Treb. Soc. Cat. Biol., Vol. 39 (1986) 49-71

NUCLEOSYNTHESIS OF THE CHEMICAL ELEMENTS

VICTOR E. VIOLA, JR.

Department of Chemistry and Cyclotron Laboratory. University of Maryland. College Park, MD 20742. USA.

SUMMARY

From our previous discussions we have seen that cosmological nucleosynthesis is primarily responsible for the formation of 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 (or heavier), and the abundances calculated on the basis of these two models agree rather well with experimental data. Furthermore, formation of the elements lithium, beryllium, and boron can also be understood when one adds interactions of galactic cosmic rays with the interstellar medium. Undoubtedly, cosmic ray interactions also contribute very small amounts to the abundances of other elements, but these probably represent only a minor perturbation of the major elemental 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.

INTRODUCTION

During the 15 billion years or so that have elapsed since the Big Bang – from which we trace the origin of our universe – a complex array of evolutionary processes has occurred. These phenomena, including the emergence of galaxies, stars, planetary bodies, and their constitutent chemical elements, have been vital precursors to the formation of intelligent life on our planet (or elsewhere). The synthesis of atomic nuclei via nuclear reactions in cosmological processes (nucleosynthesis) is an especially important precursor for the development of life.

It is currently believed that the primordial universe was composed largely of the simplest constituents of matter, the elementary particles. Until such a time in our history when the element carbon had evolved, there was no possibility for even the simplest organic molecules to form. Similarly, the existence of increasingly complex molecules of biological significance depended upon the existence of other complex atoms, such as nitrogen, oxygen, phosphorus, iron, etc. Of further significance, in order for living systems to sustain themselves, a constant source of energy was essential. As we shall discuss below, this energy was provided by nuclear reactions which synthesize the elements in stars.

Despite what might at first appear to be an exceedingly complex problem, during recent years great progress has been made in understanding the origin of the elements. Important early contributions rest on the theories of nucleosynthesis proposed by Gamow (1); Burbidge, Burbidge, Fowler and Hoyle (2), and Cameron (3). For a detailed review of both the historical and current status of this subject the interested reader is referred to the excellent review article by Trimble (4).

The present model for the origin of the elements draws upon many diverse fields of science. In Fig. 1 we schematically show the idealized picture that is followed in the present development of the subject. The model contains three basic components, all of which must be self consistent:

1. The basic principles – First of all a cosmological setting must be proposed that is consistent with the observed behavior of matter in the universe. Into this environment we then introduce the presently known fundamental particles and the basic forces of nature. Thus, we must first review the salient properties and basic laws which describe the particles and forces.

2. Interaction processes – Given the system defined by the above principles, we must then ask what reactions will occur. Since in this discussion we are primarily concerned with the formation of atomic nuclei, our main concern here will be nuclear reactions. In order to understand these we must draw on extensive experimental and theoretical results derived from the study of nuclear science.

3. Products – Finally, the products that are predicted from the interactions that occur in the model system must correspond to observed experimental data. Specifically, in the context of this paper, this means that the abundances of the chemical elements and their isotopic ratios in nature must be adequately predicted.

THE MODEL

In practice, there has been considerable interplay between the various parts of the model outlined in Figure 1, as indicated by the arrows between the components. For example, our knowledge of the abundances of the elements has frequently served as a guide to the types of nuclear interactions that have been responsible for their production. Now let us review these model components in more detail.

A. Principles

In general all cosmological phenomena must be considered as possible sites of nucleosynthesis. However, we know that in order for most nuclear reactions to occur, the colliding nuclei must posses energies on the order of a million electron volts (MeV) or more. This energy corresponds to a temperature of about 10^{10} °K (that is, 10 thousand million degrees Kelvin) and hence, this criterion restricts our possible sites to very hot energetic phases of the universe.

The fundamental particles which are the starting ingredients for forming atomic nuclei in these environments are summarized in Table I. These particles include the pro-

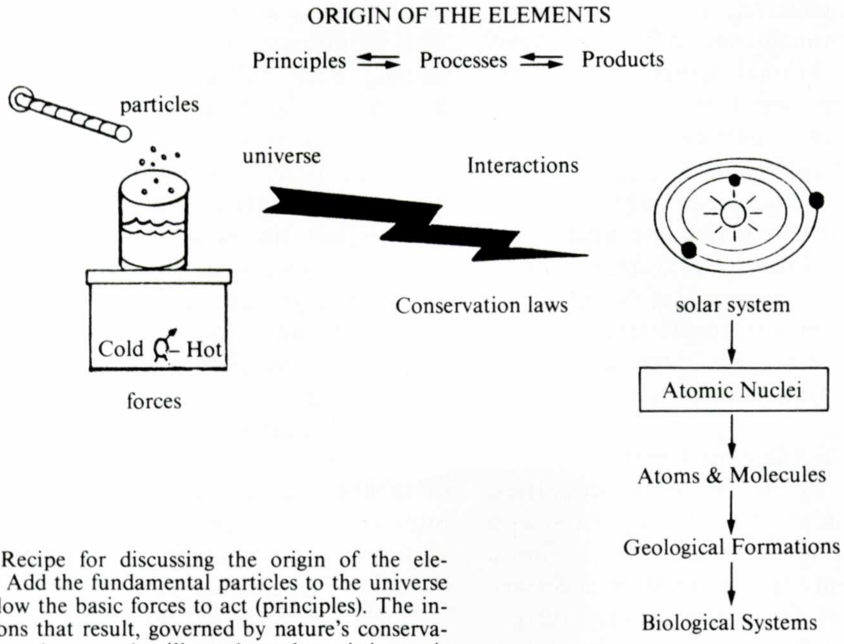


Fig. 1. Recipe for discussing the origin of the elements. Add the fundamental particles to the universe and allow the basic forces to act (principles). The interactions that result, governed by nature's conservation laws (processes) will produce the existing universe (products).

TABLE I

Particles and forces of concern in nucleosynthesis

FUNDAMENTAL PARTICLES			mass	charge
Baryons	protons	$^{1}_{1}H$	1.0078 amu	+1
	neutrons	$^{1}_{0}n$	1.0087 amu	0
Leptons	electron	$^{0}_{-1}e$	0.00054 amu	−1
	neutrino	$^{0}_{0}z$	~ 0	0
Photons	light, x-ray, γ-ray, etc.		0	0

BASIC FORCES

Gravity-mass
Electromagnetism-charge
Nuclear-baryons

ton; neutron, electron, neutrino, and photon (or electromagnetic radiation). Although many additional particles are known, they have very short lifetimes. Thus, only the small group of particles listed in Table I live sufficiently long to play a significant role in the structure of our universe. It should be noted here that the neutron in free space is radioactive and decays into a proton with an average lifetime of about 16 minutes. However, inside atomic nuclei the neutron is stable, i.e. it retains its identity for the lifetime of the nucleus in which it resides.

Each of the fundamental particles can be characterized by two primary properties, mass and charge. Other properties also serve to distinguish the particles more completely, but these will not be necessary for the present discussion. There also exists a class of particles called antiparticles. These are essentially the same as the particles in Table I, except that all their properties are reversed. For example, the antielectron (or positron) is an electron with a positive charge (+1) and negative mass of – 0.0054 amu.

The two particles in which most of the present mass of the universe resides are the proton and the neutron, which belong to a class of particles called baryons. These have nearly identical masses and differ only in that the proton has a charge of + 1 and the neutron has a neutral charge (0). The electron and neutrino belong to another class of particles, called leptons. The electron has a very small mass relative to the baryons and has a negative charge. We shall say very little about the electron in this discussion since under the conditions of nucleosynthesis, the temperatures are so high that all atoms are completely ionized. The primary importance of the electron in this description becomes clear when we discuss nuclear β decay, a radioactive decay process whereby a neutron changes into a proton, an electron and an antineutrino. The neutrino is an elusive particle with an unmeasureably small mass and no charge. Both the electron and neutrino have very important roles to play in the evolution of stars (5), but these will not be discussed here. The final particle is the photon, or electromagnetic radiation. The photon has no mass or charge, and is known by several names depending upon its wavelength and source. For example, light, ultraviolet, infrared, microwave and γ-radiation are all different forms of the photon (e.g. γ rays are very short wavelength radiation which originate in nuclei).

