Formation of the Chemical Elements and the Evolution of Our Universe

V. E. Viola
Indiana University, Bloomington, IN 47405

During the 15 billion years that have elapsed since the big bang—from which we trace the origin of our universe—a complex array of evolutionary processes has shaped our present environment. The emergence of galaxies, stars, planetary bodies, and eventually life itself from the primordial big bang dust represents the consequences of interactions between nature's basic forces and fundamental particles. Underlying the great diversity of our present-day universe has been the formation of the chemical elements. Element synthesis (or nucleosynthesis) is now understood in terms of nuclear reactions that occur in a variety of cosmological settings. The recent supernova that became visible in 1987 is one of the more spectacular examples of such settings (*1*).

Despite what might at first appear to be an exceedingly complicated task, during recent years major progress has been made in understanding the origin of the chemical elements. Largely due to the pioneering efforts of Burbidge, Burbidge, Fowler and Hoyle (*2*), and Cameron (*3*), we now have a self-consistent astrophysical scenario which accounts for nature's elements. The present model for the origin of the elements (*4–6*) draws upon information from many diverse fields of science, e.g., astronomy, astrophysics, nuclear science, elementary particle and theoretical physics, atomic and molecular spectroscopy, and geochemistry.

In order to construct a meaningful model of nucleosynthesis, one must first propose a cosmological setting that is consistent with the observed behavior of matter in the universe. Into this environment the known particles are introduced and nature's forces allowed to act upon them. In the table we summarize the particles and forces of primary concern in this discussion. Next one must ask, what nuclear reactions will occur in this environment? To answer this question we must consider results from the study of nuclear stability and reaction probabilities, since it is the atomic nucleus that defines each element. In Figure 1 the stability of nuclear matter is summarized in terms of a "sea of nuclear instability" (*7*), in which all possible neutron–proton combinations are represented in the horizontal plane. The elevation in this plot represents the stability of a given nucleus. Thus, the most stable nuclei are those that protrude out of the sea most prominently, giving rise to a "peninsula of stability". It should be noted that ^{56}Fe is the most stable nucleus rising out of the sea; hence, nature exerts a driving force toward formation of elements near ^{56}Fe. That this conversion is far from complete is demonstrated in Figure 2, where the natural abundances of the elements in the solar system are summarized. This plot shows that the lightest elements still dominate our universe. The litmus test of any theory of nucleosynthesis is its ability to account for the features of Figure 2.

Research over the past 30 years has indicated that there are three major sources responsible for the synthesis of the elements. These include: (1) cosmological nucleosynthesis in the big bang, (2) nucleosynthesis during stellar evolution, and (3) nucleosynthesis in the intersellar medium induced by galactic–cosmic rays, the very high energy particles that permeate space. The third of these mechanisms will lead us

Primary Particles of Concern in Nucleosynthesis[a]

Particles of Concern in Nucleosynthesis		mass	charge	spin
Nucleons	proton $^1_1$H	1.0078 u[b]	+1	1/2
	neutron $^1_0$n	1.0087 u	0	1/2
Leptons	electron $^{0}_{-1}$e	5.4×10^{-4} u	−1	1/2
	neutrino $^0_0\nu$	$<2 \times 10^{-8}$ u	0	1/2
Photon	light, x-ray, γ-ray, etc.	0	0	1

Nature's Forces	relevant property	relative strength
Gravity	mass	$\sim 10^{-39}$
Electromagnetism	charge	$\sim 1/137$
Nuclear		
Strong	nucleon	1
Weak	lepton	$\sim 10^{-11}$

[a] Antiparticles have opposite properties; for example, the antiparticle of the electron, the positron, has a charge +1. Antiparticles are signified by placing a bar above the symbol; thus, the positron $\bar{e}^-$ can also be written e^+.

[b] Mass of neutral $^1_1$H atom.

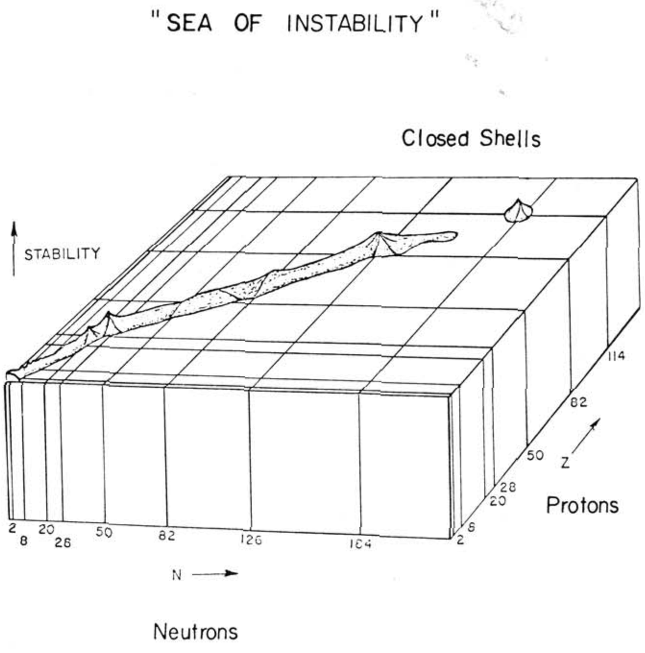

Figure 1. The "sea of nuclear instability" represents the relative stability of possible neutron–proton combinations in nuclei. Neutron and proton numbers are plotted in the horizontal plane, whereas stability is indicated by the vertical dimension. Here "sea level" corresponds to a half-life of about 1 s for a given nucleus, giving rise to a "peninsula of stability for the stable nuclei in nature. Solid lines correspond to closed nuclear shells. The "island of stability" near 114 protons and 184 neutrons represents predicted "superheavy nuclei" which have not yet been observed.

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to consider the eventual fate of our universe; i.e., will it continue its present expansion, or will it someday collapse again into a hot fireball of fundamental particles similar to its big bang origin?

We shall now turn to a discussion of each of these processes in more detail.

Cosmological Nucleosynthesis

The earliest era to which we can trace the origin of our universe is that of the big bang explosion, which is believed to have occurred about 15 billion years ago (*8*). Under the initial conditions of the big bang, all matter and energy existed in the form of a hot, dense fireball that contained only the elementary particles. The expansion of this material into space eventually led to the formation of the more complex systems we now observe—nuclei, molecules, galaxies, and life itself.

Experimental evidence for the big bang rests primarily on two important observations (*6, 8*):

(1) *Red-shift measurements.* The light spectra of stars in all distant galaxies of the visible universe are known to be Doppler-shifted toward the red, indicating that these sources are receding from the earth. Thus, just as we can infer whether a train is coming or going from the varying sound waves we receive, we can apply this principle to the wavelength shifts of light to deduce that we live in a universe that is currently expanding. The magnitude of the red shift increases in direct proportion to the distance of the galaxy from our own, which permits one to estimate that the initial expansion of the universe began about 15×10^9 years ago.

