22 August 1958, Volume 128, Number 3321 SCIENCE

CURRENT PROBLEMS IN RESEARCH

Formation of Elements in the Stars

To build all the elements requires that eight nuclear processes occur as the conditions become ripe.

Margaret and Geoffrey Burbidge

The origin of the chemical elements, from the lightest, hydrogen, to the heaviest, has always been a fascinating problem for physicists, chemists, and astronomers. Recently there have been developments in nuclear physics and in both theoretical and observational astrophysics which have made possible a new attack on this problem.

The raw material which must form the starting-point for any theory of the origin of the elements is a knowledge of the relative abundances, not only of the different chemical elements, but also of all the different isotopes of each element. The first question to be asked is: What is the relative abundance distribution among all the isotopes of every element in the material forming the crust of the earth? This can be answered by the geochemists, and more and more accurate results have become available in the last few years. The composition of meteorites can also be directly and accurately determined.

The next step, however, is harder. To determine the composition of the sun, spectroscopic analysis must be used, and this means that, with few exceptions, isotopic abundances cannot be determined. Also, information can be obtained only about those atoms which are excited to show spectral lines under the conditions of temperature and pressure found in the sun's atmosphere, and in the wavelength range transmitted by the earth's atmosphere.

With these reservations, however, it has been found that the differences in composition between the sun, the earth, and meteorites can be explained through the loss of the lighter and more volatile elements by the less heavy bodies in the early history of the solar system.

The next step, however, to ask whether the composition of all the stars in our galaxy, and of all other galaxies, is the same as that of the solar system, is a far more difficult problem. In the first place, so much less light is available from stars than from the sun that less powerful spectrographs have to be used, and less precise results are obtained. Despite the difficulties, however, and despite the large amount of labor involved in finding the composition of one single star, some results have been obtained for stars relatively near the sun, although for a pitifully small sample of stars compared with the 10^{11} or so stars that compose our galaxy. With some notable exceptions, which we shall discuss later, the composition of these stars, as far as it can be determined, is quite similar to that of the sun.

The gas which lies between the stars in our galaxy can also be studied, particularly where it lies close enough to hot stars so that its atoms are excited by their radiation and emit radiation of their own. As far as we can tell at present, this gas also has a composition fairly similar to that of the hot stars embedded in it.

To talk of an average composition of the material fairly near to the sun does, therefore, have meaning, so long as it is never forgotten that this average refers only to a small sample of our galaxy alone. However, another point to be remembered is that the spectroscopic analyses of the sun and stars refer only to their surface layers and do not necessarily give information about the composition of their interiors. Throughout most of the lifetimes of stars, mixing between their deep interiors and surfaces does not take place, and, as we shall see, nuclear transmutations of material must be happening in the interiors.

A schematic curve showing the relative abundances of the elements, plotted logarithmically against the atomic weight, A, is shown in Fig. 1. This curve is based on a recent weighting of all available results, geochemical and astrophysical, made by Suess and Urey (*1*). The first fact that stands out is that hydrogen, the lightest, is the most abundant element, and there is a steep decline in abundance with increasing atomic weight until one reaches about $A = 100$ (the elements molybdenum and ruthenium). After this point, the curve tends to flatten out.

Superimposed on this general trend are a number of peaks and separate groupings of elements which give the curve a very complicated appearance. The main features are the low-lying light elements lithium, beryllium, and boron; a group of elements between $A = 12$ and $A = 40$ lying above the general trend; a sharp peak centered on iron at $A = 56$; three sets of twin peaks near $A = 90$, 140, and 200; and finally, a group of isotopes between $A = 70$ and 200 lying below the main curve by a factor of about 100.

Starting from this observed abundance distribution, the possibility can be investigated that matter was created in as simple a form as possible (for example, in the form of pure hydrogen, the lightest and simplest chemical element, or in the form of the fundamental particles, protons, neutrons, and electrons and possibly their antiparticles, antipro-

The authors are on the staff of the Yerkes Observatory of the University of Chicago, William Bay, Wis.

tons, antineutrons, and positrons), and that the rest of the elements have been produced subsequently, at some time or times during the history of the universe, by physical processes, according to known physical laws. That this is the case is supported, as we shall see, by a linking between some of the complexities of the abundance curve and the properties of nuclei.

There are two major theories for the origin of the elements. In the first, it is supposed that the universe was created at a particular instant of time and has been expanding ever since. In the first few minutes of its existence all of the elements were built by reactions taking place in a mixture of fundamental particles—protons, neutrons, electrons, positrons, mesons, and radiation. The same physical laws which operate today are postulated to have been valid at that time and to have governed the ways in which these reactions occurred.

This theory was pursued during a period about ten years ago, mainly by Gamow and his chief collaborators, Alpher and Herman, although many other distinguished scientists—Fermi and Turkevitch, for example—also made important studies bearing on the subject. An extensive review article developing this point of view is available (*2*). Gamow called his theory the "ylem" theory, ylem (*3*) being his name for the hot primeval mixture of particles and radiation.

The alternative theory seeks to explain the building of the elements by suggesting that it has occurred, and is continuously occurring, in places where we know that the temperature and density are high enough for nuclear reactions and the transmutation of one element to another to occur. Such places are the interiors of stars; the structure of stars demands high temperatures and pressures here, and many people feel that it is preferable to build a theory upon known present-day conditions than upon a hypothetical state of the universe at some time in the past.

Also, the many complexities of the abundance curve can, as we shall show, be explained by the different sets of conditions that can occur at different stages of a star's evolutionary path, or in stars of different masses. These same complexities always proved a stumbling block to the ylem theory, since conditions that may be right for building some elements will not serve for others, and so short a time was available for the whole production of all the elements to take place that the conditions of temperature and pressure had to be rather rigidly specified.