The basic forces listed in Table I determine how the fundamental particles will interact with one another – i.e. they represent the glue whereby the fundamental particles are held together. These are:

1. *The gravitational force.* This is an attractive force that depends upon the mass of the constituent particles in a system. Hence, it will primarily affect protons and neutrons, and to a much lesser extent electrons. This force is normally very weak with respect to the other forces listed below. But, for massive astronomical bodies such as the sun, $M_o = 2 \times 10^{33}$ grams (M_o = mass of the sun), it can become very important.

2. *The electromagnetic force.* This force represents a repulsion between charged particles of the same charge and an attraction between opposite charges. Thus, the proton attracts the electron to form the hydrogen atom (^1H). Two protons will repel one another and hence, must be accelerated toward one another in order to overcome this repulsion and bring them together. The electromagnetic force between two fundamental particles is about 10^{37} times stronger than the gravitational force.

3. *The nuclear force.* The nuclear force is attractive and acts primarly between baryons. It is the strongest of the forces, about 137 times stronger than the electromagnetic force. It is effective only when the particles are very close together ($\sim 10^{-12}$ cm), whereas gravity and electromagnetism exert their force over much longer distances. Hence, in order to generate nuclear reactions, it is necessary to bring baryons (or nuclei) very close together.

Two additional fundamental relationships will also be necessary to understand nucleosynthesis. The first of these is the well known Einstein equation:

$$E = Mc^2 \tag{1}$$

That is, energy (E) and mass (M) are interconvertible. In many nuclear reactions that occur in stars, substantial mass is converted into energy. This relationship determines the amount of energy our sun (or any star) emits. The second fact to keep in mind is that:

$$T \propto \rho^{1/3}$$

where T is temperature and ρ stands for the density of a body. Under the force of gravity, massive astronomical bodies contract, thereby increasing their density. The resultant gravitational pressure causes massive amounts of cosmological matter to heat up, leading to the formation of stars. In this way very high temperatures can be obtained that provide a means of increasing the energies of nuclear particles to the point where they can react with one another, converting mass into energy and providing a long-term energy source for our universe. At the same time new elements are created.

4. *The weak force.* In contrast to the nuclear force, the weak force (also referred to as the *weak nuclear* force) does not lead to the release of large amounts of energy in nuclear reactions. As its name implies, this is a very weak force with a strength that falls between that of the electromagnetic force and the gravitational force. Its range is even shorter than the range of the nuclear force.

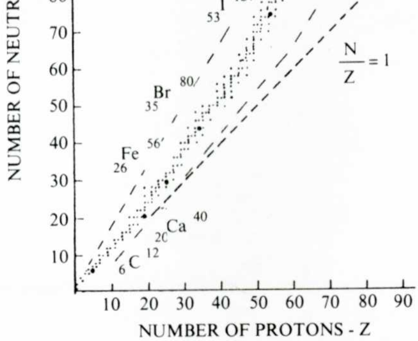


Fig. 2. Plot of the proton number (Z) versus neutron number (N) for the stable nuclei observed in nature (dots). The long-dashed line encompasses most of the nuclei that have been observed in the laboratory and the short-dashed line represents nuclei with equal neutron and proton numbers. Representative stable nuclei are indicated by heavy dots.

B. Nuclear Interactions

Extensive studies of nuclear reaction processes and the systemic behavior of nuclear matter have made it possible to refine our theories on the origin of the elements. In order to combine the basic ingredients in such a way that the observed solar system abundances of the elements result, it is valuable to ask the question: Assuming all possible combinations of neutrons and protons may exist, what atomic nuclei are actually observed? Measured trends in nuclear stability serve as an important guide in this respect.

In Figure 2 a plot of neutron number (N) versus proton number (Z) is shown for the stable nuclei found in nature. It is apparent that light nuclei prefer to have approximately equal numbers of protons and neutrons, whereas increasingly heavy elements tend to have an excess of neutrons over protons. It should be noted that the neutron-proton ratio is a rather continuous function that forms a very narrow band of stable nuclear species.

In Fig. 3 the energetic behavior of nuclei is summarized in terms of a plot of the average binding energy of a nucleus (the average energy with which the observed nuclei are held together). In such a plot nuclei that have the highest binding energies are held together most strongly and hence are the most stable. Note that ^{56}Fe is at the peak of this curve, making it the most stable nucleus in nature. This fact has important consequences for the synthesis of heavy elements. Figure 3 can be used to estimate the energetic trends in nuclear reactions. For example, reactions bet-

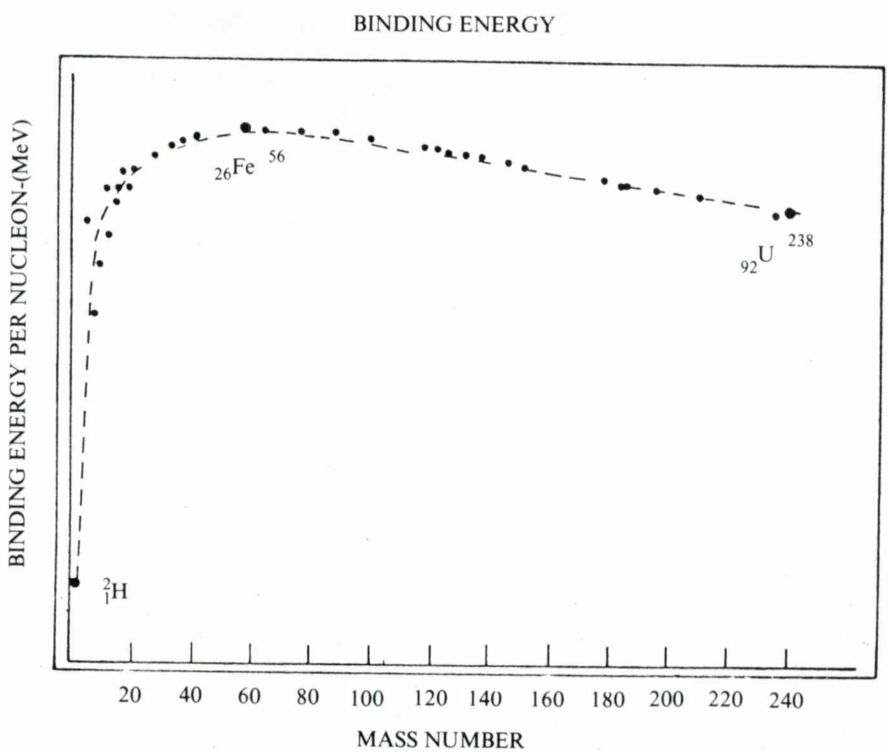


Fig. 3. Plot of the binding energy per nucleon versus mass number for the stable nuclei. The binding energy represents the strength with which the neutrons and protons in a nucleus are held together.

ween light nuclei (*fusion*) will generally lead to more stable nuclei and thus will *release* energy. In contrast, reactions between heavy nuclei will have the opposite energetic trends and therefore must absorb energy. Similarly, by splitting a heavy nucleus into two pieces (*fission*) to form more stable lighter nuclei, energy will be *released.* When considering whether or not a nuclear process will release or absorb energy, Fig. 3 provides an important predictive tool.

The information in Figures 2 and 3 is combined in Fig. 4 to present an allegorical summary of nuclear stability trends, known as the «sea of nuclear instability» (6). Here the neutron and proton numbers for the various known nuclear combinations are shown in the horizontal plane and the vertical dimension represents the degree of nuclear stability (or binding energy). Sea level on this plot corresponds to nuclei which are sufficiently stable to retain their identity for about one second or more. It is observed that the nuclei stable enough for us to study in a laboratory (~ 1800 of them) form a rather narrow peninsula extending into the sea of instability. All other species are submerged below sea level; i.e., they are very unstable and thus disintegrate before they can be observed. Further topographical structure arises when the quantum mechanical effects on nuclear stability imposed by closed shells (or magic numbers) are included. These are indicated by the solid lines for certain proton and neutron numbers.