(2) *The universal 2.8 K background radiation.* Radioastronomy measurements have shown that there exists a background of photons in the universe that corresponds to a black-body source at a temperature of about 2.8 K. The uniform distribution of this background radiation field implies that it is of cosmological rather than galactic origin (in the latter case the radiation would have a directional bias toward the center of the galaxy). This radiation field is presumed to be the embers of the big bang explosion and provides us with an insight into the temperature history of the universe.

From these two facts a great deal can be inferred about the primordial condition of the universe. The theory that has evolved to describe the big bang—the standard model—permits us to reconstruct a time evolution of the universe. Elementary particle theorists are currently exploring the possible conditions of the universe at very early stages ($\ll$1 s), in which matter existed in phases composed of more fundamental particles such as mesons, quarks, gluons, etc. (*9*). However, since our objective here is to synthesize nature's elements, we shall not be concerned with the earliest stages but instead begin at a time about 1 s after the big bang expansion, when the temperature of the universe had "cooled" to about 10^{10} K.

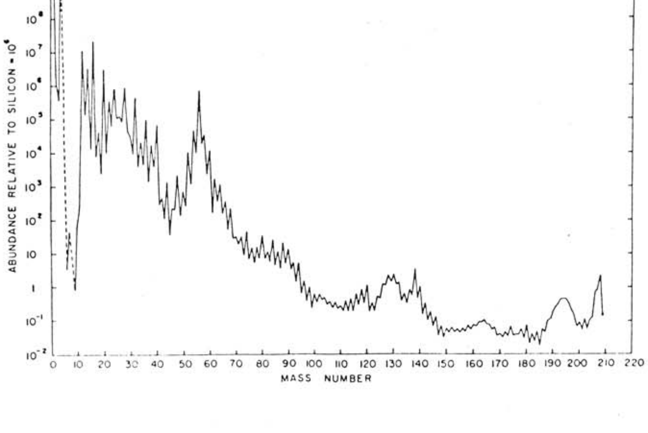

Figure 2. Solar system abundances (number of atoms) of the elements relative to silicon (Si = 10^6) as a function of atomic number.

At this time the universe consisted of a sea of photons, electrons and positrons (the antiparticle of the electron), neutrinos and antineutrinos, plus neutrons and protons (*8*). The properties of these particles are listed in the table. These particles existed in statistical equilibrium with one another according to the following equations:

$$\begin{aligned} {}^{1}\mathrm{H} + e^- &\rightleftarrows {}^{1}\mathrm{n} + \nu \\ {}^{1}\mathrm{n} + e^+ &\rightleftarrows {}^{1}\mathrm{H} + \bar{\nu} \end{aligned} \qquad (1)$$

The essential first step in the synthesis of more complex nuclei—the combination of a neutron and proton under the influence of the attractive nuclear force to form deuterium (^{2}H)—is not possible at such high temperatures because the ^{2}H nuclei instantaneously disintegrate, much as an atom ionizes when exposed to high temperatures.

Here the basic principles of refrigeration come into play: expand a gas and it cools; compress it and it heats up. Thus, as the universe continued to expand, the temperature decreased to a point where ^{2}H nuclei could survive for a finite length of time. At this point, only minutes after the initial explosion, the temperature dropped to about 10^9 K, where the following network of reactions—all rather well studied in the laboratories—became possible.

$$\begin{gathered} {}^{1}\mathrm{H} + {}^{1}\mathrm{n} \rightarrow {}^{2}\mathrm{H} + \gamma \\ {}^{2}\mathrm{H} + {}^{1}\mathrm{n} \rightarrow {}^{3}\mathrm{H} + \gamma;\ {}^{3}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \gamma \\ {}^{2}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \gamma;\ {}^{3}\mathrm{He} + {}^{1}\mathrm{n} \rightarrow {}^{4}\mathrm{He} + \gamma \\ {}^{3}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{7}\mathrm{Be};\ {}^{7}\mathrm{Be} + e^- \rightarrow {}^{7}\mathrm{Li} + \nu \end{gathered} \qquad (2)$$

The formation of nuclei heavier than ^{7}Li in the big bang is prevented by the fact that nuclei with mass numbers $A = 5$ and 8 are extremely unstable due to quantum shell effects—analogous to the chemical instability of the alkali metals.

Within about 3 min, the universe had expanded and cooled to a point where nuclear reactions could no longer be sustained. The remaining neutrons then decayed to protons as follows:

$${}^{1}\mathrm{n} \rightarrow {}^{1}\mathrm{H} + e^- + \bar{\nu} \text{ (half-life = 11 min)} \qquad (3)$$

The unreacted protons and neutrons from the big bang formed the large residual hydrogen abundance we see in the universe today. The primary nuclear reaction product of the big bang was ^{4}He. These two elements make up about 98% of nature's elements (Fig. 2)—mostly in stars.

One strong argument in favor of the big bang hypothesis is that the abundance of ^{4}He appears to be remarkably uniform everywhere we look in the universe, giving rise to the conclusion that most of the helium must have been made at approximately the same time. Otherwise, there would be much greater differentiation in helium composition among the stars of different ages, as is the case for heavier elements. Thus, cosmological nucleosynthesis in the big bang produces primarily ^{4}He, along with trace amounts of deuterium, ^{3}He and ^{7}Li. There is a strong concordance between the measured abundances for the big bang products and those calculated from our knowledge of nuclear reaction rates. From this we are able to infer whether the universe will continue to expand forever. We shall return to this subject in the final section.

Beyond this brief instant in the early expansion of the universe, nucleosynthesis was no longer possible, due to the decreased temperature and density of the expanding medium. Chemistry did not emerge until millions of years later, when the temperature had cooled below about 10,000 K, where H, He, and Li atoms could form. On a macroscopic scale the universe has continued to expand and cool to its present size and temperature.

Stellar Evolution

In the aftermath of the big bang, cosmological dust consisting largely of hydrogen and helium atoms filled the expanding universe. Without gravity and the existence of density fluctuations, element synthesis would have ceased at this stage, leaving us with a rather bland universe. Fortunately, the attractive force of gravity, acting upon regions of higher-than-average density, eventually produced massive concentrations of matter in isolated localities throughout space. This process represented the beginning of galaxy and star formation—and at the same time provided us with a new environment for synthesizing elements (*5, 6*).

As gas clouds condensed from the big bang dust to form embyronic stars, the associated gravitational compression produced a reheating of this localized matter, reaching temperatures and densities in the core of the star approaching 10 million K and 100 g/cm^3, respectively. Such conditions are certainly extreme when compared with those existing for hydrogen on earth, which is about 10^{-4} g/cm^3 at 300 K. On the other hand, this is much less dense than nuclear matter, which has a density of about 10^{14} g/cm^3. It is important to realize that only the core of a star reaches the maximum temperature and density; for example, the temperature at the surface of our sun is only about 5,700 K, while its core is thought to have a temperature of about 14,000,000 K. The density and temperature profiles characteristic of stars like our sun are illustrated in Figure 3.