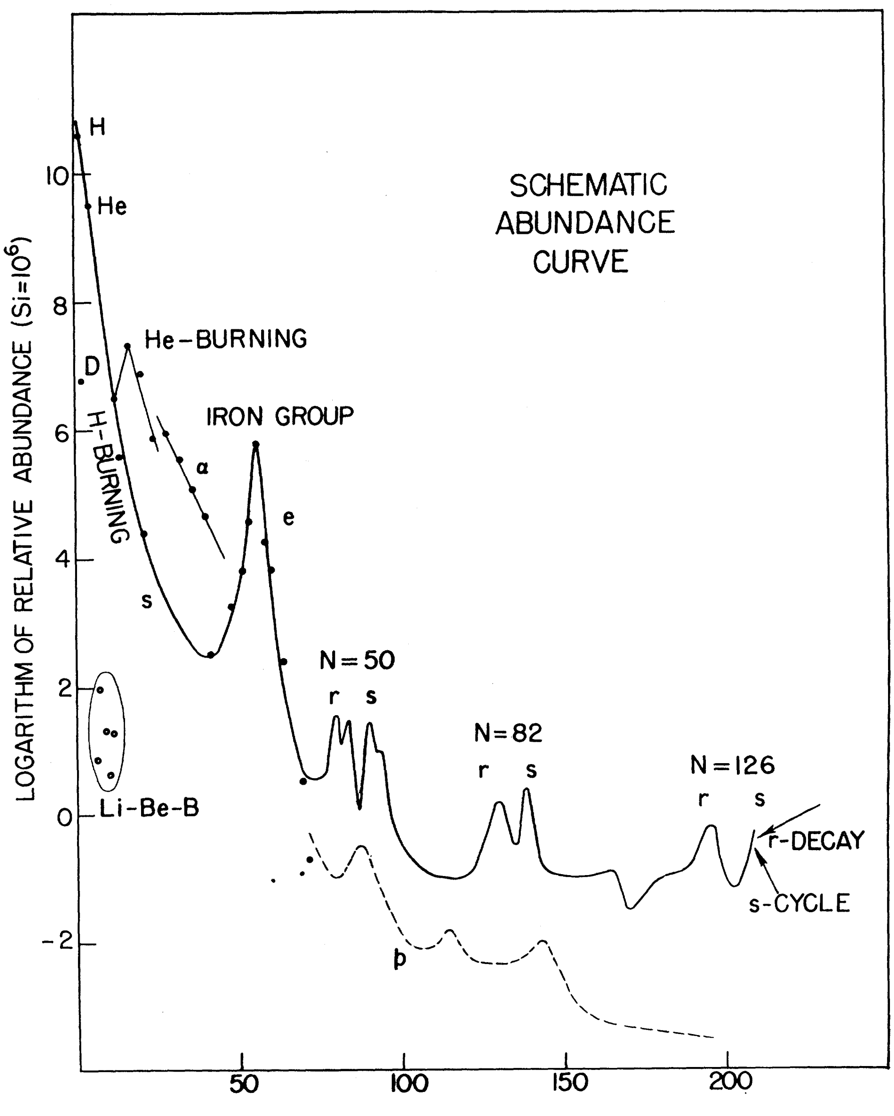

Fig. 1. Schematic curve of atomic abundances as a function of atomic weight based on the data of Suess and Urey (*1*). There is still considerable spread of the individual abundances about the curve illustrated, but the general features shown are now fairly well established. Note the overabundances relative to their neighbors of the α-particle nuclei $A = 16, 20, \ldots 40$, the peak at the iron-group nuclei, and the twin peaks at $A = 80$ and 90, at 130 and 138, and at 194 and 208. [Courtesy *Reviews of Modern Physics* (*19*)]

Cosmological Background

The ylem theory, based upon a giant explosion that occurs at the creation of the universe and starts its expansion, is obviously tied to a particular class of cosmological models. It also predicts that the relative abundances of the elements, except for the possible effects of later modifying processes, will be uniform throughout the universe.

A new approach to the cosmological problem, the steady-state theory of Hoyle, Bondi, and Gold (*4*) has been proposed. In this theory, the rate of disappearance of matter at the boundary of the expanding universe is balanced by the continuous creation of matter at a uniform rate throughout space; the universe had no beginning and will continue for an infinite time. This theory of course would be quite incompatible with Gamow's ylem origin of the elements.

There has also been a recent revival of interest in oscillating world models, which are also incompatible with an ylem theory. Furthermore, the possible existence of antimatter on the universal scale (*5*) may also lead to profound changes in cosmological theories.

Since it has sometimes been proposed that each of the two theories of the origin of the elements is supported by a particular cosmological model, or vice versa, it is of importance to say something about the observational evidence concerning the cosmological problem at the present time.

A number of cosmological tests, all exceedingly difficult, are available, but none has yet led to any noticeable weeding out of the available theories. Some years ago Stebbins and Whitford (*6*) thought that they had found an apparent reddening of distant galaxies, over and above that expected from their velocities of recession which cause their spectra to be shifted to the red. Such an effect would imply that distant parts of space are populated by galaxies with different properties from those in our own neighborhood, and this is contrary to the predictions of the steady-state theory. Recently, however, Whitford and Code have found that this effect, which is extremely hard to measure, probably does not exist (*7*).

Attempts to distinguish between different cosmological models by analyzing the distributions of very distant radio sources have led to complete confusion so far and to very considerable disagreement between radio astronomers in England and Australia who use different techniques (*8*).

The optical method of using the relation between velocity and distance, as deduced from measured redshifts and brightnesses for distant clusters of galaxies, has led to great advances in the hands of Hubble, Humason, Mayall, and Sandage. However, the spectroscopic techniques have now been pushed practically to the limit possible with the 200-inch telescope (photoelectric photometry may lead to further advances in this field, since it is possible to measure the colors of extremely faint galaxies, but so far the results are disappointingly few). In 1956 all of the results then available were described (*9*). The velocity-distance relation was shown to be linear out to values of about 60,000 kilometers per second. However, the curvature in this relation beyond this point which would, if determined precisely, enable us to exclude some cosmological models, remained very uncertain. The value of the Hubble constant was found to be 180 kilometers per second per 10^6 parsec, corresponding to an "age" of 5.4×10^9 years, an increase of a factor of about three from that given by Hubble and Humason some twenty years before. This included all of the corrections previously suggested, particularly that enunciated by Baade (a result which had been partly foreshadowed by Mineur). Since 1956 a further revision in the distance scale has been proposed by Sandage (*10*). The Hubble constant derived by Sandage is only about 75 kilometers per second per 10^6 parsec, corresponding to an "age" of about 13×10^9 years (*11*). We are warned by Sandage that many uncertainties still remain.

Another cosmological test is available in the analysis of the distribution of external galaxies and clusters of galaxies, but although much work has been done in this field, particularly by Shane and his collaborators and by Zwicky and Abell, no definitive results are available.