Uranium, element 92, is the heaviest element observed in nature, whereas elements as high as atomic number 106 have been observed in the laboratory (7). Beyond the known limit of existing nuclei there is a small island of nuclei near

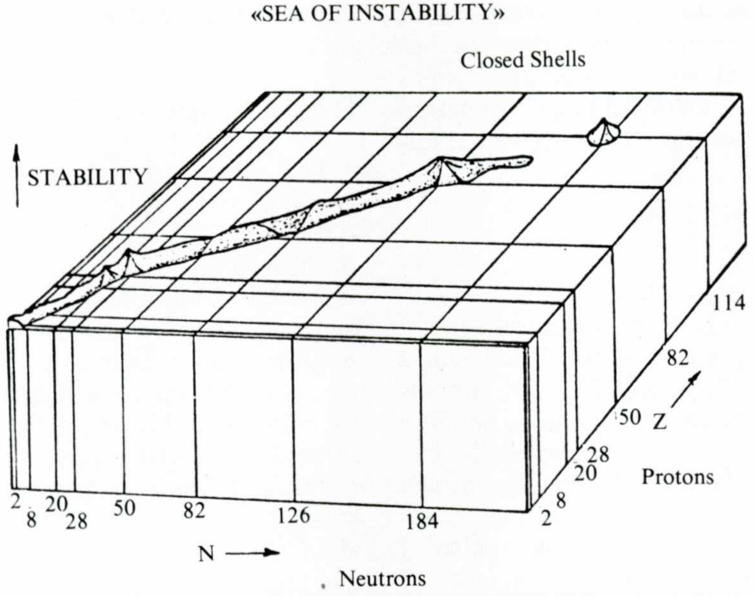


Fig. 4. The «Sea of Instability» represents a summary of the stability of nuclei which survive for about one second or longer. Neutron and proton numbers are plotted in the horizontal plane, whereas stability is indicated by the vertical dimension. Solid lines correspond to closed nuclear shells. The «island of stability» near 114 protons and 184 neutrons represents «superheavy nuclei», which have not yet been observed.

Z = 114 and N = 184. These are the hypothesized superheavy elements which, if they exist, are a consequence of the stability associated with nuclear shells with these proton and neutron numbers. Thus far, searches for the existence of these species in both nature and in the laboratory have been unsuccessful. (For a thorough review of the more or less current status of this subject the reader is referred to reference 7.)

Once it is known whether or not a nucleus is stable, the probability of it forming in nuclear reactions must be considered. Extensive measurements of the probabilities of nuclear reactions, or the reaction rates, have been made in many laboratories throughout the world, in particular at the California Institute of Technology (5). Based upon these measurements one can evaluate the course of any chain of nuclear events that might lead from the fundamental particles to more complex systems. In order to discuss these nuclear reactions we should take a moment and define the nomenclature that will be used throughout this article. The standard nuclear notation for describing atomic nuclei is given as follows:

$$^{A}_{Z}X$$

Here the X stands for the chemical symbol of an element; that is, H stands for hydrogen, He for helium, etc. The Z represents the atomic number of a nucleus, or more specifically, the number of protons it contains. This subscript is frequently omitted since it is redundant with the element symbol. The A represents the mass number of a nucleus, which is the total number of protons and neutrons contained in the system. Isotopes are nuclear species X which have the same Z, but different A.

In writing nuclear equations the sum of the mass numbers for the reactants must equal that of the products. This is also true for the sum of the atomic numbers for the reactants and the products. As an example, we can consider the equation

$$^{4}_{2}He + ^{4}_{2}He \rightarrow ^{6}_{3}Li + ^{2}_{1}H$$

This equation represents the reaction of two ^{4}He nuclei (total A = 8, total Z = 4) with one another to form the isotope of ^{6}Li and deuterium, ^{2}H (total A = 8, total Z = 4). This will be our standard way of describing nuclear reactions.

By combining the known behavior of nuclear energetics and the measured probabilities for the reactions of interest in nucleosynthesis, one can then hope to predict what elements might be formed in cosmological processes and also estimate the relative abundances of these products. In cases where experimental data are lacking, one must then rely upon calculated nuclear properties and reaction rates in order to make these estimates.

C. Solar System Abundances

The critical test of any theory of nucleosynthesis is its ability to reproduce solar system abundances of the elements and their isotopic ratios. Determination of such abundance ratios is a complex task dependent upon a knowledge of the composition of all components of the solar system. Such information is derived from the study of spectral lines from the sun as well as analysis of earth, lunar and meteoritic material. Because of the varied chemical history of solar system material, elemental abundance ratios vary from place to place and thus very careful consideration of such factors is required. Isotopic ratios for a given element, on the other hand, tend to be very uniform throughout the solar system, thus providing a rigorous test of nucleosynthesis theories. Because the sun consti-

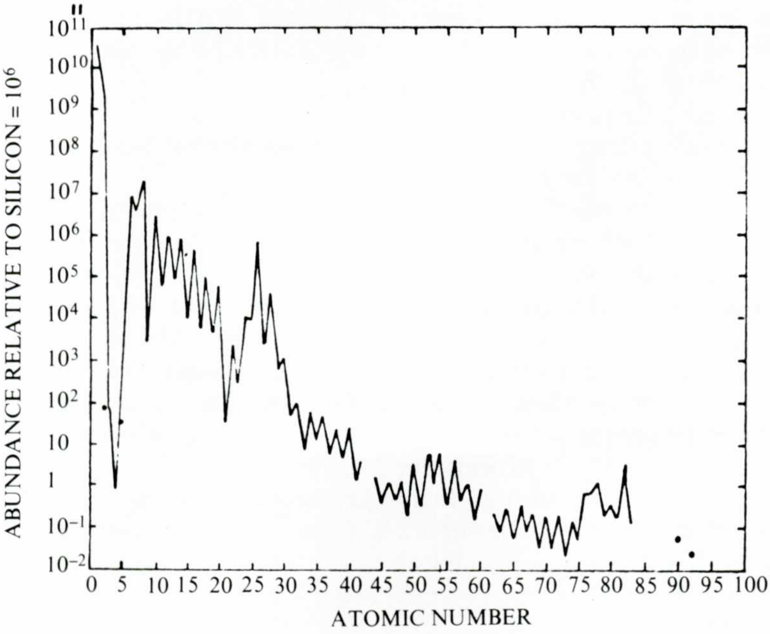


Fig. 5. Solar system abundances of the elements, relative to silicon, as a function of atomic number.

tutes the major fraction of the solar system's mass, some simplifications result. Also, by studying the spectra of other stars, one notes considerable (although certainly not complete) uniformity for much of the universe. For this reason the solar system abundances are sometimes referred to in a more adventuresome spirit as cosmological abundances.

In Table II the abundances of the elements are listed as a function of mass number. Similarly, Figure 5 gives a plot of

TABLE II
Abundance of the elements in the Solar System (by Mass)

Hydrogen: ^1H (^2H)	71 %
Helium: ^4He (^3He)	27 %
A = 5,8	0
$_3Li$, $_4Be$, $_5B$	10^{-5} %
$^{12}C - ^{20}Ne$	1.8 %
Sodium-Titanium (Z = 11-22)	0.2 %
Iron Group	0.02 %
$63 \leq A \leq 100$	10^{-5} %
$A > 100$	10^{-5} %

the relative abundances of the elements as a function of atomic number. It is important to note in Table II and Fig. 5 that most of the universe is composed of hydrogen, ^1H. In addition, there is a small amount (1 part in 10^5) of hydrogen of mass 2, or deuterium. Helium is the next most abundant element and is composed primarily of ^4He. These two elements constitute most of the mass of the universe. However, a universe composed only of this material would be very uninteresting because in order for life to evolve, the presence of carbon and more complex elements is essential.

Another important feature of the solar system abundances is that nuclei with mass numbers A = 5 and 8 do not exist in nature. Both are very unstable nuclei which do not hold together for any appreciable length of time. This fact severely limits the pathways for synthesizing heavier elements from ^1H and ^4He, and has very important consequences for our theory of nucleosynthesis. It is also interesting to note that the elements lithium, beryllium, and boron (Li, Be, B) have very small abundances. This is due to the fact that these nuclei are extremely fragile and are easily broken up. As the elements become gradually heavier, one finds that the elements carbon through neon represent about 1.8 percent of the nuclei in nature, and for increasingly heavier elements the abundances become still smaller. In Fig. 5, it is worth noting that there is a peak in the abundance curve corresponding to iron. This peak is a consequence of the unusual nuclear stability of ^{56}Fe. It is also apparent that for heavy elements beyond iron, there is some structure in the abundance curves. This is associated with features of nuclear structure that are involved in the synthesis of heavy elements.

In addition to the abundance ratios of the elements, there is also a large amount of data on the isotopic ratios of a given element. For example, the ratio of ^{5}Li to ^{6}Li in nature is known to be 12.5. Isotopic ratios have been measured with high accuracy for all of the elements and are found to be remarkably uniform throughout the solar system. Observation of anomalies in the isotopic ratios frequently indicates unusual evolutionary features of the element in question (8).

Thus, our model of nucleosynthesis begins with the basic principles, applies existing knowledge of nuclear interactions, and the final result should then describe the abundances and isotopic ratios of the elements. Research over the past 25 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 interstellar medium via galactic cosmic ray interactions. We shall now turn to a discussion of each of these processes in more detail.