Hydrogen Burning—Main Sequence Stars

When the core of a star reaches these unusually high temperatures and densities, the protons in the core acquire sufficient kinetic energy to overcome their mutual electric charge repulsion and initiate nuclear reactions. This process—hydrogen burning—characterizes main sequence stars, of which our sun is an example. About 90% of the stars in the universe are main sequence stars. Such stars burn protons into helium by means of the following series of nuclear reactions, also illustrated in Figure 4.

$$
\begin{array}{l}
{}^1\text{H} + {}^1\text{H} \rightarrow {}^2\text{H} + \beta^+ + \nu \\
{}^2\text{H} + {}^1\text{H} \rightarrow {}^3\text{He} + \gamma \\
{}^3\text{He} + {}^3\text{He} \rightarrow {}^4\text{He} + 2\,{}^1\text{H} \\
\hline
\text{net: } 4\,{}^1\text{H} \rightarrow {}^4\text{He} + 2\beta^+ + 2\nu + 26.7\ \text{MeV}
\end{array}
\tag{4}
$$

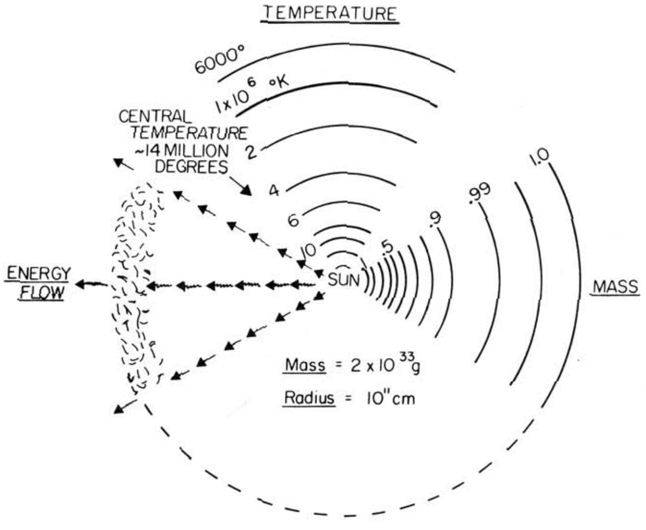

Figure 3. Schematic drawing of the structure of the sun, showing the temperature and fraction of the mass as a function of solar radius.

The above chain reaction is called the ppI cycle, and several variations are known to be possible, depending on the core temperature and composition of the star. The net effect in each case is to convert four protons in ^{4}He, which adds a small amount (~10%) to the primordial big bang ^{4}He concentration. These are examples of fusion reactions, and the amount of energy released makes this reaction chain one of the most efficient energy sources known to man. For example, there are about 6×10^{11} J of energy liberated per gram of hydrogen burned in the above reaction, about 20 million times the amount of energy liberated in the chemical burning of a gram of carbon. These are the kinds of reactions that one hopes will someday power nuclear fusion reactors as a source of electrical energy.

The energy released in hydrogen burning serves as an expansive force to stabilize a condensing star, counteracting the compressional force of gravity. Thus, the star appears to be a stable body, with the energy liberated by nuclear reactions in the core being offset by radiation loss at the surface. As long as the nuclear fuel lasts, the star continues to provide a stable source of energy in space.

The mass of a star determines the rate at which it burns nuclear fuel and therefore its lifetime. The heavier the star, the faster it burns. In main sequence stars the rate-determining step is the fusion of two protons to make deuterium. Note that positrons (antielectrons) and neutrinos are also produced, making this a weak nuclear interaction. This causes the burning process to proceed much more slowly than in most nuclear reactions, accounting for the relatively long lifetime of main sequence stars. From an experimental knowledge of how fast this reaction occurs and how much hydrogen exists in the sun, it is possible to calculate that our sun will remain a main sequence star for another 5 billion years or so.

The fact that neutrinos are emitted in this reaction also provides the opportunity to observe the nuclear reactions that occur in the sun. Since neutrinos interact very weakly with matter, they are the only radiation that can escape directly from the core of the sun and reach the earth. A massive detector to search for solar neutrinos has been operating in the Homestake gold mine in South Dakota for many years now (*10*). One of the conclusions of these studies is that the observed rate of hydrogen burning in the sun is a factor of 2–3 less than calculated. The explanation of this discrepancy constitutes one of the major problems in solar physics (*10*), and sophisticated new neutrino detectors are now being built to examine this result more closely.

In summary, hydrogen-burning reactions stabilize a condensing star and provide a vital source of energy by producing helium from hydrogen. In order to synthesize the more

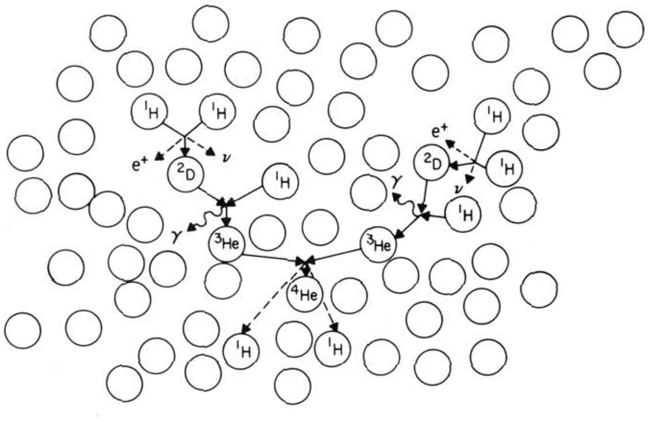

Figure 4. Hydrogen burning: the fusion of ordinary hydrogen in main sequence stars.

complex elements that provide the diversity of our solar system, we must examine more advanced stages of stellar evolution.

Helium Burning—Red Giant Stars

As a main sequence star becomes older, it begins to develop into two phases:

(1) a core composed largely of the helium produced during hydrogen burning and
(2) an outer envelope consisting largely of unburned hydrogen.

While hydrogen burning continues at the interface between the core and the envelope, reactions between +2-charged helium nuclei are inhibited because of their greater electric charge repulsion. As alluded to earlier, the elements lithium, beryllium, and boron ($Z = 3$, 4, and 5) are extremely fragile and disintegrate at temperatures above a few million degrees. For this reason Li, Be, and B are destroyed rather than formed in stars, accounting for their very low abundances in Figure 2.