Clearly, therefore, at the present time no cosmological arguments can be adduced in favor of one or another of the theories of the origin of the elements. However, it is fair to say at the present time that the idea that all of the elements have been built in the stars may be compatible with whatever cosmological model best represents the universe. For example, in the steady-state theory it is supposed that matter is created at a given rate which is determined by the value of the Hubble constant. However, so far, apart from a preliminary attempt by Pirani in the framework of the classical theory, no theory has been advanced to describe the way in which particles are created, but it has generally been supposed that the process involves either stable fundamental particles, protons and electrons, or else unstable particles such as neutrons and heavy mesons. No suggestion has ever been made that heavy nuclei are continuously created, so that from this aspect the building of elements in stars is an important adjunct to the steady-state theory. On the other hand, such a theory is also compatible with evolutionary or exploding cosmological models. In fact it might be proposed that some synthesizing processes, perhaps the production of deuterium and some helium in the ylem, followed by the production of all of the other isotopes in the interiors of stars after galaxies were formed, would overcome the difficulty in the stellar synthesis theory of producing enough deuterium, a problem which we shall discuss later.

Growth of Ideas Concerning Stellar Synthesis

As might be expected, the basic steps in the development of the stellar synthesis theory have been made on the heels of the growth in our knowledge of nuclear physics. The earliest attempts were those by Atkinson and Houtermans nearly thirty years ago to explain the sources of stellar energy in terms of the transmutation of light elements into heavy ones. These led Atkinson (*12*) to attempt to show that all of the elements could be built in the stars. The attempt was a complete failure, simply because understanding of the structure of nuclei was rudimentary at that time.

The first and most important step forward was the demonstration in 1938 by Bethe (*13*) and von Weizsäcker (*14*) that the major source of a star's energy throughout its life is the conversion of hydrogen to helium. This also showed that as a star grows older its chemical composition changes. In the decade following the work of Bethe and von Weizsäcker a number of attempts were made to consider the synthesis of the elements by use of the information on binding energies and other data which were gradually accumulating. In their attempt, Henrich and Chandrasekhar used the concept of statistical equilibrium, trying to show that all of the elements could be built at a unique temperature and density. Later extensive work in this direction was carried out in Sweden by Klein and his collaborators. The conditions for synthesis were always found to be far more extreme than any which might be expected in stars at the present time: also it was easy to see that a single process could not be held accountable for the production of all of the elements. Van Albaba considered the problem from a somewhat different direction, but in 1946 an important step forward was made by Hoyle (*15*), who showed that at least the peak in the abundance curve centered on Fe^{56} could be produced under extreme conditions of temperature and density in the interiors of stars. Hoyle believed that these conditions applied just before a star reached the end of its life and exploded as a supernova, and he proposed a possible mechanism which could trigger such an explosion. Although it was clear by then that several processes must be involved if all the elements were to be built in stars, and most of these processes still remained unknown, Hoyle was very strongly of the opinion that all these processes did occur.

The next important step forward was made by Salpeter and by Hoyle (*16*), who pointed out that although the nucleus Be^8 is unstable and spontaneously disintegrates into two α-particles, under suitable conditions in the interiors of stars the reactions

$$He^4 + He^4 \rightleftharpoons Be^8$$
$$Be^8 + He^4 \rightleftharpoons C^{12*} \longrightarrow C^{12} + \gamma$$

could take place successively. This overcame the difficulty of synthesizing isotopes heavier than He^4, a difficulty which was particularly acute for the ylem theory since there are no stable nuclei of masses 5 and 8. Experimental confirmation of this has been made at the Kellogg Radiation Laboratory, California Institute of Technology (*17*). Recently this has encouraged some of the proponents of the ylem theory in Japan to propose that the initial conditions in the ylem are suitable for this process to occur.

Since then, there have been a number of major developments, particularly the discovery that at certain stages in a star's life reactions which lead to neutron production may take place, and some astrophysical evidence to show that transuranic elements can be built in supernova explosions. These have all led us to believe that a strong case can be made out for supposing that all of the elements were built in the stars. However, before proceeding to give a detailed account of this work it is necessary to make a digression in order to explain some of the aspects of the evolution of stars which are involved.

Evolution of Stars

When a star first condenses out of the interstellar gas and dust, it goes through a period of gravitational contraction and eventually, when its central temperature becomes sufficiently high, it begins to obtain its energy from the conversion of hydrogen to helium. Now the luminosity of such a star depends upon its mass according to a law of the form

$$L \propto M^{\alpha}$$

where $\alpha \approx 3$ to 4 for stars more massive than the sun, and $\alpha \approx 2$ for stars of very low mass. The surface temperature is also determined by the mass. If the two quantities which can fairly easily be measured for the nearer stars, the surface temperature and the energy radiated, are plotted, most of the stars lie in a fairly narrow band shown in Fig. 2, called the "main sequence." In addition there are some stars at the upper right of the diagram. Since these stars have high luminosities yet low surface temperatures, they must have large radii; they are called the red giants. Such stars must have different structures from the main-sequence stars.

Let us consider what happens to a star which has just condensed out of the interstellar gas and arrived on the main sequence. It will begin to convert hydrogen to helium in its central core. A number of workers, Mestel, Öpik, and Sweet, have shown that, except for the stars of very small mass, there is no mixing between the core and the envelope of such a star. After a time, the star will have developed an inhomogeneity in composition between its core and envelope, and its structure will change slightly so that it remains in equilibrium under these changed conditions. This means that it will become slightly brighter and move a little above the main sequence in the luminosity-temperature (L-T) diagram (Fig. 2).

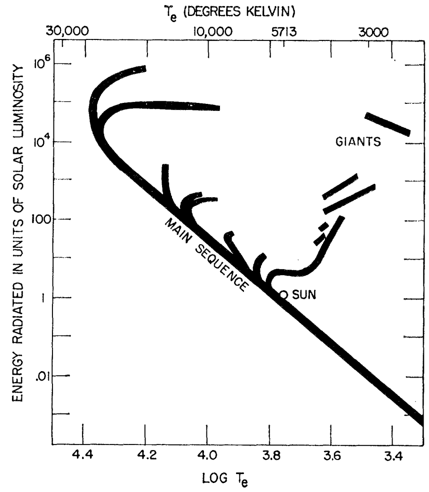

Fig. 2. Schematic plot of luminosity (in solar units) versus logarithm of T_e (approximate surface temperature) for stars in a number of star clusters. The black bands are the regions where the stars occur (relative density of points is not indicated). The point for the sun is also plotted. Most of the stars lie on or just to the right of the main sequence that is common to all the clusters. Many of the clusters also contain a few giant stars of low surface temperature, toward the top right-hand part of the diagram. In each cluster the distribution of stars breaks away to the right from the main sequence and comes to an abrupt end, with a well-marked gap between these stars and the giants. The position of the end of the main sequence provides a means of determining the age of clusters. Those in the figure range from 10^6 years (brightest stars) to 5×10^9 years (break-off point just above the sun). [Adapted from the work of Sandage (*18*)]

It was first shown by Schoenberg and Chandrasekhar that by the time the helium core has grown to contain about 10 percent of the total mass, the star can no longer remain in equilibrium unless it changes its structure drastically. What happens as this point is reached is that its core contracts, releasing gravitational energy to supplement its energy output and heat up its interior, while the outer envelope expands greatly and cools. The star thus moves rapidly to the right in the luminosity-temperature diagram and becomes a red giant. Such a star will now have an inert (as far as energy from hydrogen-burning is concerned) helium core, a shell around this which still contains hydrogen and which is the main source of its energy, and an extended envelope composed of the original material of the star. As the helium core goes on growing, it continues to contract and heat, until eventually it becomes hot and dense enough for nuclei with charges greater than hydrogen to interact. Thus the Salpeter reactions leading to the production of C^{12} can take place.

