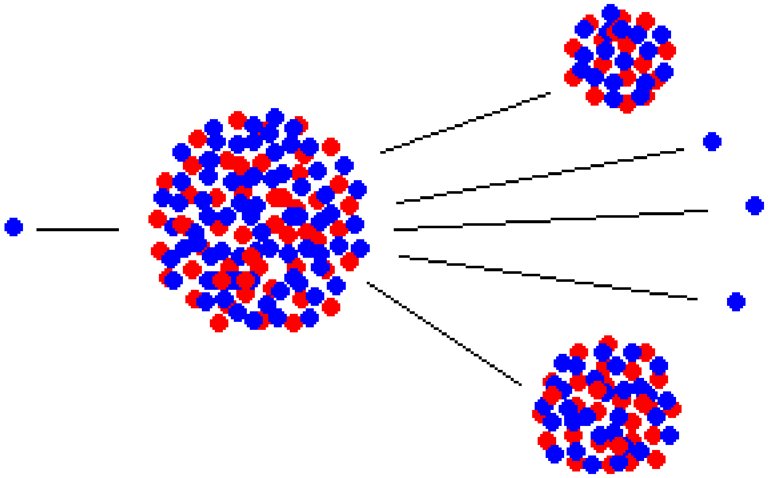
This is enough energy to lift 100,000,000 cars 100 km above the ground!

1.2.1 Fission

Nuclear fission is the splitting apart of the nucleus of a heavy atom. In this process some of the mass is converted into energy ($E = mc^2$). Energy is released only if the nucleus to be split is heavier than iron. A heavy atom has many protons and neutrons in its nucleus. The positively charged protons do not like being near each other - the electromagnetic repulsion gets stronger and stronger as more and more protons are added to the nucleus (the neutrons act to keep the protons separated). Some isotopes of heavy atoms are unstable due to large numbers of protons and deficiency of neutrons. For example, Uranium-238 has 92 protons and 146 neutrons and is relatively stable (but still radioactive!). Whereas Uranium-235 (92 protons and 143 neutrons) is very unstable and is used in nuclear weapons and nuclear reactors. The United States generates about 20% of its electricity in power plants that use nuclear fission. Many parts of the world generate 80% of their electricity needs via this process. One of the possible fission reactions is shown below (protons in red, neutrons in blue). Note: we don't show the electrons because they are very far away and don't participate in this reaction.

Example

$${}^{1}_{0}\mathrm{n} + {}^{235}_{92}\mathrm{U} \rightarrow {}^{36}_{91}\mathrm{Kr} + {}^{142}_{56}\mathrm{Ba} + 3\ {}^{1}_{0}\mathrm{n}$$

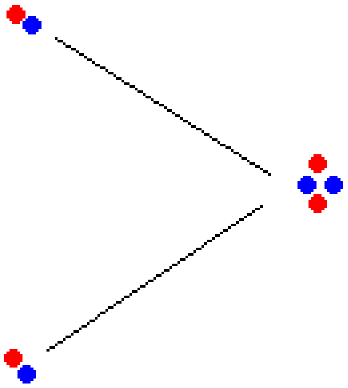


1.2.2 Fusion

Nuclear fusion is the building up of heavier nuclei from lighter nuclei. In this process some of the mass is converted into energy ($E = mc^2$). Energy is released only if the nucleus to be built is less massive than iron. Fusion occurs if nuclei get close enough for the strong force to act (remember the strong force is a short range force). It is difficult to get nuclei close together because the electromagnetic force of repulsion is very large. To get nuclei close they must be moving at high speeds and thus fusion reactions only occur at very high temperatures (millions of kelvins). Fusion reactions someday may provide us with a nearly endless source of energy - but at present we only use fusion reactions for the most powerful weapons on Earth - Thermonuclear Weapons (sometimes called hydrogen bombs). Below is an example of fusion between isotopes of hydrogen (protons in red, neutrons in blue).