MAJOR SOURCES OF THE ELEMENTS

A. 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 (9). Under the initial conditions of the Big Bang, all matter and energy existed in the form of a hot, dense fireball which contained only the elementary particles. The expansion of this material into space, and subsequent cooling, 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:

(1) Red-shift measurements – The spectra of stars in all galaxies of the visible universe are known to be Doppler-shifted toward the red, indicating that the light sources are receding from the earth. The implication of this fact is that we live in a universe that is currently expanding.

(2) The universal 2.7 °K background radiation – Radioastronomical measurements have shown that a uniform background radiation exists in the universe which corresponds to a black-body source at 2.7°K. Penzias and Wilson recently received the Nobel Prize for this discovery. This background radiation field is presumed to be the remnant of the radiation field associated with the Big Bang explosion. From these two facts, a great deal can be inferred about the primordial condition of the universe.

During the first few minutes of the big bang, the fundamental particles existed in an intense sea of radiation at temperatures of 10^{10} to 10^{12} °K or greater (9). Neutrons and protons existed in equilibrium with one another according to the following equations:

$$^1H + e^- \rightleftharpoons {}^1n + \nu$$

$$^1n + e^+ \rightleftharpoons {}^1H + \nu$$

The combination of a neutron and a proton to form deuterium (^2H) –the essential first step in the synthesis of more complex nuclei– is not possible at such high temperatures because the ^2H nuclei instantaneously disintegrate.

However, as the universe continued to expand, the temperature eventually decreased to a point where ^2H nuclei could survive for a finite length of time. At this point, approximately three minutes after the initial explosion (9, 10), the temperature had dropped below about 10^{10} °K, and the following series of reactions – all rather well studied in the laboratory – became possible

$$^1H + {}^1n \rightarrow {}^2H + \gamma$$

$$^2H + {}^1n \rightarrow {}^3H + \gamma;\ {}^3H + {}^1H \rightarrow {}^4He + \gamma$$

$$^2H + {}^1H \rightarrow {}^3He + \gamma;\ {}^3He + {}^1n \rightarrow {}^4He + \gamma$$

$$^3He + {}^4He \rightarrow {}^7Be + \gamma$$

The formation of nuclei heavier than ^7Li during the Big Bang was strongly inhibited by the instability of nuclei with mass A = 5 and 8, shown in Table II.

With continued expansion and decreased density, the universe eventually cooled to a point where nuclear reactions could no longer be sustained. The remaining neutrons then decayed to protons as follows:

$$^1n \rightarrow {}^1H + e^- + \bar{\nu}$$

(average life times = 16 minutes)

Thus, the unreacted protons and neutrons from the Big Bang resulted in a large residual hydrogen abundance in the universe. The primary nuclear reaction product of the Big Bang was ^4He.

One strong argument in favor of this hypothesis is that the abundance of ^4He appears to be rather uniform (~ 24-28 %) everywhere we look in the universe, thus 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 compositions among the stars of different galaxies. Thus, we believe that cosmological nucleosynthesis in the Big Bang produced primarily ^4He, plus the residue of protons that led to the very large abundance of hydrogen atoms in the universe. In addition, trace amounts of deuterium, ^3He, and ^7Li were also formed and this process is thought to be primarily responsible for these isotopes.

B. Stellar Evolution

In the aftermath of the Big Bang, cosmological dust consisting largely of hydrogen and helium atoms filled the expanding universe. The decreasing density which accompanied this expansion cooled the Big Bang remnants to temperatures well below those at which nuclear reactions could occur. If it were not for the force of gravity, element synthesis would have ceased at this stage. From our personal point of view the result would be a very dull universe, for it would not allow for the existence of carbon and heavier elements, the essential atoms for biological systems.

However, eventually the attractive force of gravity began to produce massive lumps of matter in 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.

As these embryonic stars condensed, their density increased and they began to

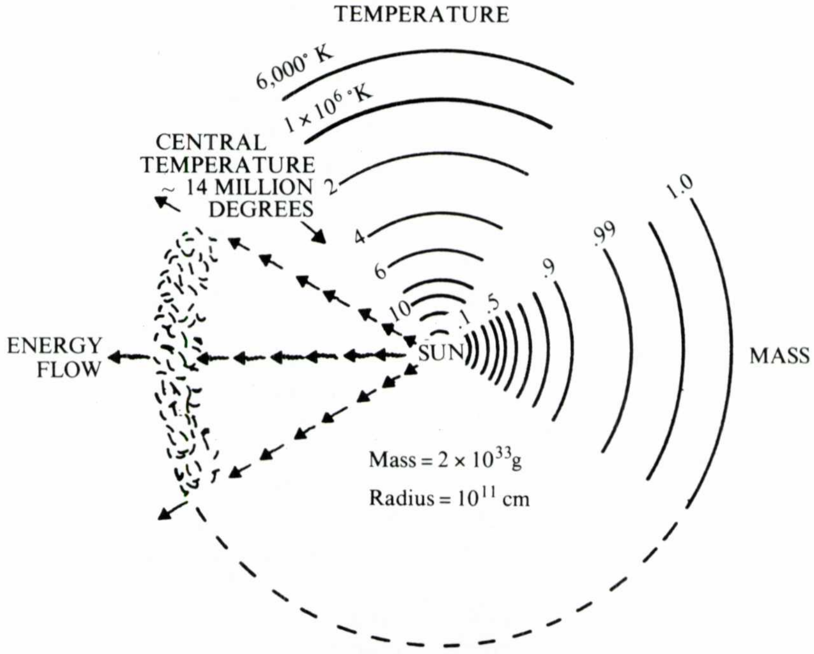


Fig. 6. Schematic drawing of the structure of the sun, showing the temperature and fraction of mass as a function of solar radius.

heat up once again. At sufficiently high tempe-ratures, about 10,000 °K, hydrogen atoms become ionized into protons and electrons. Under increasing gravitational pressure, the density of the nuclei in the core of a developing star eventually reaches very high values, corresponding to about 100 g/cm^3, or a temperature of about 15 million °K. Such conditions are certainly extreme when compared with those existing for hydrogen on earth, which is about 300° K and 0.001 g/cm^3. 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 the star reaches the maximum temperatures and densities; 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 Fig. 6.

Hydrogen Burning: Main Sequence Stars

When the core of a star reaches a temperature of approximately 10 to 20 million °K and densities approaching 100 g/cm^3, the protons in the core acquire sufficient energy that nuclear reactions again become possible. The process of hydrogen burning (or proton burning) characterizes what are called main sequence stars, of which our sun is an example (11). About 90 percent 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 7.

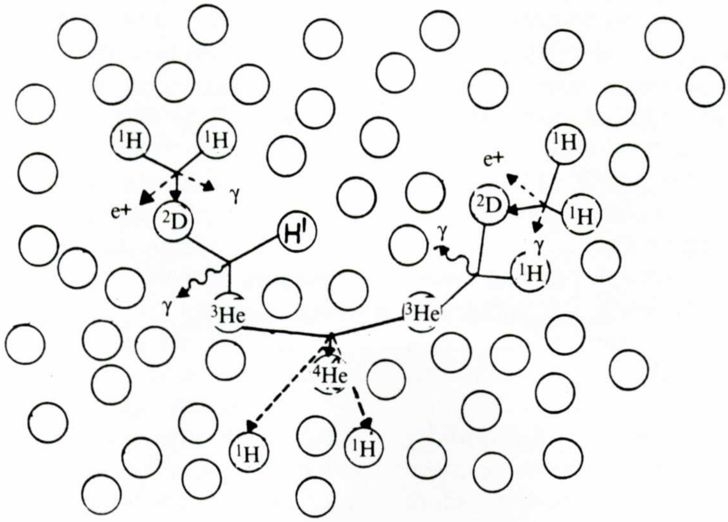
$$^1H + {}^1H \rightarrow {}^2H + \beta^+ + \nu$$

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

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

$$\text{NET: } 4\,{}^1H \rightarrow {}^4He + 2\beta^+ + 2\nu + 26.7\ \text{MeV}$$

HYDROGEN BURNING:
THE FUSION OF ORDINARY HYDROGEN
IN MAIN SEQUENCE STARS



Density ≈ 100 grams/cm^3
Temperature ≈ 10-20 × 10^6 °K

$^1H + {}^1H \rightarrow {}^2H + \beta^+ + \nu$

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

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

NET: $4\,{}^1H \rightarrow {}^4He + 2\beta^+ + 2\nu + 26.7$ MeV

Fig. 7. Schematic diagram and equations describing the hydrogenburning process in which hydrogen is fused into ^{4}He nuclei in main sequence stars.