The fact that stars rapidly leave the main sequence region when the hydrogen in about 10 percent of the mass is consumed provides a means of dating groups of stars. A cluster of stars can be assumed to consist of stars with a range of masses, all of the same age. The more massive stars will reach the 10-percent limit more rapidly than the less massive ones because of the power-law form of the relation between mass and luminosity. A cluster of stars of any given age will have a main sequence extending up to a well-defined point; all stars originally on the main sequence above this point will have become red giants and then have evolved even further. This is exactly what is observed: Fig. 2 [adapted from the work of Sandage (*18*)] is a composite luminosity-temperature diagram for a number of star clusters of different ages. Each cluster has a well-defined termination to its main sequence from which its age can be deduced.

As a star evolves further we can imagine the process to repeat itself: helium as a nuclear fuel will begin to be exhausted, so that the core must contract further, providing more gravitational energy, and the central regions will become still hotter. This means that, successively, nuclei with greater and greater Z values can overcome the Coulomb barrier and interact, thus building heavier and heavier nuclei and releasing energy, though the energy release at the later stages is small compared with that released by hydrogen-burning. This process can continue until the most tightly bound nuclei centered around Fe^{56}, those at the bottom of the packing-fraction curve, are reached.

Stellar models have been computed for main-sequence and red-giant stars, so that we have detailed information on the astrophysical conditions for hydrogen-burning and helium-burning, but none is available as yet for the later stages of evolution. Most of this work has been done in recent years by Schwarzschild and Hoyle and their collaborators. But this qualitative argument for the later sequence of events is logical; a star, as long as it contains nuclear fuel, has a built-in mechanism for adjusting its structure, when one fuel is exhausted, so as to heat up its interior until the next heavier fuel is brought into operation.

Finally, there will come a time when a star must have exhausted all of its fuel. This is a long time for stars of the same mass as the sun ($\sim 10^{11}$ years), but it is only of the order of tens of millions of years for the most massive stars. Consequently, stars must continually be dying and fresh ones must be forming out of the interstellar gas. When a star nears the end of its life, it may either undergo a gigantic catastrophic explosion as a supernova or settle down quietly in the form of collapsed or degenerate matter as a white dwarf, or both. However, Chandrasekhar proved that a white dwarf is stable only if it has less than a certain limiting mass, which is about 1.4 solar masses, though this is slightly dependent on the chemical composition. Therefore all the more massive stars must lose some of their mass, either steadily or explosively, before they can settle down as white dwarfs.

We shall consider the consequences of this continual birth and death of stars later, but now let us turn to the various nuclear processes which can occur as conditions in stellar interiors become right for them. In all, eight processes (see Fig. 3) are required to build all of the elements, and the work described in the remainder of this article has been taken from an extensive paper on all aspects of the problem (*19*).

