LECTURE 8 (1/24): PRINCIPLES OF STELLAR STRUCTURE
III. NUCLEAR ENERGY

8.1 ENERGY FROM NUCLEAR FUSION

The nucleus of a hydrogen atom is a single proton.
The nucleus of a helium atom is two protons and two neutrons.

The mass of four protons is 6.690×10^{-24} g.
The mass of a helium nucleus is 6.643×10^{-24} g, 0.7% lighter.

Einstein (1905) demonstrated equivalence of mass and energy, $E = mc^2$.

Eddington (1920's) suggested that the sun might generate energy by fusing hydrogen into helium.

Energy per fusion is small (4×10^{-5} ergs, and the luminosity of the sun is 4×10^{33} ergs/second), but there are lots of atoms in the sun.

To understand how fusion occurs, we must know more about subatomic particles and the interactions between them.

8.2 SUBATOMIC PARTICLES

Atoms are made of protons, neutrons, and electrons. Protons and neutrons make up the nucleus, which is much more compact than the atom itself.

An electron has a negative electric charge.

A proton has a positive electric charge, and its mass is about 2000 times the mass of an electron.

A neutron is similar to a proton (same mass), but it has no electric charge.

Protons and neutrons are made up of smaller particles called quarks. Electrons are thought to be "fundamental" (not made up of smaller particles).

Other particles that will be important to us are photons (particles of light, massless) and neutrinos (which are produced in some radioactive decays). Neutrinos are difficult to detect, and we do not know whether they have mass.

All of these particles also have anti-particles. A photon is its own anti-particle.

8.3 THE FUNDAMENTAL INTERACTIONS

Particles influence each other through four fundamental interactions (sometimes called the four forces):

Gravitational – mass attracts mass

Electromagnetic – like charges repel, opposite charges attract; holds electrons to atomic nucleus

Nuclear – holds together protons and neutrons in an atomic nucleus

Weak – allows protons to turn into neutrons and vice versa

The electromagnetic and gravitational interactions are "long range": their strength falls off like the square of distance. Our everyday experience is related to these two interactions.

The nuclear and weak interactions are "short range"; they can only operate over nuclear distances.

From strongest to weakest, the forces are: nuclear, electromagnetic, weak, gravitational. The ratio of the electromagnetic repulsion between two protons to the gravitational attraction between them is 10^{36} !

Gravity is very weak; we notice it because it is long range and it *always* attracts.

8.4 PARTICLES AND INTERACTIONS

Different interactions affect different particles.

Nuclear: protons, neutrons

Electromagnetic: protons, electrons, photons

Weak: protons, neutrons, electrons, neutrinos

Gravitational: everything

8.5 THE PROTON-PROTON CHAIN

To make helium ($ppnn$) from hydrogen (p): fuse four protons, convert two of them to neutrons.

Getting four protons to collide at once is highly improbable. Fusion in stars like the sun proceeds in steps (see Figure 12-10):

(1) Two protons fuse, one converts to a neutron, making deuterium (pn).
$\longrightarrow$ Conversion of proton produces a neutrino and an anti-electron
$\longrightarrow$ The anti-electron annihilates a nearby electron, producing photons, which carry off energy.

(2) A deuterium nucleus fuses with a proton, making helium-3 (ppn).
$\longrightarrow$ This reaction produces a photon, which carries off more energy.

(3) Two helium-3 nuclei fuse to make helium (*ppnn*)
$\longrightarrow$ Two protons are left over, to play again. They carry energy.

This chain of reactions is called the *proton-proton chain*.

Protons must be moving very fast to overcome their electromagnetic repulsion. Fusion can only occur in gas that is *very hot* ($\sim$ 10 million degrees).

Step (1) requires a weak interaction to convert the proton to a neutron, so it happens rarely. This step controls the rate of fusion in the sun.

8.6 COMMENTS ON FUSION

Other fusion reactions also occur in the sun and other stars. They also release energy.

The proton-proton chain is the most important reaction for producing energy in the sun.

The *carbon cycle* produces most of the energy in stars more than about twice the mass of the sun.

Helium can fuse into heavier elements, but only at temperatures and densities much higher than those in the center of the sun.

8.7 AGE OF THE SUN, AGAIN

If the sun were made entirely of hydrogen, it would contain $M_\odot/m_p = 10^{57}$ protons.

If all of these protons fuse into helium, they turn 0.7% of the sun's mass into energy. The total energy supply is $0.007 M_\odot c^2 = 1.3 \times 10^{52}$ ergs.

Dividing this energy supply by the luminosity of the sun, 4×10^{33} ergs/second, implies a lifetime of 100 billion years, more than enough to accommodate geology.

In fact, the sun is only 70% hydrogen, and only the inner 13% of this gets hot enough to fuse. The expected main sequence lifetime is therefore about 9 billion years.

Solar models and geological evidence imply that the sun is 4.5 billion years old, halfway through its main sequence life.

8.8 SUMMARY

A helium nucleus has 0.7% less mass than four hydrogen nuclei, so fusion of hydrogen into helium can release $E = mc^2$ energy.

Fusion in the sun proceeds via the *proton-proton chain*. Protons must move very fast to overcome their electromagnetic repulsion, so fusion only occurs in gas that is very hot.

With hydrogen fusion as an energy source, the sun can maintain its luminosity for about 9 billion years.

The solution to the 19th century astrophysics/geology conflict involved new fundamental physics: nuclear fusion and $E = mc^2$.