If the mass of a star is sufficiently large, the force of gravity begins to contract the core once again, leading to still higher temperatures and densities. This causes the envelope of the star to expand greatly and gives rise to a new stage in its evolution, called the red giant phase. Stars that do not contain sufficient mass to sustain more advanced stages of nuclear burning simply exhaust their hydrogen fuel and undergo no further evolution. These become tiny white dwarf stars, which represent the stellar graveyard.

During the red giant stage of a star, gravitational pressure continues to compress and heat the core. When the temperature reaches about 10^8 K, which corresponds to a density of 10^4 g/cm^3, a new type of nuclear reaction becomes possible. Of the several possibilities that might lead to the production of heavier elements from hydrogen and helium at such temperatures, laboratory studies have led us to believe that only one is likely. This exothermic reaction, called helium burning, is represented by the equations

$$\begin{aligned} &{}^4\mathrm{He} + {}^4\mathrm{He} \rightarrow [{}^8\mathrm{Be}]^* + \gamma \qquad (\text{lifetime} = 10^{-16}\ \mathrm{s}) \\ &[{}^8\mathrm{Be}]^* + {}^4\mathrm{He} \rightarrow {}^{12}\mathrm{C} + \gamma \qquad (5) \end{aligned}$$

In effect, to produce a helium-burning reaction, three ^{4}He nuclei must collide almost simultaneously, as shown in Figure 5. The rate of this reaction is low due to the very short lifetime of the ^{8}Be intermediate (or activated complex), which is about 10^{-16} s. Thus, the red giant stage of a star can last for tens of millions of years. At this stage in the star's development the basic element for the formation of biological compounds—carbon—is synthesized.

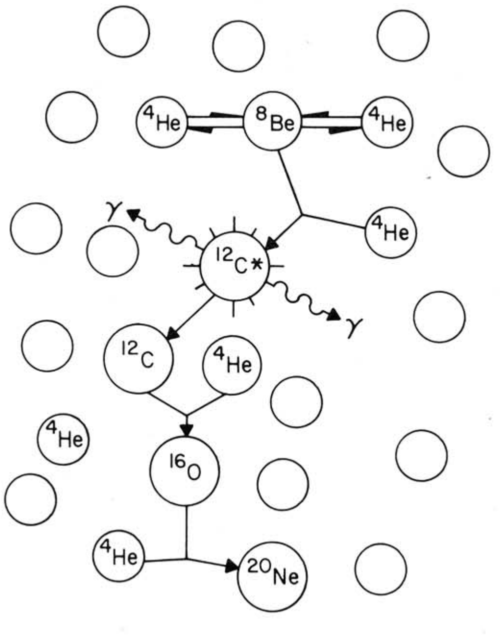

Figure 5. Helium Burning: the fusion of helium in red giant stars.

Once helium burning begins, the core of the star becomes stabilized against further gravitational contraction by the evolution of nuclear energy, producing a new equilibrium situation. At the same time oxygen can be produced via the reaction:

$$ {}^4\mathrm{He} + {}^{12}\mathrm{C} \rightarrow {}^{16}\mathrm{O} + \gamma \qquad (6)$$

The evolutionary cycle of our schematic star is indicated in Figure 6. It begins by burning hydrogen on the main sequence and converting this into helium nuclei. As the helium concentration increases, the core of the star heats up further to the point where helium nuclei fuse to form ^{12}C and, depending upon the conditions of the star, ^{16}O. If the star is of sufficiently low mass, it will burn out and become a white dwarf. On the other hand, if the mass is sufficiently great, a much more dramatic sequence of processes ensues.

Explosive Nucleosynthesis—Massive Stars

As a massive star passes through the red giant phase, new core conditions eventually develop, as illustrated in Figure 6. For the most part the core contains ^{12}C and ^{16}O surrounded by envelopes composed of helium and hydrogen, respectively. The electrostatic repulsion arising from the large nuclear charges of ^{12}C and ^{16}O inhibit nuclear reactions at He-burning temperatures, leading to further gravitational contraction and heating. A star's subsequent fate under these conditions is one of the more poorly understood phases of stellar evolution. The stellar core may continue to evolve via processes similar to the equilibrium situations that exist in main sequence and red giant stars, although on a much shorter time scale. On the other hand, explosive conditions may develop under which nucleosynthesis occurs very rapidly, leading to supernova explosions.

If the core temperature and density reach about 500×10^6 K and 5×10^5 g/cm^3, new avenues of nuclear burning become available. One such reaction involves the fusion of the ^{12}C and ^{16}O remnants from helium burning to form still heavier

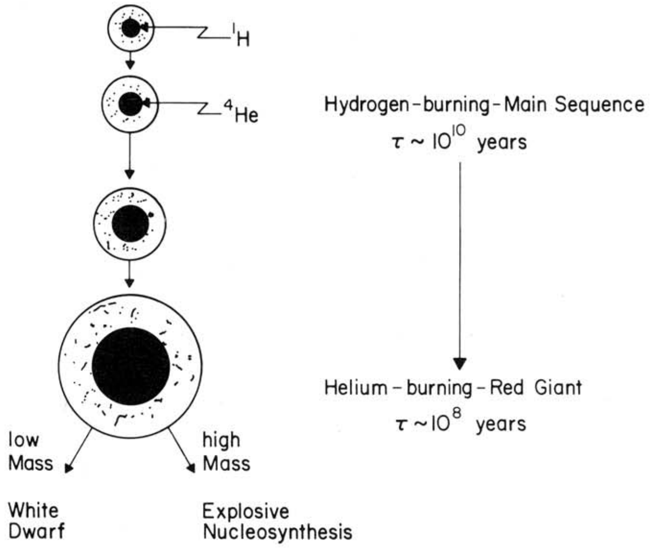

Figure 6. Schematic diagram of stellar evolution from the main sequence to the red giant phase for a star with the mass of the sun. Hydrogen-burning core in the main sequence phase evolves into ^{4}He core. This eventually undergoes helium burning, leading to a greatly expanded envelope in the red giant phase. Low-mass stars become white dwarfs, whereas heavier stars undergo more advanced stages of nuclear evolution.

nuclei. These reactions are complicated, but can be summarized by the following set of exothermic processes:

$$\begin{aligned} {}^{12}\mathrm{C} + {}^{12}\mathrm{C} &\rightarrow {}^{20}\mathrm{Ne} + {}^{4}\mathrm{He} \\ {}^{16}\mathrm{O} + {}^{16}\mathrm{O} &\rightarrow {}^{28}\mathrm{Si} + {}^{4}\mathrm{He} \\ {}^{12}\mathrm{C} + {}^{16}\mathrm{O} &\rightarrow {}^{24}\mathrm{Mg} + {}^{4}\mathrm{He} \end{aligned} \tag{7}$$