In this way the element helium is synthesized during hydrogen burning. The above reactions have been studied in the laboratory and several variations of this reaction sequence are known to be possible, depending on the temperature at the core of the star. The net effect in each case is to convert ^{1}H into ^{4}He. These are examples of fusion reactions which serve to fuse two nuclei together and form a heavier nucleus. The amount of energy released in this reaction makes it one of the most efficient energy sources known. For example, there are about 1.5×10^{11} calories liberated per gram of hydrogen burned in the above reaction, more than 20 million times the amount of energy liberated in the chemical burning of a gram of carbon. The energy released in hydrogen burning serves to stabilize a condensing star, counteracting the force of gravity. When these two effects counterbalance one another, the star appears to be a stable body. As long as the nuclear fuel lasts, the star continues to provide a constant source of energy in space.

The mass of a star determines the rate at which it burns nuclear fuel and thus how long it will live. The heavier the star, the faster it burns. In main sequence stars the slowest step is the fusion of two protons to make deuterium. Note that positrons (antielectrons) are produced in this reaction (the first of the above equations). This is unusual in nuclear reactions and usually causes the nuclear process to proceed very slowly, 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 continue to shine for another 5 billion years or so.

In summary, hydrogen-burning reactions stabilize a condensing star and generate energy by producing helium from hydrogen. However, the net product of this process is only a small amount of helium, which was already present in the initially formed star. In order to synthesize more complex elements, 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. Hydrogen burning continues at the interface between the core and the envelope. However, at temperatures of 15 million °K, reactions between helium nuclei are inhibited because of the electromagnetic repulsion between the two nuclei. Furthermore, studies of the nuclear stability of the elements lithium, beryllium, and boron ($Z = 3$, 4 and 5) show that these are extremely fragile nuclei and that at temperatures above about 1 million °K they disintegrate. For this reason Li, Be and B cannot be formed in any appreciable amount in stars (see Table II). Hence, further element synthesis subsides in the core.

If the mass of the 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 the evolution of the star, called the red giant stage. Stars which are not heavy enough to sustain more advanced stages of nuclear burning simply exhaust their hydrogen fuel and undergo no further evolution. These are known as white dwarf stars, which represent the stellar graveyard.

During the red giant stage of a star the gravitational force continues to contract the core. When the temperature reaches about 10^8 °K, which corresponds to a density of 10^5 g/cm^3, a new type of nuclear reaction becomes possible. Of the several possible nuclear reactions that might conceivably 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 reaction, called helium burning, is represented by the equation:

$$^4He + {}^4He \rightarrow [^8Be]^* + \gamma$$
(lifetime = 10^{-16} seconds)

$$[^8Be]^* + {}^4He \rightarrow {}^{12}C + \gamma$$

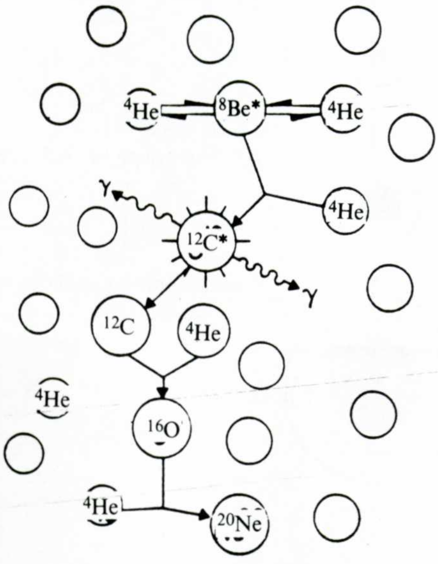
To produce a helium-burning reaction, three ^{4}He nuclei must collide almost simultaneously, as shown in Figure 8. The chances of this occurring are low due to the very short half-life of the ^{8}Be intermediate, which is about 10^{-16} seconds. As a consequence, the red giant stage of a star can last for millions of years. Thus, the element-synthesis chain skips over the elements lithium, beryllium, and boron to produce carbon. At this stage in the star's development the basic element for the formation of biological compounds has now been synthesized.

Once helium burning begins, the core of the star is again stabilized and a new equilibrium situation results. Under this new condition, gravitational contraction and expansive nuclear burning again offset one another. At the same time it is possible to produce oxygen by means of the following reaction:

$$^{4}\mathrm{He} + {}^{12}\mathrm{C} \rightarrow {}^{16}\mathrm{O} + \gamma$$

The evolutionary cycle of our schematic star thus far is indicated in Figure 9. The star has begun by burning hydrogen in the main sequence and converting this into helium nuclei. As the helium concentration increases, the core of the star heats up further to the place where three helium nuclei fuse to form ^{12}C and, depending upon the conditions of the star, ^{16}O. At this stage 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, much more complicated sets of nuclear reactions can occur. These are described below.

HELIUM BURNING:
THE FUSION OF HELIUM IN RED GIANT STARS



Density $\approx 10^5$ grams/cm^3

Temperature $\approx 10^8$ °K

$$^{4}\mathrm{He} + {}^{4}\mathrm{He} \rightleftharpoons [{}^{8}\mathrm{Be}^{*}];\ t_{1/2} = 10^{-16}\ \mathrm{sec}$$

$$[{}^{8}\mathrm{Be}^{*}] + {}^{4}\mathrm{He} \rightarrow {}^{12}\mathrm{C} + \gamma$$

$$^{12}\mathrm{C} + {}^{4}\mathrm{He} \rightarrow {}^{16}\mathrm{O} + \gamma$$

Fig. 8. Schematic diagram and equations describing the helium-burning process in which ^{4}He is fused into ^{12}C in red giant stars.

Carbon and Silicon Burning: Massive Stars

As a star passes through the red giant stage, new core conditions eventually develop, as illustrated in Figure 9. For the most part the core contains ^{12}C and ^{16}O surrounded by envelopes composed of helium and hydrogen. The large charge of the ^{12}C nucleus prevents the occurrence of nuclear reactions at these temperatures. Hence, the core undergoes further gravitational contraction and heating if the star is sufficiently massive. Its subsequent fate under these conditions is probably one of the more poorly understood phases of nucleosynthesis. The core of he star may continue to evolve via processes similar to the equilibrium situations that exist in main sequence and red giant stars, although the latter stage would be much shorter lived. On the other hand, the evolution of the star may become quite rapid and develop explosive conditions under which nucleosynthesis occurs very rapidly.

If the core temperature and density reach about 600 million °K and 5 × 10^5 g/cm^3, new types of nuclear burning begin. The first type that becomes possible is called carbon burning. This reaction involves the fusion of the ^{12}C and ^{16}O remnants from helium burning which form still heavier nuclei. These reactions are complicated but can be represented by equations of the type:

$$^{12}\mathrm{C} + {}^{12}\mathrm{C} \rightarrow {}^{20}\mathrm{Ne} + {}^{4}\mathrm{He}$$

$$^{16}\mathrm{O} + {}^{16}\mathrm{O} \rightarrow {}^{28}\mathrm{Si} + {}^{4}\mathrm{He}$$

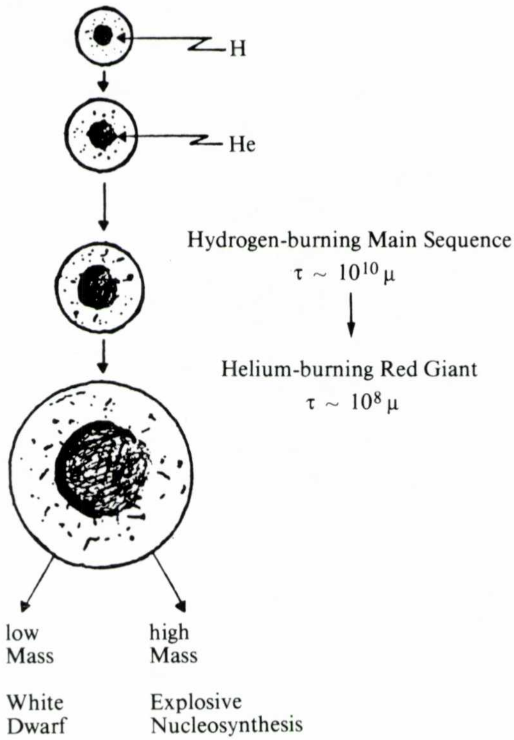


Fig. 9. Schematic diagram of stellar evolution from the main sequence to the red giant phase. Hydrogen-burning core in main sequence phase evolves into ^{4}He core. This eventually undergoes helium-burning, leading to a greatly expanded envelope in the red giant phase. Low mass stars become white dwarfs whereas heavier stars undergo more advanced stages of nuclear evolution.