Example

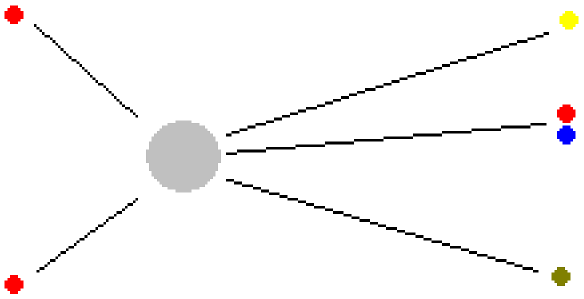
$$^{2}_{1}\mathrm{H} + ^{2}_{1}\mathrm{H} \rightarrow ^{4}_{2}\mathrm{He}$$



1.3 Powering the Sun

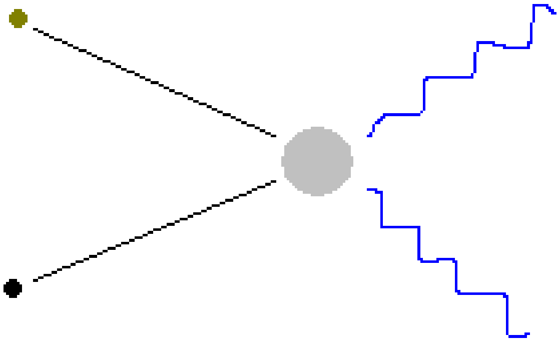
The process that powers the Sun is a multi-step process. Heavy isotopes of hydrogen form from protons via the weak force and fusion (protons in red, neutrons in blue, anti-electron in green, and neutrino in yellow)

$$^{1}_{1}\mathrm{H} + ^{1}_{1}\mathrm{H} \rightarrow \nu + ^{2}_{1}\mathrm{H} + \mathrm{e}^{+}$$



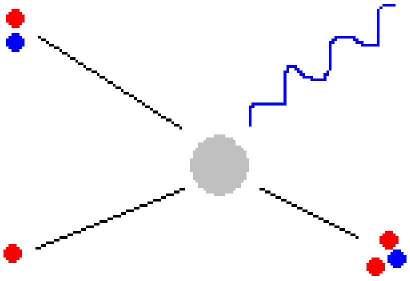
The anti-electron combines with a electron and the mass of the electron and anti-electron is converted into pure energy (light) (anti-electron in green, electron in black, light in wavy blue)

$$\mathrm{e}^{+} + \mathrm{e}^{-} \rightarrow \gamma + \gamma$$



The next step is the production of an isotope of helium and a photon of light via fusion of a heavy isotope of hydrogen with hydrogen. (protons in red, neutrons in blue, light in wavy blue)

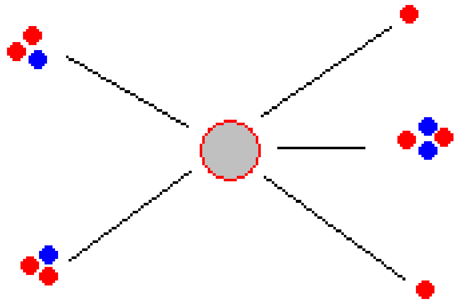
$${}^{1}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + \gamma$$



These two processes generate the vast majority of the light that the Sun, and other main sequence stars, produce.

Finally, isotopes of Helium-3 fuse to give Helium-4 and a couple of protons.

$$^{3}_{2}\mathrm{He} + ^{3}_{2}\mathrm{He} \rightarrow ^{4}_{2}\mathrm{He} + ^{1}_{1}\mathrm{H} + ^{1}_{1}\mathrm{H}$$



1.4 Star Type and Fusion Process

Core Temperature	**Fusion Process**	**Star Type**
> 10,000,000 K	Hydrogen Fusion	Main Sequence
> 100,000,000 K	Helium Fusion	Giant
> 600,000,000 K	Heavy Element Fusion	Super Giant

Fusion powers stars. Which type of fusion process a star uses depends on the temperature a star can generate at its core. All stars start out using hydrogen fusion. Some stars can do other fusion processes after they run out of hydrogen - but only if the core temperature is high enough for the process. Some stars can only use hydrogen for fuel. Some stars have higher core temperatures and can use helium after running out of hydrogen. Some rare stars with very high core temperatures can use heavier elements for fuel after running out of hydrogen and helium.