Because these reactions can occur relatively rapidly at high temperatures, the evolution of the star proceeds much faster at this stage, and a more varied nuclear composition develops. As the life cycle of a heavy star continues, a core composed largely of nuclei near ^{28}Si evolves. At temperatures near 10^9 K and densities about 10^6 g/cm^3, a new process (silicon burning, or the e process; e for equilibrium) begins. Because of the large electric charge on nuclei such as silicon, it becomes increasingly difficult for fusion reactions between two ^{28}Si nuclei to proceed. However, a wide variety of alternative nuclear reaction paths become possible in this advanced stage of stellar evolution. These reactions involve both the ejection of an α particle (^{4}He) by high-energy photons present in the hot core and the inverse process in which ^{4}He is captured by the surrounding nuclei. This complex reaction chain is summarized as follows:

$$\begin{aligned} {}^{28}\mathrm{Si} + \gamma &\rightleftarrows {}^{24}\mathrm{Mg} + {}^{4}\mathrm{He} \\ {}^{4}\mathrm{He} + {}^{28}\mathrm{Si} &\rightleftarrows {}^{32}\mathrm{S} + \gamma \\ {}^{32}\mathrm{S} + {}^{4}\mathrm{He} &\rightleftarrows {}^{36}\mathrm{Ar} + \gamma \\ \text{net: } {}^{28}\mathrm{Si} \overset{(\alpha,\gamma)}{\rightleftarrows} {}^{32}\mathrm{S} &\overset{(\alpha,\gamma)}{\rightleftarrows} {}^{36}\mathrm{Ar} \overset{(\alpha,\gamma)}{\rightleftarrows} \ldots {}^{56}\mathrm{Ni} \xrightarrow{e^+} \xrightarrow{e^+} {}^{56}\mathrm{Fe} \end{aligned} \tag{8}$$

Here, (α, γ) is shorthand for $x + {}^4\mathrm{He} \rightarrow y + \gamma$. The symbol $\xrightarrow{e^+}$ means radioactive decay by emission of a positron. The e process reactions can go in either direction, but the reactions going toward the right (all of which are exothermic) are favored. This chain of reactions produces primarily nuclei with even atomic numbers and mass numbers A = 32, 36, 40, 44, 48, 52, and 56, which turn out to be unusually abundant in nature (see Fig. 2 and ref *4*, or refer to the periodic table). In addition, because of the richer composition of nuclear matter that exists in the stellar core during the e process, a much more diverse batch of additional nuclear reaction products is possible. This leads to the synthesis of many other nuclei lighter than ^{56}Fe, but in smaller quantities.

This chain of reactions stops near mass number $A = 56$. Recall that ^{56}Fe is nature's most stable nucleus (Fig. 1). Thus, when an iron core develops in a star, the ability of energy-liberating nuclear reactions to provide support for resisting gravitational contraction becomes limited. At this point, a rather complex unstable star has developed, containing most of the elements up to iron in various layers. This is illustrated in Figure 7. Most of the elements required to sustain life have now come into existence. At each stage of evolution, the synthesis processes become less efficient and more diverse, accounting for the steadily decreasing abundances of the elements, observed in Figure 2. Due to the special stability of ^{56}Fe nuclei, a sink is created that accumulates ironlike elements, producing the abundance peak at iron in Figure 2. It also accounts for the low abundance of the heavier elements.

Heavy Element Production—The r Process

The accumulation of iron-group elements in the core of stars with masses greater than about 10 times the mass of the sun leads to catastrophic conditions (*1*). Without the stabilizing influence of nuclear energy evolution, the gravitational force causes the core to collapse; that is, an implosion of the core upon itself results, indicated in Figure 7 in the central region. The implosion occurs on a time scale as short as seconds, during which the density of nuclear matter may reach 10^8 g/cm^3 with a corresponding temperature well over 10^9 K in the center of the core. This rapid heating is followed by a massive shock wave that leads to explosion of the star, a process believed to be associated with supernovae (*1, 11*) such as 1987A (*12*), which was observed in February 1987. Supernovae are relatively rare events, and the study of 1987A promises to provide critical tests of our understanding of stellar evolution theories (*1*).

There are two important consequences of gravitational collapse and the rapid heating that follows. First the temperature increase triggers an extensive network of nuclear reactions throughout the outer envelopes of the star. This leads to a diversity of nuclear species for the elements previously formed. Second, the conditions in the very center of the core, where the temperature and density are highest, cause the iron nuclei to break up by means of photodisintegration reactions, leading to the following schematic processes:

$$\begin{aligned} {}^{56}\mathrm{Fe} + \gamma &\rightarrow 13\,{}^{4}\mathrm{He} + 4\,{}^{1}\mathrm{n} \\ {}^{4}\mathrm{He} + \gamma &\rightarrow 2\,{}^{1}\mathrm{H} + 2\,{}^{1}\mathrm{n} \\ {}^{1}\mathrm{H} + e^- &\rightarrow {}^{1}\mathrm{n} + \nu \end{aligned} \tag{9}$$

As far as nucleosynthesis is concerned, the important point is that large numbers of neutrons are produced in the central core region. Because neutrons have no electric charge, they can interact with previously processed nuclear matter without the constraint of electromagnetic repulsion, which serves to inhibit collisions involving charged particles. This further enriches the variety of nuclei and produces nature's heaviest elements.

This stage of nucleosynthesis is called the r process (r for rapid) and proceeds according to the following series of reactions:

$$ {}^{56}_{26}\mathrm{Fe} \overset{(\mathrm{n},\gamma)}{\rightarrow} {}^{57}\mathrm{Fe} \overset{(\mathrm{n},\gamma)}{\rightarrow} {}^{58}\mathrm{Fe} \underset{\text{etc.}}{\overset{(\mathrm{n},\gamma)}{\rightarrow}} \ldots \rightarrow \rightarrow {}^{79}_{26}\mathrm{Fe} \tag{10}$$

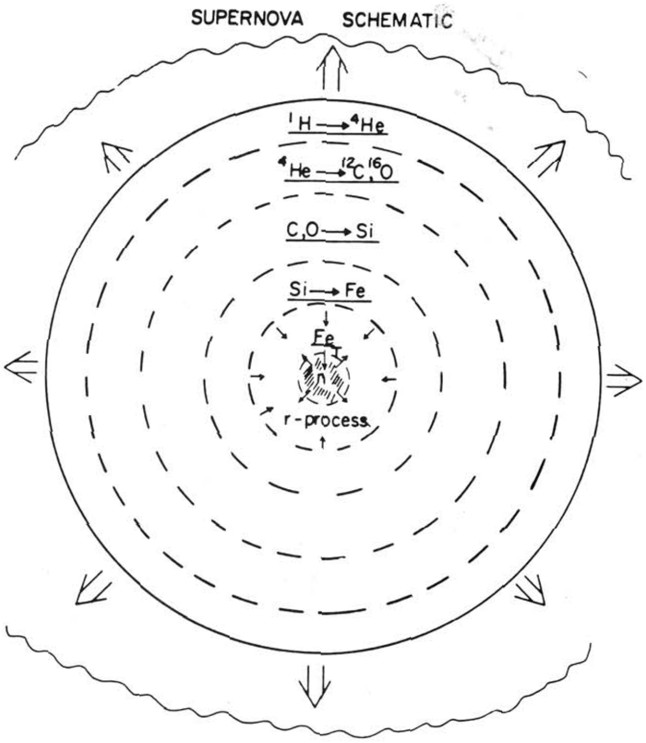

Figure 7. Schematic diagram of stellar structure at the onset of the supernova stage. Nuclear burning processes are indicated for each layer. The r process is associated with the disintegration of iron nuclei in the central region of the star, a process which liberates neutrons.