Because these reactions can occur relatively rapidly at high temperatures, the evolution of the star proceeds much faster at this stage and a much more varied nuclear composition develops. As the life cycle of a heavy star continues, a new core composed largely of nuclei near ^{28}Si evolves. At temperatures near 1×10^9 °K and densities about 1×10^6 g/cm^3, a process known as silicon burning 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, because of the high temperatures and the variety of nuclear reactions that can occur in this advanced stage of stellar evolution, reactions involving ejection of an α-particle (^{4}He) by γ-rays [(γ, α) reactions] and the inverse process of ^{4}He capture [(α, γ) reactions] begin to occur. This complex reaction chain is summarized as follows:

$$^{28}\mathrm{Si} + \gamma \rightleftharpoons {}^{24}\mathrm{Mg} + {}^{4}\mathrm{He}$$

$$^{4}\mathrm{He} + {}^{28}\mathrm{Si} \rightarrow {}^{32}\mathrm{S} + \gamma$$

$$^{32}\mathrm{S} + {}^{4}\mathrm{He} \rightleftharpoons {}^{36}\mathrm{Ar} + \gamma$$

$$\text{Net: } {}^{28}\mathrm{Si} \overset{(\alpha,\gamma)}{\rightleftharpoons} {}^{32}\mathrm{S} \overset{(\alpha,\gamma)}{\rightleftharpoons} {}^{36}\mathrm{Ar} \overset{(\alpha,\gamma)}{\rightleftharpoons} {}^{40}\mathrm{Ca} \overset{(\alpha,\gamma)}{\rightleftharpoons} \text{etc.}$$

$A = 56$ (^{56}Fe)

These reactions can go in either direction but the reaction going toward the right always occurs to some extent. This chain of reactions primarily produces nuclei with mass numbers $A = 32$, 36, 40, 44, 48, 52, and 56, which turn out to be unusually abundant in nature. In addition, because of the much richer composition of nuclear matter that exists in the stellar core during silicon burning, a much more diverse batch of other nuclear reaction products is possible. Hence, many of the remaining nuclei below ^{56}Fe will also be synthesized, but in smaller quantities.

Of particular importance in the silicon-burning process is the fact that it stops near mass number $A = 56$. Recall that we stated earlier (Fig. 3) that ^{56}Fe is nature's most stable nucleus. Because of this fact, fusion reactions which produce nuclei heavier than ^{56}Fe in the stellar core absorb energy rather than releasing it. Thus, when an iron core develops, the absence of energy-liberating nuclear reactions removes the major source of stellar support resisting gravitational contraction.

To summarize our account of stellar evolution to this point, we have described a rather complex star, containing most of the elements up to iron in various layers. This is indicated in Figure 10. Most of the elements needed to sustain life have now been constructed. At each stage of stellar evolution, the processes become less efficient and more diverse, accounting for the steadily decreasing abundances of the elements, observed in Figure 3 and Table II. The difficulty in producing nuclei beyond iron creates a sink for Fe-like nuclei, producing the peak at iron in Figure 3, and also accounts for the low abundances of the heavier elements. Further, the unusual stability of nuclei in the iron region also means that nuclear reactions can no longer act as a source of energy to sustain the structure of a star against strong attractive forces of gravity that exist at these very high densities.

Heavy Element Production: the r-Process

The accumulation of the iron group elements in the core of a star leads to catastrophic conditions. Because nuclear reactions can no longer release energy and provide their stabilizing influence, gravitational force causes the core to collapse; that is, an implosion of core upon itself results, as indicated in Figure 10 in the central region. The implosion process 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 of 6×10^9 °K in the center of the core. It is thought that this process of gravitational collapse and rapid heating is followed by a massive shock wave that leads to explosion of the star. This phenomenon is believed to be associated with supernova explosions.

There are two important consequences of gravitational collapse and the rapid heating which follows. First, the temperature increase triggers a varied array of nuclear reactions throughout the outer envelopes of the star. This leads to an enrichment of nuclear species from the elements previously formed. A second important consequence stems from the conditions in the very center of the core where the temperature and density are highest. Under these extreme conditions iron nuclei begin to break up by means of photodisintegration reactions, leading to the following schematic processes:

$$^{56}\mathrm{Fe} + \gamma \rightarrow 13\,^{4}\mathrm{He} + 4\,^{1}\mathrm{n}$$

$$^{4}\mathrm{He} + \gamma \rightarrow 2\,^{1}\mathrm{H} + 2\,^{1}\mathrm{n}$$

$$^{1}\mathrm{H} + e^{-} \rightarrow {}^{1}\mathrm{n} + \nu$$

The important point is that large numbers of neutrons are produced in the central core region. The "laboratory" analogue of this process is found in thermonuclear explosions (hydrogen bombs), which have permitted us to gain useful insights into this mechanism. The neutrons serve as a source of nuclear particles which can interact with previously processed nuclear material in the star and further enrich the variety of nuclei that are produced. Because neutrons have no electric charge, they can be absorbed by the iron group nuclei without the restrictions of electromagnetic repulsion experienced by charged particles.

This stage of nucleosynthesis is called the r-process (r for rapid) and is assumed to be responsible for elements beyond iron according to the following series of reactions:

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

These reactions produce highly neutron-rich nuclei which are well submerged below the sea of instability in Figure 3. As

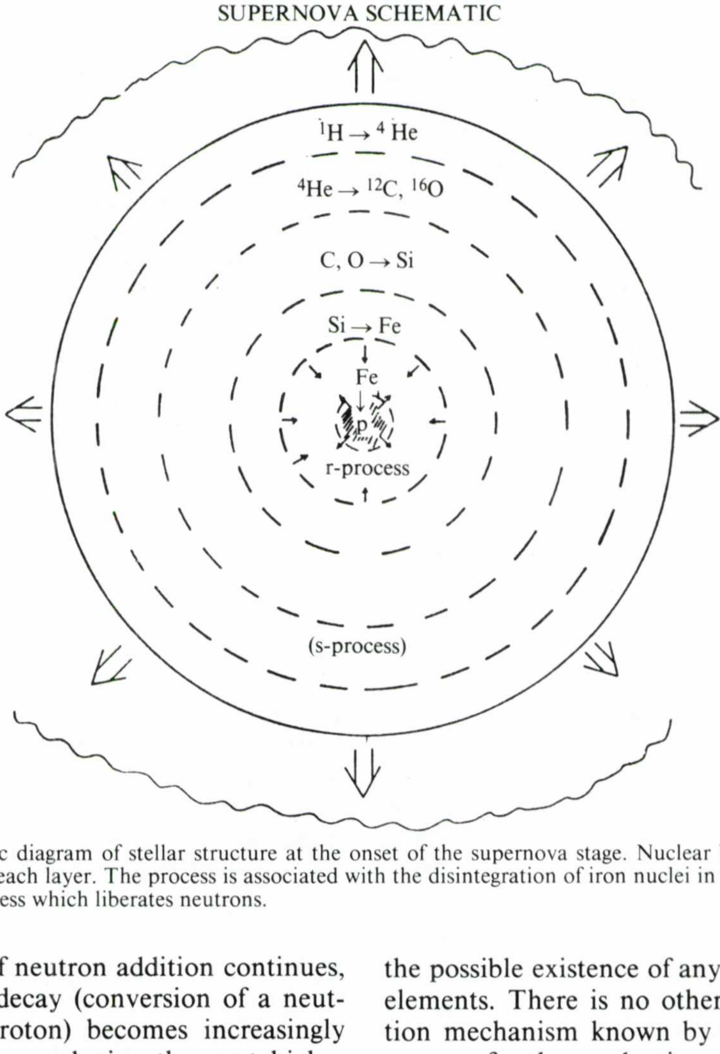


Fig. 10. Schematic diagram of stellar structure at the onset of the supernova stage. Nuclear burning processes are indicated for each layer. The process is associated with the disintegration of iron nuclei in the central region of the star; a process which liberates neutrons.

this process of neutron addition continues, nuclear beta-decay (conversion of a neutron into a proton) becomes increasingly probable, thus producing the next higher element, as shown below:

$$^{79}_{26}Fe \rightarrow {}^{79}_{27}Co + e^- + \bar{\nu}$$

$$^{79}Co \xrightarrow{(n,\gamma)} {}^{80}Co \xrightarrow{(n,\gamma)} {}^{81}Co$$

$$^{81}Co \rightarrow {}^{81}Ni + e^- + \bar{\nu}$$

This sequence of neutron-capture and beta decay produces heavier and heavier elements.