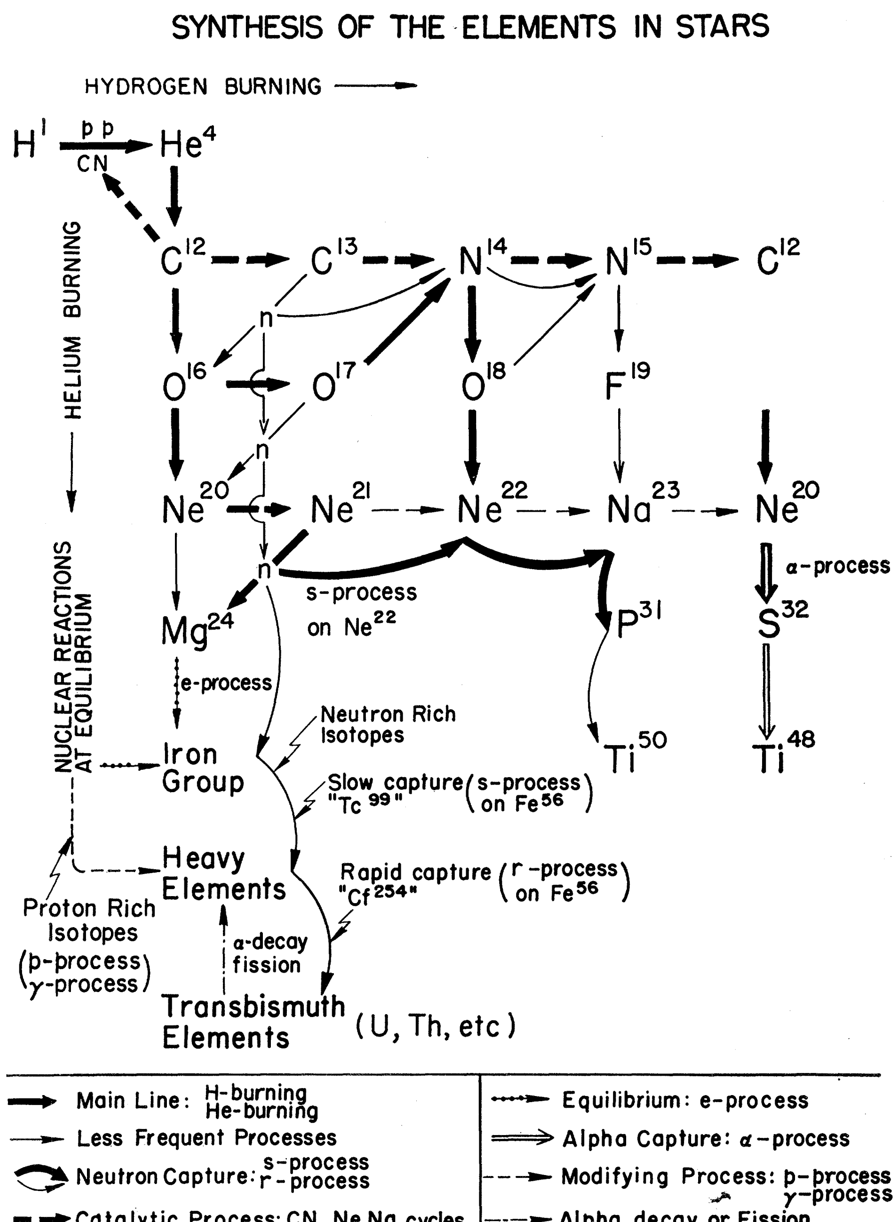

Fig. 3. A schematic diagram of the nuclear processes by which the synthesis of the elements in stars takes place. Elements synthesized by interactions with protons (hydrogen-burning) are listed horizontally. Elements synthesized by interactions with alpha particles (helium-burning) and by still more complicated processes are listed vertically. The details of the production of all of the known stable isotopes of carbon, nitrogen, oxygen, fluorine, neon, and sodium are shown completely. Neutron capture processes by which the highly charged heavy elements are synthesized are indicated by curved arrows. [Courtesy *Reviews of Modern Physics* (*19*)]

Hydrogen-Burning and Helium-Burning

The first process is the basic one of the conversion of hydrogen to helium, either through the carbon-nitrogen cycle for stars on the brighter part of the main sequence (masses $\geqq$ 2 solar masses), or by the proton-proton chain for stars in the lower part of the main sequence. The reactions involved in the carbon-nitrogen cycle are:

$$C^{12}(p,\gamma)N^{13}(\beta^{+}\nu_{+})C^{13}$$
$$C^{13}(p,\gamma)N^{14}$$
$$N^{14}(p,\gamma)O^{15}(\beta^{+}\nu_{+})N^{15}$$
$$N^{15}(p,\alpha)C^{12}.$$

Laboratory studies of these reactions have been under way at the Kellogg Radiation Laboratory for many years, and recently at the University of California Radiation Laboratory at Livermore. Full references are given elsewhere (*19*). Reactions in the proton-proton chain are given in Fig. 4. Hydrogen-burning also takes place in the shell around the core after the star has left the main sequence and become a red giant. It occurs over a range of stellar temperatures from a few million degrees upward.

The basic reactions in helium-burning which were mentioned above reduce to

$$3He^{4} \rightarrow C^{12*} \rightarrow C^{12} + \gamma.$$

For this process to occur, temperatures in excess of 10^8 degrees and densities upward of 10^3 grams per cubic centimeter are required. These conditions are known

$$H^1(p,\beta^+\nu_+)H^2(p,\gamma)He^3 \begin{cases} (He^3,2p)He^4 \\ (\alpha,\gamma)Be^7 \begin{cases} (e^-,\nu_+)Li^7(p,\gamma)2He^4 \\ (p,\gamma)B^8(\beta^+\nu_+)Be^{8*}(\alpha)He^4 \end{cases} \end{cases}$$

Fig. 4. Reactions in the proton-proton chain.

to prevail in the cores of red-giant stars, and they are almost certainly achieved also in the evolutionary stages subsequent to the red giants. Under similar conditions the further reactions

$$C^{12}(\alpha,\gamma)O^{16}(\alpha,\gamma)Ne^{20}$$

and, to a small degree,

$$Ne^{20}(\alpha,\gamma)Mg^{24}$$

can also take place. The successive captures of α-particles effectively cease at this point because of the increasing strength of the Coulomb barrier.

Helium-burning yields only about one-tenth as much energy, per gram of material, as was provided by hydrogen-burning. Although it is an important source of energy, therefore, it cannot last as long as hydrogen-burning before all the helium fuel in a star will be consumed. The time scale is probably 10^7 to 10^8 years. Provided that nuclei which are made by helium-burning—that is, C^{12}, O^{16}, Ne^{20}—are present already, hydrogen-burning in a gas containing these isotopes will synthesize the majority of the less abundant isotopes of carbon, oxygen, and neon, and also nitrogen.

Observational evidence for the occurrence of hydrogen-burning and helium-burning might be expected to appear on the surfaces of stars in advanced evolutionary stages, because, although mixing does not occur in main-sequence stars, it probably does take place later, possibly already in the red-giant stage for massive stars. Several different kinds of stars are observed whose spectra show the products of hydrogen- and helium-burning in abnormally large abundance, and also deficiency of hydrogen. Some are illustrated in Figs. 5 and 6.

The star υ Sagittarii (Fig. 5) has very weak hydrogen lines in its spectrum, compared with the normal star of similar surface temperature, η Leonis. There are even more extreme examples, showing no hydrogen at all. Such stars tend to have strong helium lines and may be lacking in oxygen, which is destroyed in hydrogen-burning at high enough temperatures. Some have large amounts of nitrogen, which is produced from carbon in the carbon-nitrogen cycle. Many white dwarfs show no hydrogen at all; those that do show some may have picked up a thin skin of it during their passage through the interstellar gas, which contains about 75 percent hydrogen by mass.