These reactions produce highly neutron-rich nuclei that are well submerged below the sea of instability in Figure 1. As neutron addition continues, nuclear beta decay (conversion of a neutron into a proton within the nucleus) becomes increasingly probable. This produces the next higher element as shown below:

$$ {}^{79}_{26}\mathrm{Fe} \rightarrow {}^{79}_{27}\mathrm{Co} + \mathrm{e}^- + \bar{\nu};\ {}^{79}\mathrm{Co} \xrightarrow{(\mathrm{n},\gamma)} {}^{80}\mathrm{Co} \xrightarrow{(n,\gamma)} {}^{81}_{27}\mathrm{Co};\ {}^{81}_{27}\mathrm{Co} \rightarrow {}^{81}_{28}\mathrm{Ni} + \mathrm{e}^- + \bar{\nu}, \text{ etc.} \quad (11) $$

This sequence of neutron captures followed by beta decay produces heavier elements, with higher atomic numbers.

It is the r process that forms thorium and uranium ($Z = 90$ and 92) and must account for the possible existence of any "superheavy" elements in nature, indicated by the island of stability at $Z = 114$ and $N = 184$ in Figure 1. There is no other nuclear reaction mechanism known by which we can account for the production of the amounts of uranium and thorium present in the universe today. A schematic diagram of the r process is shown in Figure 8. The upper limit to element synthesis in the r process is imposed by nuclear fission reactions, which split heavy nuclei into two lighter fragments of nearly equal mass. In this way the nucleosynthesis process is terminated and nuclear material simply cycles between the build-up of very heavy elements and fission into intermediate-mass elements. It is not clear at what point fission becomes dominant in the r proces chain of mass build-up, but most probably (*13*) it occurs around mass number $A \simeq 270$, which would prevent formation of superheavy elements ($A \approx 300$) in nature.

Although there are other significant processes responsible for element production (to be discussed below), the r process is thought to conclude the life cycle of a first-generation star, that is, a star composed of original big bang material. Following gravitational collapse, the neutron-rich supernova core may form a dense neutron star or perhaps even a black hole ($\rho \geq 10^{16}$ g/cm^3) (*11*). Pulsars, or tiny rotating stars that emit regular bursts of radiofrequency radiation, are believed to be neutron stars. This theory is supported by observations of the Crab Nebula, the remnant of a supernova that exploded in 1054 A.D., which has a pulsar at its center. Black holes cannot be directly observed since they are so dense that not even photons can escape. In Figure 9 we compare the sizes of black holes with other astronomical bodies.

A supernova explosion ejects processed nuclear material into the cooler intersellar medium where the temperatures and densities are much lower. All of the elements essential for life are now present, as well as the heaviest elements in nature. This material then cools, attracts electrons to form netural atoms and molecules, and the entire cycle begins anew. First, the gravitational force begins to condense matter to form second-generation stars, or, for smaller amounts of mass, planets, meteorites, and cosmic dust may form. In this way succeeding generations of stars, richer in nuclear reaction possibilities, evolve. Our sun must be at least a second-generation star because we see evidence of heavy elements in its photosphere.

The life cycle of a star is depicted in Figure 10. If one recalls the abundances of the elements shown in Figure 2, it is clear that the successive stages of element synthesis need not be very effiicent in order to produce nature's elements.

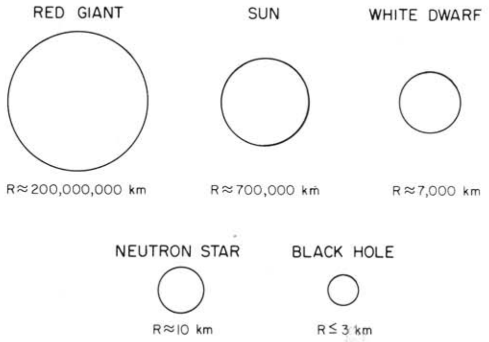

Figure 9. Relative sizes of main sequence stars, red giants, white dwarfs, pulsars, and black holes for objects that have the same mass as our sun.

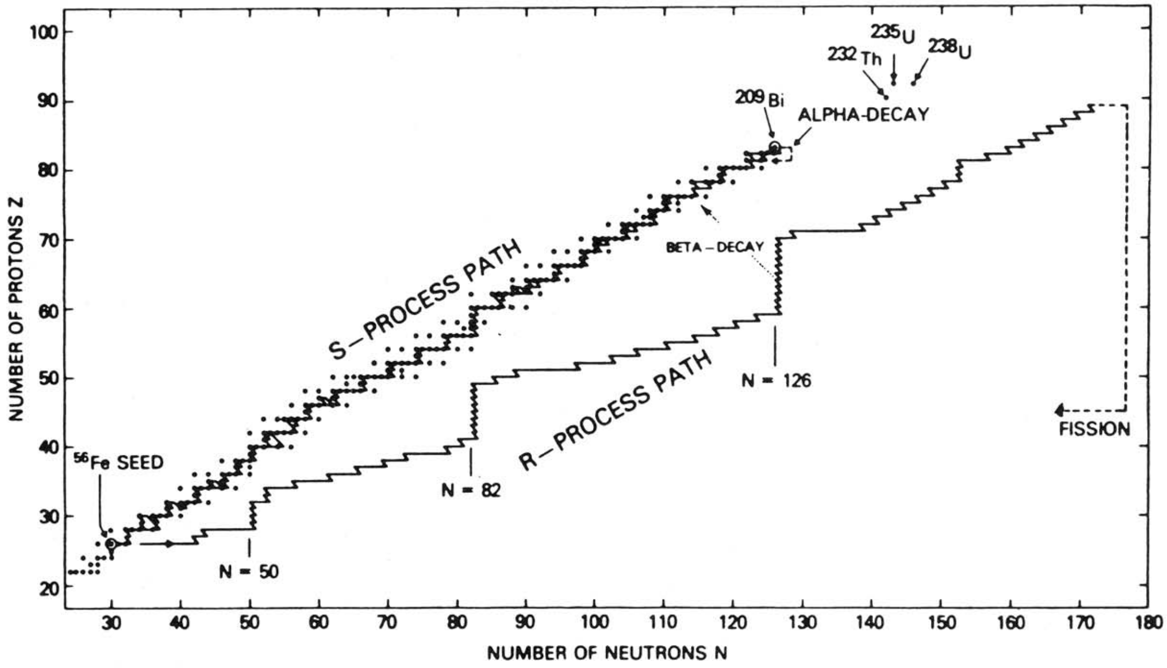

Figure 8. Diagram of the neutron capture paths along the peninsula of stability (Fig. 1) in the r (lower) and s (upper) processes, beginning with ^{56}Fe seed nuclei. Vertical scale is the atomic number and horizontal scale is the neutron number of the products. Stable nuclei in nature are indicated by solid dots.