It is the r-process that forms the heaviest elements in nature and must account for the possible existence of any "superheavy" elements. There is no other nuclear reaction mechanism known by which we can account for the production of the amounts of uranium and thorium that we find in nature today. A schematic diagram of the r-process is shown in Figure 11. The upper limit to element synthesis in the r-process is imposed by nuclear fission reactions which become increasingly probable as the nuclear charge increases beyond $Z \approx 90$. Fission involves division of the nucleus into two nuclei of roughly the same mass numbers. Thus, the nucleosynthesis process is terminated and nuclear material simply cycles between the buildup of very heavy elements and their fission into in-

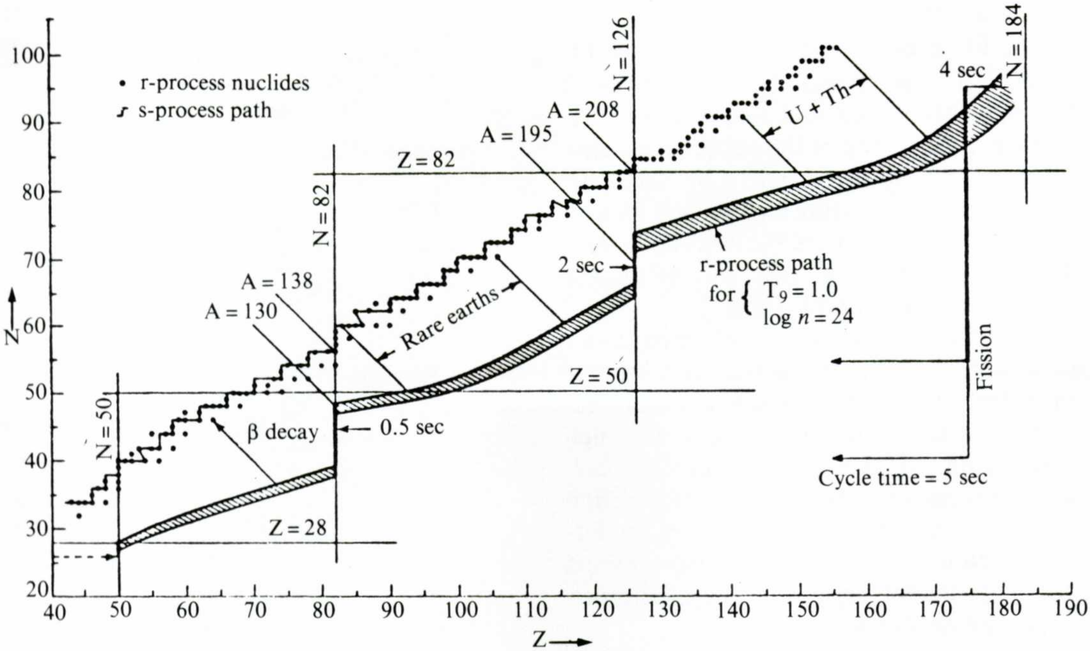


Fig. 11. Diagram of the r-process path on a proton versus neutron number plot. The stable heavy isotopes are indicated by the open circles. The dashed region shows the the path followed by the r-process, which is terminated by nuclear fission (heavy vertical line). The s-process path is given by the solid line through the stable heavy isotopes.

termediate-mass elements. It is not clear at what point fission becomes dominant in the r-process chain of mass buildup, but most probably it occurs around mass number A ≅ 270, which would mean that the superheavy elements (A ~ 300) are probably not produced in nature. At the present time attempts to discover these elements experimentally, both in nature and via nuclear reaction studies in the laboratory, have been unsuccessful (7). However, these attempts continue and it may well be possible that eventually superheavy elements will be observed.

Although there are other significant processes responsible for element production (to be discussed in the next section), 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 supernova core is believed to form a dense neutron star (density ~ 10^{14} g/cm^3). Neutron stars are believed to be the explanation for the existence of pulsars, which are small, massive sources of periodic radiowave emission.

The supernova explosion itself ejects processed nuclear material out into space where the temperatures and densities are much lower. This material then attracts electrons to form neutral atoms and molecules and the entire cycle begins anew. First, the gravitational force begins to condense matter to form second generation stars, or, in the case of smaller amounts of mass, planets, meteorites, and cosmic dust are formed. 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 that it contains heavy elements in addition to its hydrogen and helium content.

The life cycle of a star is depicted in Figure 12. If one recalls the abundances of the elements shown in Table II and Fig. 5, it is clear that none of the successive stages of element synthesis need to be very efficient to produce nature's elements. Hence, even after the complete evolution of a star, 98 % of the material still will be in the form of hydrogen and helium.

At this point, our basic picture of stellar evolution and the production of elements in nature is roughly complete. Many refinements are required to give a thorough description of these processes; in fact, many pieces of experimental information are still lacking or incompletely understood. Nonetheless, the model represents our best current understanding of the origin of the elements.

The s-Process

Up to now we have emphasized the production of new 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 such mechanisms is what is called the s-process (s for slow). This process, like the r-process, involves the capture of neutrons, but it takes place in relatively stable stars where nuclear reactions produce neutrons at a slow, steady rate. For example, in red giant stars neutrons can be produced by means of reactions of the following type:

$$^{13}C + {}^{4}He \longrightarrow {}^{16}O + {}^{1}n$$

$$^{17}O + {}^{4}He \longrightarrow {}^{20}Ne + {}^{1}n$$

When sizeable amounts of iron group elements are present as seed nuclei, it is

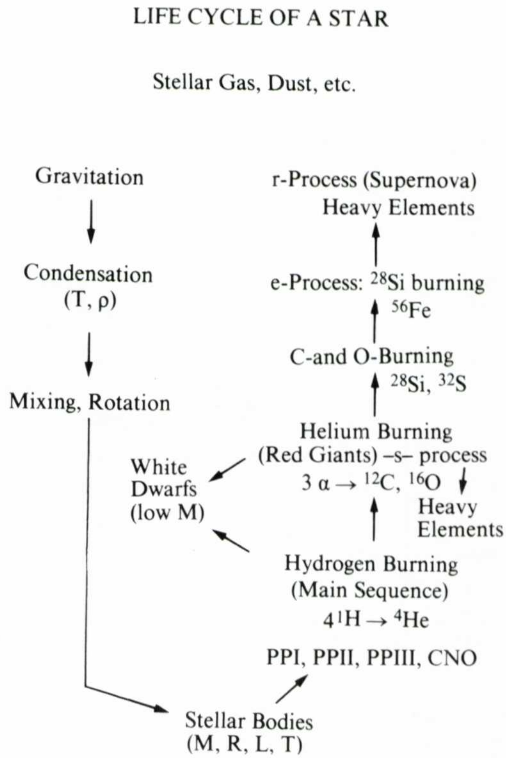


Fig. 12. Life cycle of a star. M, R, L, T refer to the mass, radius, luminosity and temperature of a star.

possible to build up heavy elements much the same way as in the r-process. However, unlike the r-process – where many neutrons are captured by a single nucleus in a matter of seconds – in the s-process a single nucleus captures a neutron every few thousand years or so (hence, slowly) and therefore beta-decay can occur before another neutron is captured. Since red giants exist for millions of years, the s-process can exert a strong influence on the production of heavy elements in stars. The difference in time scales between the s-process and the r-process results in the formation of different isotopes in the elements. For example, compare the following chain of s-process reactions on ^{56}Fe seed nuclei with that for the r-process on ^{56}Fe in the preceding section:

$$^{56}_{26}Fe \xrightarrow{(n,\gamma)} {}^{57}Fe \xrightarrow{(n,\gamma)} {}^{58}Fe \xrightarrow{(n,\gamma)} {}^{59}Fe \rightarrow {}^{59}Co + e^- + \bar{\nu}$$

$$^{59}Co \xrightarrow{(n,\gamma)} {}^{60}Co \rightarrow {}^{60}Ni + e^- + \bar{\nu} \quad \text{etc.}$$

The r-process tends to form the heavier isotopes of a given element, whereas the s-process forms the lighter isotopes. This is illustrated in Figure 13 where both the s– and the r–process paths are shown for a given region of atomic nuclei. The s-process can be studied extensively in nuclear reactors and is thought to be understood fairly well.