Among the red giants, there are some stars (Fig. 6) which have an abnor-

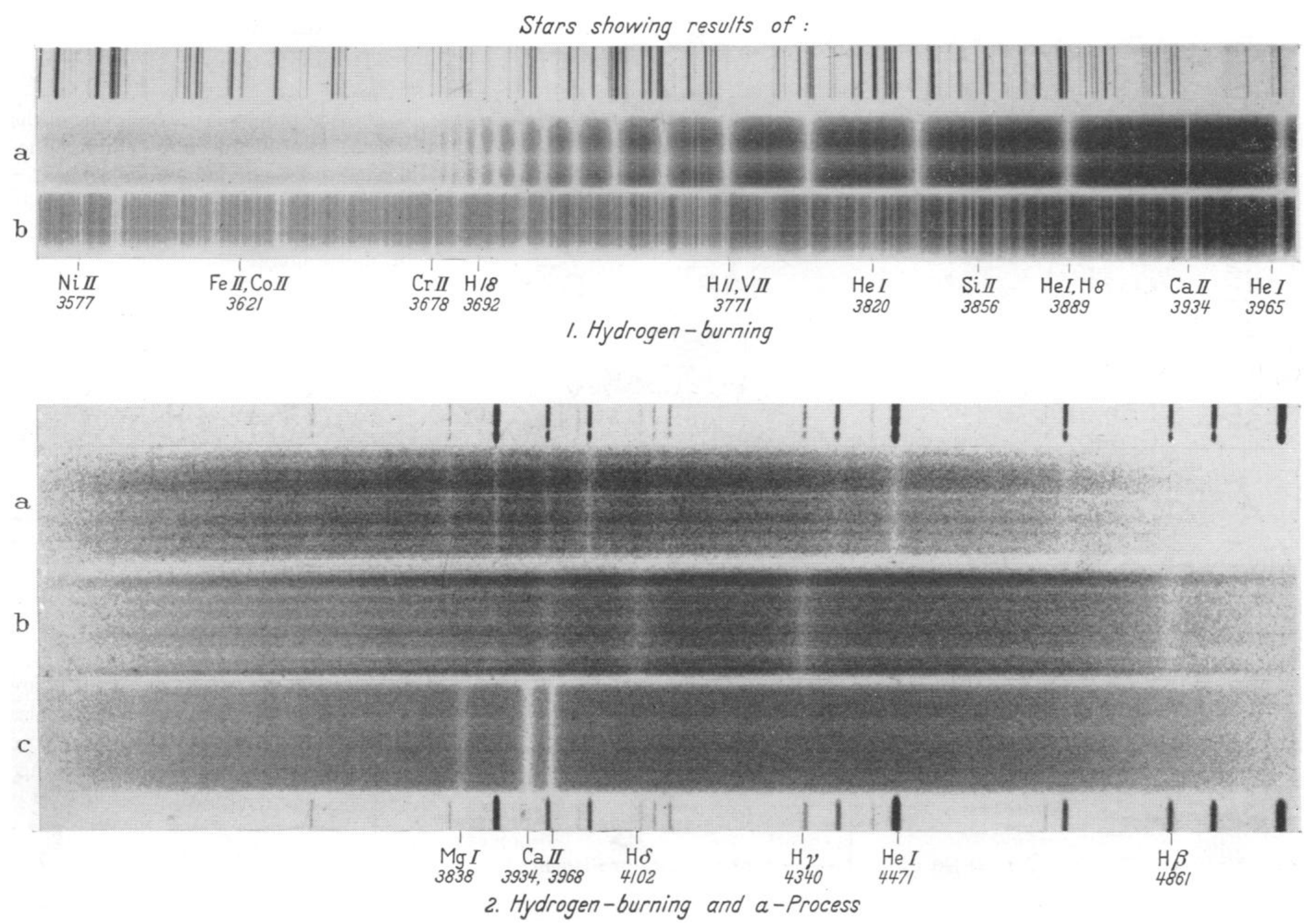

Fig. 5. Portions of the spectra of stars showing the results of hydrogen-burning and possibly the α-process. Top: (*a*) Normal star, η Leonis, showing strong Balmer lines of hydrogen and strong absorption at the series limit. (*b*) Peculiar star, υ Sagittarii, in which hydrogen has a much smaller abundance than normal. Bottom: (*a*) White dwarf, L 1573-31, in which hydrogen is apparently absent. The comparison spectrum above the star is of a helium discharge tube; note the lines of helium in the star's spectrum. (*b*) White dwarf, L 770-3, which shows broad lines due to hydrogen only, for comparison with (*a*) and (*c*). (*c*) White dwarf, Ross 640, which shows only the two lines due to calcium and a feature due to magnesium. All the spectrograms in this plate were obtained by J. L. Greenstein; the upper two are McDonald Observatory plates, and the lower three are Palomar Observatory plates.

mally high abundance of carbon relative to oxygen. Possibly the carbon has been produced by helium-burning. In these cool stars bands due to the molecule C_2 show, and thus isotopic abundances, C^{12}/C^{13}, can be determined. Most carbon stars have $C^{12}/C^{13} = 3$ or 4, in distinction from the material of the solar system, where $C^{12}/C^{13} = 90$. Now an equilibrium ratio of 4.6 is set up by the carbon-nitrogen cycle; these stars therefore probably have on their surfaces matter which has been through a hydrogen-burning region.

There are some even more peculiar carbon stars which apparently have very little hydrogen and no C^{13}. Perhaps C^{12}, produced in the interior, did not mix out to the surface until almost all of the hydrogen had been consumed throughout the star, and thus never passed through a hydrogen-burning region.

The Wolf-Rayet stars are massive, very hot, apparently unstable stars, which are highly evolved. In some, carbon is very abundant, in others, nitrogen. Such stars probably show the results of hydrogen- and helium-burning combined.

Although all these examples are striking, they are, except for the white dwarfs, not numerous compared with the total number of stars in our galaxy. This may be because stars at so late an evolutionary stage cannot last long, so that the chances of catching a star at this stage are correspondingly small.

The α-Process

When helium is exhausted in the core of a star, the core must shrink and release gravitational energy, some of which will heat the core. When the core reaches a temperature of about 10^9 degrees, the gamma rays will become energetic enough to remove the last α-particles bound by nuclei, in particular by Ne^{20}. These can be captured by remaining Ne^{20} to make Mg^{24}. The reactions are

$$Ne^{20} + \gamma \rightarrow O^{16} + He^{4} - 4.75 \text{ Mev}$$
$$Ne^{20} + He^{4} \rightarrow Mg^{24} + \gamma + 9.31 \text{ Mev}$$

Thus more energy is released by the capture than was used in freeing the α-particles, so that this process provides a nuclear fuel. Further reactions utilizing the α-particles freed from Ne^{20} can also take place; they are

$$Mg^{24}(\alpha,\gamma)Si^{28}(\alpha,\gamma)S^{32}$$

and so forth. By such reactions the four-structure nuclei, lying above their neighbors in the abundance curve (Fig. 1), will be built at least up to Ca^{40}, and probably some Ca^{44} and Ti^{48} also. We have called this the α-process (*19*). The time scale for this process is probably about 100 to 10,000 years; consequently it probably occurs toward the end of a star's active life.