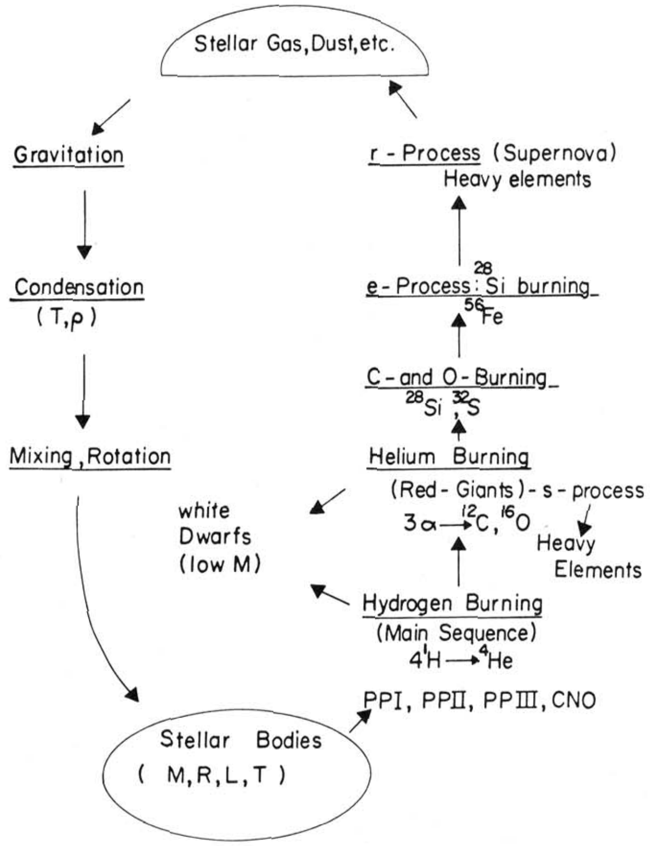

Figure 10. Life cycle of a star.

Hence, even after the complete evolution of a star, 98% of the material will still be in the form of hydrogen and helium.

The s Process

Up to now we have emphasized the production of elements in the initial cycle of the star's lifetime. In later generation stars the presence of previously processed nuclear material makes it possible to form elements in many new ways. Among the most important of these mechanisms is the s process (s for slow). Like the r process, the s process involves sequential neutron-capture and beta decay steps, but it takes place in relatively stable stars such as red giants where neutrons are produced at a slow, steady rate.

The difference in time scales between the s process and the r process results in the formation of different isotopes of the elements. The r process tends to form the heavier isotopes of a given element (those with excess neutrons), whereas the s process forms medium-mass and lighter isotopes. This is illustrated in Figure 8 where both the s and r process paths are shown for a given range of atomic nuclei. The s process, which can be studied extensively in nuclear reactors, is a continuing process, as evidenced by the fact that we see the atomic spectra of element 43, technetium, in some stars. Technetium is extinct on Earth because the longest lifetime of any of its isotopes is only 4 million years, which is much shorter than the 4.5×10^9-year age of the Earth. The s process synthesizes elements up to bismuth ($z = 83$), where the chain is terminated by the very short half-lives of nuclei with $A = 210$–220.

In summary, the sequence of nuclear reactions that begins with hydrogen burning and subsequently evolves through the s and r processes results in the formation of the elements between carbon and uranium (and perhaps heavier). At the same time these reactions provide the source of energy that powers the solar system and leads to the great diversity of cosmological phenomena that we observe in our universe, ranging from main sequence stars to supernovae.

Nucleosynthesis in the Interstellar Medium

Cosmological nucleosynthesis in the big bang and element synthesis during stellar evolution, as discussed in the previous sections, can account for nearly all the elements of the periodic table and their relative abundances (*4–6*). However, three elements have been omitted from this scenario: the thermally fragile Li, Be, and B nuclei (LiBeB). Some ^{7}Li may remain from the big bang, but the remaining isotopes, ^{6}Li, ^{9}Be, ^{10}B, and ^{11}B, must have been produced by some other mechanism. One compelling clue to the origin of LiBeB is that they are enriched by a factor of about a million in galactic cosmic rays relative to solar system material, as shown in Figure 11. It is currently believed that they originate in interactions of galactic cosmic rays with the gas and dust of the interstellar medium.

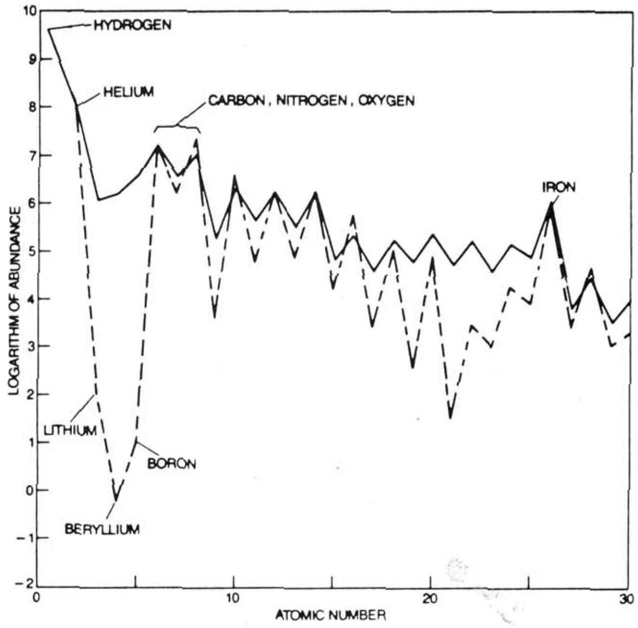

Figure 11. Relative abundances of elements in the solar system (dashed line) and in galactic cosmic rays measured above the Earth's atmosphere (solid line).

Cosmic rays are very energetic nuclei, primarily H and He, that permeate our galaxy. While their origin is poorly understood (supernovae explosions have been proposed as a source), their properties have been studied extensively in balloon and satellite flights above the Earth's atmosphere. LiBeB nuclei are believed to be formed when cosmic rays interact with the ^{4}He, carbon, nitrogen, and oxygen nuclei present in the interstellar medium, i.e., the gas and dust dispersed throughout space. These reactions occur at energies much higher than those characteristic of the big bang and stellar evolution but in an environment which has a very low density. Consequently, the temperature is low, and the LiBeB products do not burn up after their formation, as they do in stellar interiors.