One other process, the p-process, is responsible for forming the lightest isotopes of many heavy elements. In general the abundances of the p-process isotopes are extremely small because they are formed by (p, γ) and (γ, n) reactions on the s– and r–process residues.

In the various processes ranging from hydrogen burning through the s– and r–processes one sees that stellar evolution results in the formation of all of the elements between carbon and uranium, and perhaps heavier ones, as yet undiscovered. Simultaneously, stellar evolution leads not only to the formation of the elements, but also to the richness of cosmological phenomena that we observe in our universe, ranging from main sequence stars to supernovae.

C. Nucleosynthesis in the Interstellar Medium

From our previous discussions it is seen that cosmological nucleosynthesis in the Big Bang and element synthesis during stellar evolution can account for nearly all the elements of the periodic table. However, three elements have been omitted in our scenario: the elements lithium, beryllium, and boron. As we stated earlier, these elements are known to be extremely fragile and consequently disintegrate quite readily during stellar evolution and cannot survive. It is thought that some ^{7}Li has survived since the Big Bang, but the remaining isotopes of these elements, ^{6}Li, ^{9}Be, ^{10}B and ^{11}B, must have been produced by some other mechanism. It is currently believed that these elements have their origin in interactions of galactic cosmic rays with the gas and dust of the interstellar medium. Such reactions involve primarily reactions of protons and ^{4}He nuclei with other ^{4}He and carbon, nitrogen and oxygen nuclei present in the interstellar medium. These reactions occur at rather high 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 Li, Be and B products can survive after their formation.

This is one case of a nucleosynthesis process where rather extensive knowledge exists for both the salient nuclear reactions and the astrophysical processes involved (12). 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 cross sections for these systems should allow one to calculate the elemental abundances observed for lithium, beryllium and boron if this proposed mechanism is correct. It is found that one is able to reproduce the abundances of ^{6}Li, ^{9}Be, ^{10}B, and ^{11}B quite well with this model. However, the isotope ^{7}Li is greatly underproduced, which further strengthens the belief that ^{7}Li was synthesized in the Big Bang.

In fact, if one assumes that the additional ^{7}Li necessary to match the abundances of the lithium isotopes in the solar system comes from the Big Bang, it is possible to infer basic conditions which characterized the Big Bang from this information. In Figure 14 we show a plot of the ratio of the

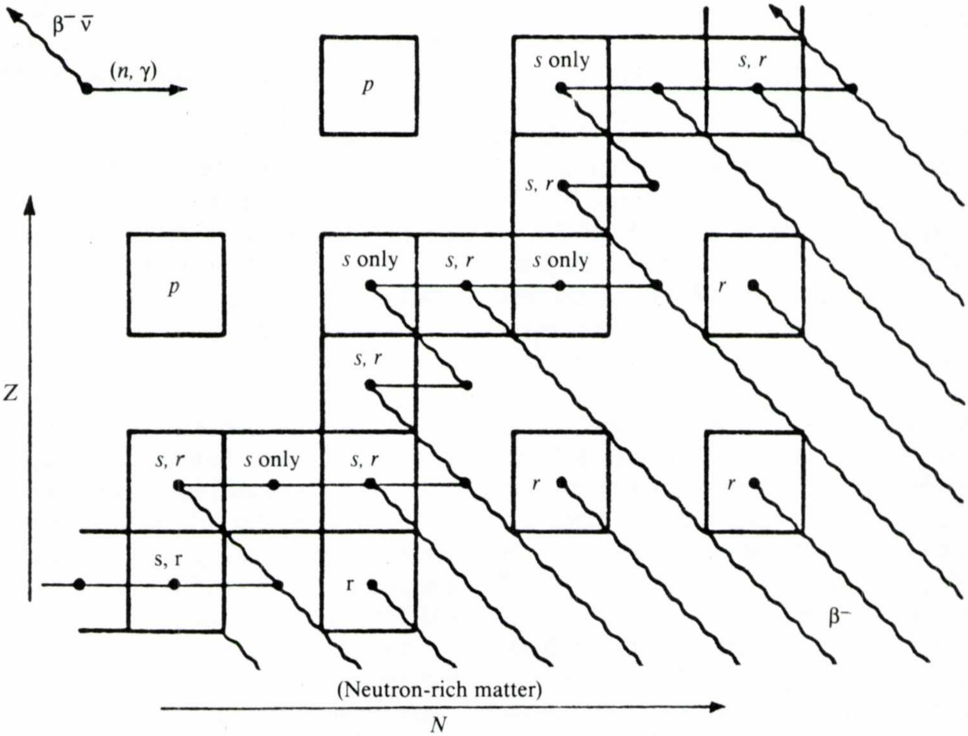


Fig. 13. Plot of N versus Z (as in Figs. 3 and 11) showing production of isotopes of the elements by the r–, s– and p–processes. The squares represent the stable isotopes of an element. Wavy lines indicate the beta-decay path of neutron-excess isotopes produced in the r–process. The solid line through the center of the stable isotopes shows the s-process path of neutron capture.

abundance of ^{7}Li, which we attribute to the Big Bang, 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 curves are the predicted ^{7}Li/^{2}H ratios for the Big Bang as a function of the density of the universe, based upon calculations involving all possible nuclear reaction cross sections for these species (10). It is observed that the ratio of ^{7}Li to deuterium corresponds to a present matter density of the universe of about 6×10^{-30} g/cm^3. This density would have been much greater at the time of the Big Bang, since our universe has been expanding for 15 billion years.

An important related question is whether or not the universe will continue to expand forever. Do we live in an ever-expanding (open) universe, or will it eventually stop expanding under the force of gravity and contract again (a closed universe)? In the latter case, a primeval fireball corresponding to the Big Bang might once again result. 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 or not the universe is open or closed from these data. The estimated density required to close the universe is about 6×10^{-29} g/cm^3, as indicated by the arrow in Figure 14. The present results indicate that the matter density of the universe is thus too low by about a factor of ten to permit a closed universe. Hence, these nu-

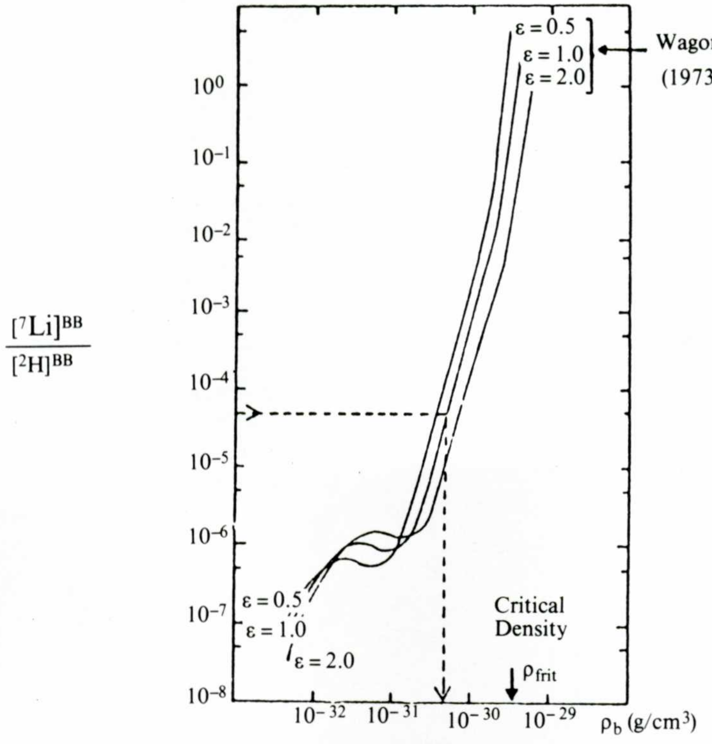


Fig. 14. Solid lines show a plot of the ratio of ^7Li to ^2H formed in the Big Band as a function of the present density of the universe, as calculated by Wagoner (10). The dashed line corresponds to the observed $^7Li/^2H$ ratio and the corresponding density. The density required to close the universe, ρ_{crit}, is shown by the heavy arrow. Curves marked $\xi = 0.5$, 1.0 and 2.0 correspond to different assumptions concerning the parameters involved in the calculation.

cleosynthesis data also impinge on very fundamental concepts of our universe and indicate that the universe is open and will continue expanding forever.

ACKNOWLEDGEMENTS

The General Research Board of the University of Maryland is acknowledged for providing a Faculty Research Grant for the Spring 1979 semester, during which time this paper was prepared. This research program was supported by grants from the U.S. Department of Energy and the National Science Foundation.

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