Chapter 10 Origin of the Elements

Approximately 73% of the mass of the visible universe is in the form of hydrogen. Helium makes up about 25% of the mass, and everything else represents only 2%. While the abundance of these more massive ("heavy", $A > 4$) elements seems quite low, it is important to remember that most of the matter in our bodies and in the Earth are a part of this small portion of the matter of the universe. The low-mass elements, hydrogen and helium, were produced in the hot, dense conditions of the birth of the universe itself. The birth, life, and death of a star are described in terms of nuclear reactions. The chemical elements that make up the matter we observe throughout the universe were created in these reactions.

Approximately 15 billion years ago the universe began as an extremely hot and dense environment, the Big Bang. Immediately after its formation, it began to expand and cool. The high energy density produced quark-antiquark electron-positron, and other particle-antiparticle pairs. However, as the particles and antiparticles collided with each other, they would annihilate. As the universe expanded, the average energy of the radiation became smaller. Particle creation and annihilation continued until the temperature cooled enough so that pair creation became no longer energetically possible.

One of the signatures of the Big Bang that persists today is the long-wavelength electromagnetic radiation that fills the universe. This is radiation left over from the original fireball. The present temperature of this "background" radiation is 2.7 K. (The temperature, T, of a gas or plasma and average particle kinetic energy, E, are related by the Boltzmann constant, $k = 1.38 \times 10^{-23}$ J/K, in the equation $E = kT$.) Figure 1 shows the temperature at various stages in the time evolution of the universe from the era of the quark-gluon plasma to the present time.

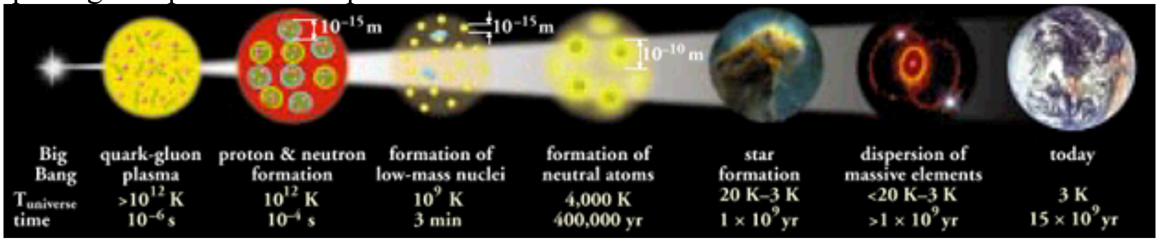

Fig. 10-1. The evolution of the universe

At first quarks and electrons had only a fleeting existence as a plasma because annihilation removed them as fast as they were created. As the universe cooled, the quarks condensed into nucleons. This process was similar to the way steam condenses to liquid droplets as water vapor cools. Further expansion and cooling allowed the neutrons and some of the protons to fuse to helium nuclei. The 73% hydrogen and 25% helium abundances that exists throughout the universe today come from that condensation period during the first three minutes in the history of the universe. The 2% of nuclei more massive than helium present in the universe today were created later in stars.

The nuclear reactions that formed ^{4}He from neutrons and protons were radiative capture reactions. Free neutrons and protons fused to deuterium (d or ^{2}H) with the excess energy emitted as a 2.2 MeV gamma ray,

$$n + p \rightarrow d + \gamma.$$

These deuterons could capture another neutron or free proton to form tritium (^{3}H) or ^{3}He,

$$d + n \rightarrow {}^3H + \gamma \text{ and } \quad d + p \rightarrow {}^3He + \gamma.$$

Finally, ^{4}He was produced by the reactions:

$$d + d \rightarrow {}^4He + \gamma, \qquad {}^3He + n \rightarrow {}^4He + \gamma \quad \text{and} \quad {}^3H + p \rightarrow {}^4He + \gamma.$$

Substantial quantities of nuclei more massive than ^{4}He were not made in the Big Bang because the densities and energies of the particles were not great enough to initiate further nuclear reactions.

It took hundreds of thousands of years of further cooling until the average energies of nuclei and electrons were low enough to form electrically neutral hydrogen and helium atoms. After about a billion years, clouds of cold atomic hydrogen and helium gas began to be drawn together under the influence of their mutual gravitational forces. The clouds warmed as they contracted to higher densities. When the temperature of the hydrogen gas reached a few million Kelvin, nuclear reactions began in the cores of these protostars. Now more massive elements began to be formed in the cores of stars.

The Sun

The Sun produces 4×10^{26} joules per second of electromagnetic radiation — a fraction of this energy is intercepted by Earth. The source of this energy is a series of reactions that convert four protons into one helium nucleus plus 26.7 MeV of energy that appears as energy in the reaction products. Since 1 MeV is equivalent to 1.6×10^{-13} J, there must be

$$\frac{4\times10^{26}\, J/s}{\left(267\frac{MeV}{reaction}\right)\times\left(1.6\times10^{13}\frac{J}{MeV}\right)} = 9.4 \times 10^{38} \text{ reactions/s}$$

occurring in the sun to maintain its energy flow. The basic reaction chain (86% of the time) is the fusion sequence:

$$\begin{aligned} {}^1H + {}^1H &\rightarrow {}^2H + e^+ + n_e, \\ {}^2H + {}^1H &\rightarrow {}^3He + \gamma, \\ {}^3He + {}^3He &\rightarrow {}^4He + {}^1H + {}^1H. \end{aligned}$$

These fusion reactions occur only at the center of the Sun where the high temperature (~10^7 K) gives the hydrogen and helium isotopes enough kinetic energy to overcome the long-range repulsive Coulomb force and come within the short-range of the attractive strong nuclear force. The reaction energy slowly percolates to the surface of the Sun where it is radiated mainly in the visible region of the electromagnetic spectrum (Fig. 10-2). Only the neutrinos escape from the Sun without losing energy.