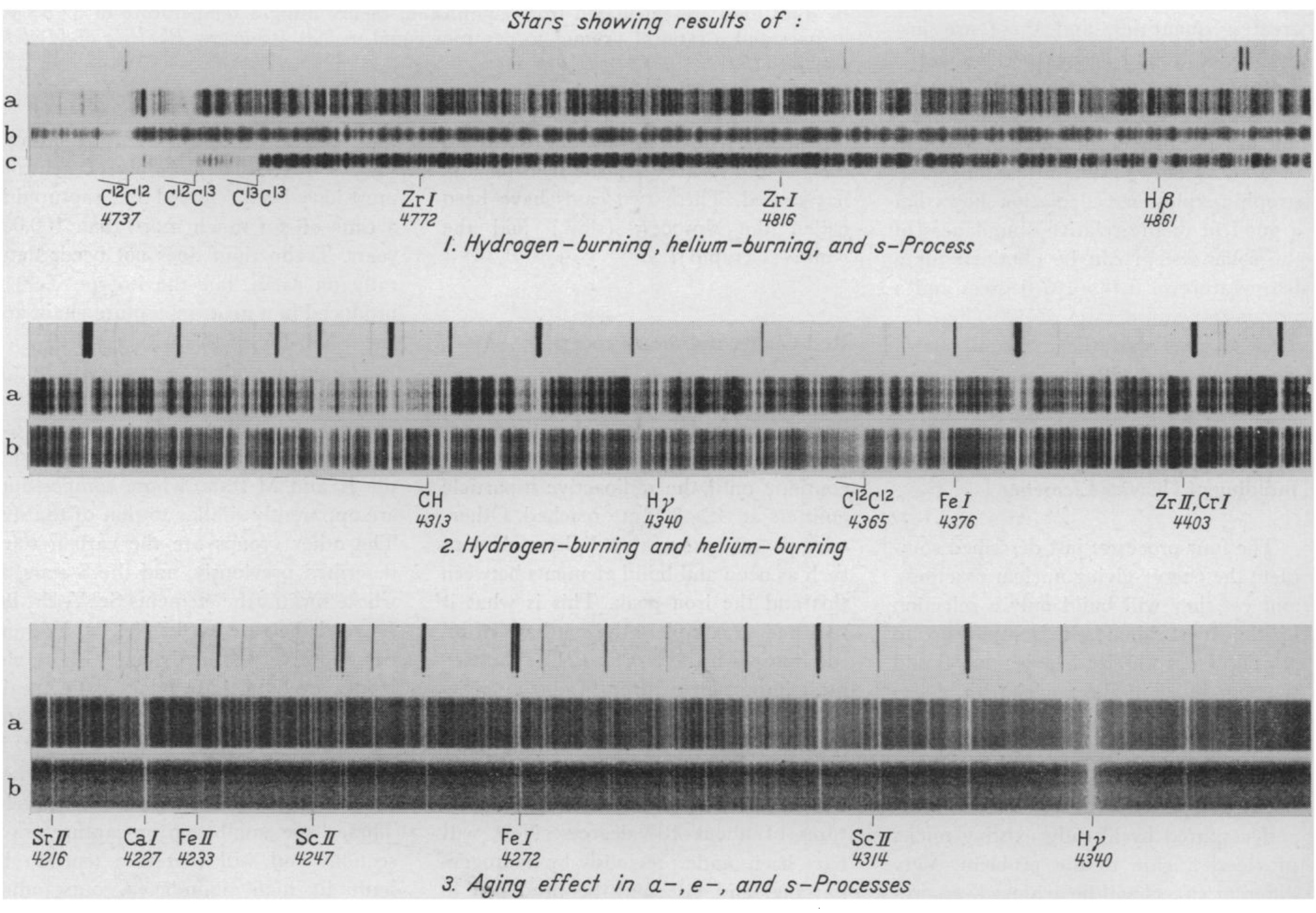

Fig. 6. Portions of the spectra of stars showing different aspects of element synthesis. Top: (*a*) Normal carbon star, *X* Cancri, which has $C^{12}/C^{13} \sim 3$ or 4. (*b*) Peculiar carbon star, HD 137613, which shows no C^{13} bands, and in which hydrogen is apparently weak. (*c*) Normal carbon star, HD 52432, which has $C^{12}/C^{13} \sim 3$ or 4. Note that zirconium lines appear to be strongest in (*a*). Middle: (*a*) Normal carbon star, HD 156074, showing the CH band and the hydrogen line Hγ. (*b*) Peculiar carbon star, HD 182040, in which CH is not seen, although the weak band of C_2 at λ 4365 is visible. Hγ is also very weak, indicating that hydrogen has a low abundance. Bottom: (*a*) Normal star, ξ Pegasi. (*b*) Peculiar star, HD 19445, which has a slightly lower temperature than ξ Pegasi, yet all lines but hydrogen are much weakened, showing that the abundances of α-, *e*-, and *s*-process elements are much lower than normal ("aging" effect). The middle two spectra were obtained by J. L. Greenstein, the remainder, with the exception of HD 137613, by E. M. and G. R. Burbidge.

In the spectrum of the white dwarf Ross 640, shown in Fig. 5, there are no features other than those attributable to magnesium and calcium (whose most abundant isotopes are produced by the α-process). Possibly this star is an example of one which has undergone this process.

The Iron Peak: the *e*-Process

After the α-process has ceased to provide energy, the star must contract further if it is to remain stable. When temperatures as high as 3×10^9 degrees are reached, a great profusion of reactions will occur, and conditions of statistical equilibrium will be reached. On this basis it is easy to calculate the relative abundances of the nuclei that will be built; the only parameters needed are the temperature and the ratio of the number of free protons to free neutrons (which is determined by the density). The most tightly bound nuclei will be built in the greatest quantities, and these are just the nuclei around Fe^{56}. We call this the *e*-process. Its time scale must be very short, of the order of seconds, and consequently it must occur right at the end of a star's active life, just before catastrophic explosion. Calculation shows that a good fit to the relative abundances of the solar system can be obtained for a temperature of 3.78×10^9 degrees and a proton-to-neutron ratio of 300 (Fig. 7). This suggests that the material out of which the solar system was made was once exposed to these conditions.

Building of Heavier Elements

The four processes just described complete the energy-giving nuclear reactions, and yet they will build only a selection of the most abundant isotopes up to $A = 60$. To synthesize heavier nuclei and the remainder of the nuclei with A less than 60, clearly some further processes must be at work. The discovery by Cameron (*20*) that under certain conditions neutrons can be released in stars and captured by already existing nuclei provided a clue to the problem. Very different effects will be achieved, according to whether the neutrons are supplied slowly or rapidly. In the first case, when unstable nuclei are reached in a neutron-capture chain (shown schematically in Fig. 8) they have time to decay by β-emission before capturing another neutron, but in the second case they do not, and building proceeds through β-unstable nuclei, which must later decay to their stable forms after the neutron flux has ceased. These two cases have been called the *s*-process (slow) and the *r*-process (rapid).