This is one case of a nucleosynthesis process where extensive direct knowledge exists for both the salient nuclear reactions and the astrophysical processes involved (*14, 15*). For example, the energy spectrum and the composition of the cosmic rays have been widely studied. Furthermore, the composition of the interstellar medium is also thought to be relatively well understood. Hence, measurement of nuclear reaction probabilities for these systems allows one to calcu-

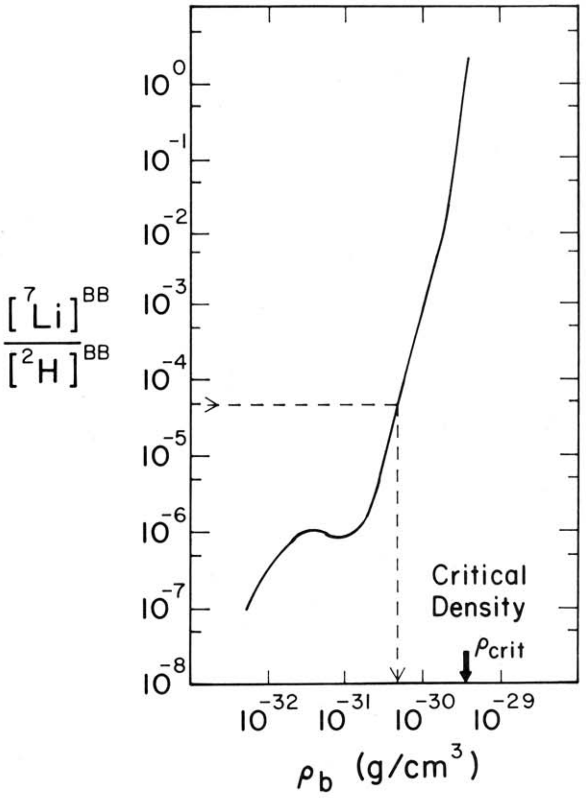

Figure 12. Solid line shows plot of the ratio of ^{7}Li to ^{2}H formed in the big bang as a function of the present density of the universe. The dashed line corresponds to the observed ^{7}Li/^{2}H ratio and the corresponding density. The density required to close the universe, ρ_{crit}, is shown by the heavy arrow.

late the expected LiBeB abundances for comparison with the observed values—and thereby test the validity of this proposed mechanism. It is found that the abundances of ^{6}Li, ^{9}Be, ^{10}B, and ^{11}B can be reproduced nearly quantitatively with the model. However, the isotope ^{7}Li is greatly underproduced, which further strengthens the belief that ^{7}Li must be synthesized primarily in the big bang.

In fact, if one assumes that the additional ^{7}Li necessary to match its abundance in the solar system comes from the big bang, it is possible to infer the basic conditions which characterized this primordial explosion. In Figure 12 we show the abundance ratio of ^{7}Li (corrected for galactic cosmic ray synthesis) divided by the abundance of deuterium (which is thought to have been formed only in the big bang) as a function of the matter density of the universe. The solid curve is the predicted ^{7}Li/^{2}H ratio for the big bang as a function of the present density of the universe, ρ, based upon calculations involving all possible nuclear reaction probabilities.

Also indicated on Figure 12 is the value of the matter density required to halt the present expansion of the universe, ρ_c, or the critical density. An important question related to the critical density is whether the universe will continue to expand forever. Do we live in an ever-expanding (open) universe, or will gravity eventually put the brakes on this expansion and cause the universe to contract again (a closed universe)? This is illustrated in Figure 13, which depicts the average separation between galaxies as a function of time. In the case where $\rho > \rho_c$, sufficient matter is present in the universe to reverse the present expansion, eventually leading to conditions similar to the original big bang. If $\rho \leq \rho_c$, then the universe will continue to expand forever; i.e., the gravitational force is not strong enough to counterbalance the present expansion. This is a subject of considerable debate in current astrophysical theory. Since the ^{7}Li to deuterium ratio is seen to be such a critical function of the density of the universe, one can estimate whether the universe is open or closed from Figure 12.

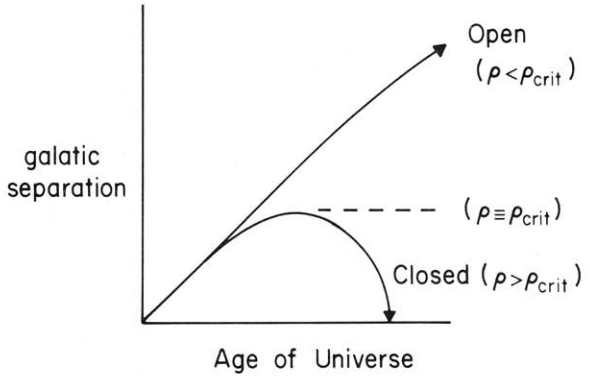

Figure 13. Average separation between galaxies as a function of the age of the universe for various assumptions concerning the density.

Based on such arguments the matter density of the universe is estimated to be about a factor of 10 too low to permit a closed universe. This result is in agreement with studies that attempt to determine ρ from the mass associated with clusters of galaxies. Hence, these nucleosynthesis data also impinge on very fundamental concepts of our universe and indicate that the universe is open and will continue expanding forever.

However, other factors may alter these conclusions. It may be that much of the universe is composed of "dark matter", i.e., matter that cannot be observed with present atronomical techniques (*16, 17*). For example, exotic particles, not yet observed in the laboratory, may constitute a large fraction of the universal mass. We must continue to examine these possibilities in order to solidify our understanding of the origin of our universe.

Summary

From our previous discussions we have seen that cosmological nucleosynthesis is primarily responsible for the formation of normal hydrogen and ^{4}He, with a small amount of deuterium, ^{3}He, and ^{7}Li also being contributed to the Earth's elements. Subsequently, stellar evolution synthesizes all the nuclei between carbon and uranium (and perhaps heavier). Furthermore, the elements lithium, beryllium, and boron can also be understood when one adds interactions of galactic cosmic rays with the nuclei which compose the interstellar medium. The abundances of the elements calculated on the basis of these models agree well with those observed in nature (Fig. 2). Undoubtedly, cosmic-ray interactions also contribute very small amounts to the abundances of other elements, but these represent only a minor perturbation on the major element abundances. Thus, with the above processes we can synthesize the atomic nuclei that make up our universe and provide an energy source for subsequent evolution of our solar system and surrounding galactic phenomena. At this stage, then, the basic materials are present to permit the subsequent evolution of planetary bodies, atoms, molecules, and eventually life.

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