A detailed mathematical model of the temperature and density profile of the Sun powered by nuclear reactions also serves as a model of other stars. We cannot observe the nuclear reactions directly for confirmation of the nuclear processes. Therefore, astrophysicists look to the neutrinos produced in the fusion of two protons to form deuterium and in the less common (14%) branch of the reaction chain where the fusion of ^{3}He with ^{4}He leads to radioactive isotopes of beryllium and boron that emit neutrinos. For many years, massive underground neutrino detectors observed electron-type neutrinos coming from the Sun, but found fewer neutrinos than expected from the model calculations. One speculation about the missing neutrinos was that they might have converted from neutrinos associated with electrons to those associated with muons or taus as they transit from the interior of the Sun to Earth. Such a conversion could only occur if at least one of the neutrino species has a non-zero mass. The Sudbury Neutrino Observatory, with its sensitivity to all types of neutrinos, has recently demonstrated that this kind of conversion does in fact occur and that two thirds of the neutrinos reaching us from the Sun are actually mu or tau neutrinos. These results also provide a measurement of the difference in masses between the types of neutrinos involved in the conversion process.

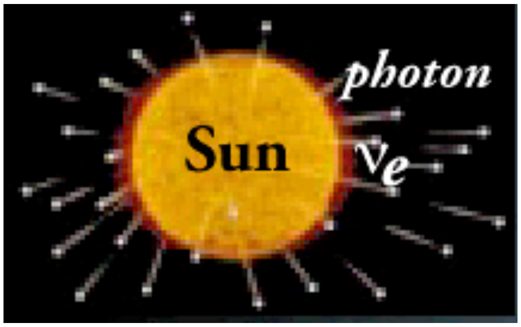

Fig. 10-2. The solar energy reactions emit photons and neutrinos.

Other Stars

A star the size of the Sun will burn hydrogen into helium until the hydrogen in the core is exhausted. At this point, the core of the star contracts and heats up until the fusion of three ^{4}He nuclei into ^{12}C can begin. Stars in this stage of evolution are known as red giants. Low mass stars such as our Sun will then evolve into a compact object called a white dwarf. All nuclear reactions in a white dwarf have stopped. Higher mass stars have internal temperatures (10^8 K) that allow the fusion of carbon with helium to produce oxygen nuclei and energy. For very massive stars, the exothermic fusion of low-mass nuclei into successively more massive nuclei can proceed all the way up to nuclei in the iron region ($A \sim 60$). Table 10-1 shows the temperature (1 keV is equivalent to 1.16×10^7 K), interior density, and process lifetime that occur in stellar evolution of a star 25 times more massive that the Sun. Note the accelerating time-scale as higher mass nuclei are burned.

Once the core of the star is converted into iron-region nuclei, the star has nearly reached the end of its life. Because the average binding energy per nucleon reaches a maximum at this point (see Fig. 2-3), there are no further energy-generating reactions possible and the core of the star collapses because the gravitational force cannot be counter-balanced by the high-temperature, high-pressure interior.

As the collapse of the core occurs, the density grows to the point where it becomes energetically favorable for electrons to be captured by protons via the weak interaction, producing neutrons and neutrinos. This process turns the core of the star into neutrons and produces a huge burst of neutrinos. When the core reaches nuclear density, it rebounds explosively, throwing off much of the mass of the surrounding star. This explosive expansion is called a supernova, one of the most spectacular events in astronomy. If the mass of the remnant core is less than two to three times the mass of the Sun, the core will settle down as a compact neutron star with no further nuclear reactions. More massive cores continue to contract due to the intense gravitational force until the size of the core diminishes to a point — a singularity called a black hole. The object is called "black" because the gravitational force is so strong nothing, not even light, can escape from it.

Table 10-1. The major stages in the evolution of a massive star.

Burning Stage	**Temperature (keV)**	**Density (kg/m^3)**	**Time-scale**
Hydrogen	5	5×10^6	7×10^6 yr
Helium	20	7×10^8	5×10^5 yr
Carbon	80	2×10^{11}	600 yr
Neon	150	4×10^{12}	1 yr
Oxygen	200	10^{13}	6 months
Silicon	350	3×10^{13}	1 day
Collapse	600	3×10^{15}	seconds
Bounce	3000	10^{17}	milliseconds
Explosive	100-600	varies	0.1-10 seconds

In February of 1987 a supernova in a companion to our galaxy, known as the Large Magellenic Cloud, was observed. Underground neutrino detectors saw the neutrinos emitted during the few seconds of the collapse and the birth of either a neutron star or a black hole. The supernova continued to glow for months in the night sky due to the decay of radioactive isotopes that were produced in the explosion. Balloon- and satellite-based detectors observed characteristic nuclear gamma rays from the decays of radioactive Ni and Co isotopes in the supernova debris. Neutron-capture reactions on iron-region nuclei during the few moments of the explosion are believed to have produced nuclei more massive than A = 60. A sequence of neutron capture reactions and beta decays can produce elements all the way up to uranium, and perhaps on further to the region of the superheavy elements.

Books and Articles:

Steven Weinberg, *The First Three Minutes*, Basic Books, New York, 1993.

David Lindley, *The End of Physics,* Basic Books, New York, 1993.

Michael W. Friedlander, *Cosmic Rays,* Harvard University Press, Cambridge, 1989

Nickolas Solomey, *The Elusive Neutrino: A Subatomic Detective Story (Scientific American Library),* W.H. Freeman Co., 1997.