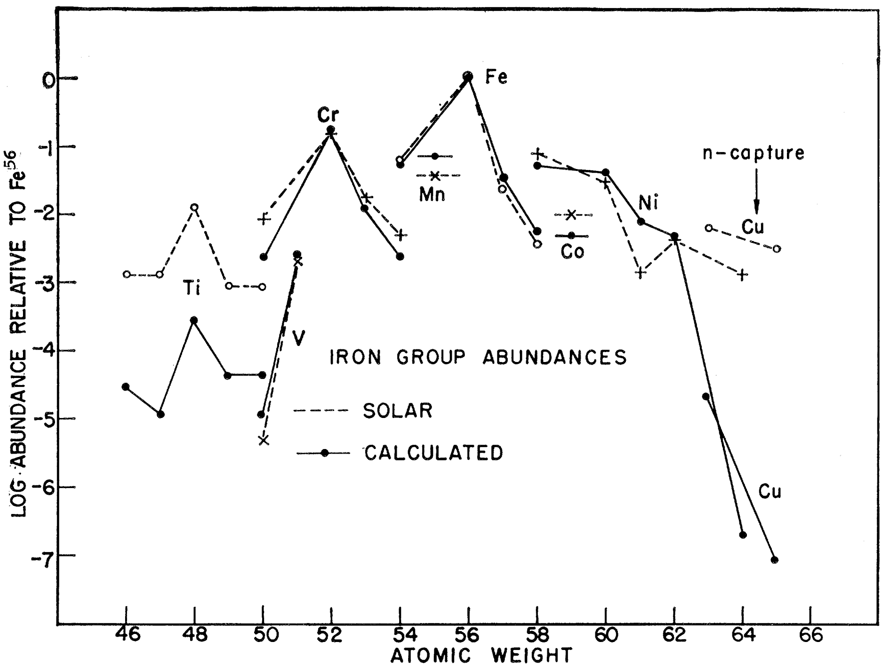

Fig. 7. Logarithmic abundance curve for the iron group isotopes relative to the abundance of Fe^{56}. The points connected by dashed lines are the solar abundances in which terrestrial isotope ratios are used to calculate isotope abundances. The points connected by solid lines are calculated from equilibrium theory using a temperature of 3.78×10^9 degrees and a ratio of protons to neutrons equal to 300. [Courtesy *Reviews of Modern Physics* (*19*)]

Red Giants and the *s*-Process

If the iron-peak elements are present in ample abundance in a star, the build-up chain will start with them and will continue until the radioactive α-particle emitters at $A > 209$ are reached. Otherwise, it may start at a lighter element such as neon and build elements between this and the iron peak. This is what is required to complete the synthesis of all the isotopes up to $A = 60$ (*21*). The two most important neutron-producing reactions are $C^{13}(\alpha,n)O^{16}$ and $Ne^{21}(\alpha,n)Mg^{24}$; conditions for them to take place can occur in the interiors of red-giant stars with large helium cores at temperatures of about 10^8 degrees. Ne^{21} will have been made previously by hydrogen-burning, and C^{13} may be produced in sufficient quantity if some mixing takes place between the core, containing C^{12} built by helium-burning, and the hydrogen in the envelope.

There is good observational evidence that this process occurs in red giant stars. In the first place, the identification of the unstable element technetium in the spectra of some stars by Merrill (*22*) showed that a supply of neutrons must have been released and captured in a time of not much more than 100,000 years. Technetium does not occur naturally on earth, but the isotope Tc^{99} is produced in a neutron-capture chain and has a half-life of 200,000 years.

The other evidence is provided by the division of the red giant stars into three groups which have different spectral characteristics. The most common are the K and M stars, whose compositions are apparently similar to that of the sun. The other groups are the carbon stars, described previously, and the S stars, in whose spectra the elements Sr, Y, Zr, Ba, La, and the rare earths Ce, Pr, Nd, and Sm show very strongly. Now these elements are just those lying in the peaks in the abundance curve at $A = 90$ and 140 (Fig. 1). Among the isotopes in these regions are those which have closed shells of 50 and 82 neutrons, respectively. These have small neutron-capture cross-sections and will therefore tend to be built in high abundance, outstanding above their neighbors. Figure 9 shows the spectra of two stars in which the *s*-process has been operating. The star HD 46407 is a giant of slightly higher temperature than the S stars, but shows the same effects, and was analyzed quantitatively by us (*23*).

Further evidence for the *s*-process

comes from the solar-system abundances of those isotopes believed to have been built this way in the two regions $23 \leqq A \leqq 46$ and $63 \leqq A \leqq 209$. In both, the products of the neutron-capture cross-sections and the abundances, plotted against A, lie on a smooth curve as would be expected in a neutron-capture chain. Measures of cross-sections for many of these heavy isotopes have been made recently at Oak Ridge and Livermore, and when these alone are used, the curve is very well-defined and smooth. Furthermore, plots for the isotopes not made by the *s*-process are scattered at random on the graph!

Supernovae and the *r*-Process

The *r*-process will occur at any point at which a very large flux of neutrons can be generated in condensed matter in a few seconds. For example, much of the radioactive debris produced in terrestrial nuclear explosions is synthesized by a man-made *r*-process. In a similar way the astrophysical circumstances of the *r*-process must be the rapid generation of energy, that is, violent explosion. The most immense stellar explosions known are supernova outbursts in which it is believed that in a very short period (seconds, minutes, or hours) a considerable fraction of the mass of a star is ejected at very high velocities ($\sim$ 10,000 kilometers per second), while the light output of the star increases tremendously, probably by a factor $\sim 10^{10}$ in some cases. The light then slowly declines over a period of years.

The light-curves of some supernovae, published by Baade, are shown in Fig. 10. An important clue to the mechanism of supernova outbursts has been given by the shapes of some of these curves. Between 50 and 100 days after maximum the curves achieve an exponential decline with a half-life of about 55 days, which continues for several hundred days in the case of the supernova followed the longest by Baade, that in the external galaxy IC 4182. It is generally believed that this exponential decline can be explained only by supposing that it is due to energy released by a radioactive nucleus with this half-life. The first suggestion was made by Borst, who proposed that Be^7 with a half-life of 53 days was responsible.

More recently it has been proposed that the transuranic isotope Cf^{254}, which was made in the Bikini nuclear tests in 1952 (and in successive tests), and which has a half-life of 56.2 ± 0.7 days, is responsible (*24*). This isotope decays by spontaneous fission and releases a large amount of energy, about 200 Mev per nucleus. Moreover, it is an isotope which will be built in the *r*-process capture chain. Thus, if we accept this suggestion, the form of the supernova light curves provides the only evidence of where the *r*-process occurs. When the Cf^{254} is built the other *r*-process nuclei will also be made, the chain of neutron capture extending up to about $A = 260$, at which point the rate at which nuclei spontaneously decay becomes faster than the rate of neutron capture, so that the chain is effectively broken.

It has been argued (*19*) that the thermonuclear explosion giving rise to the

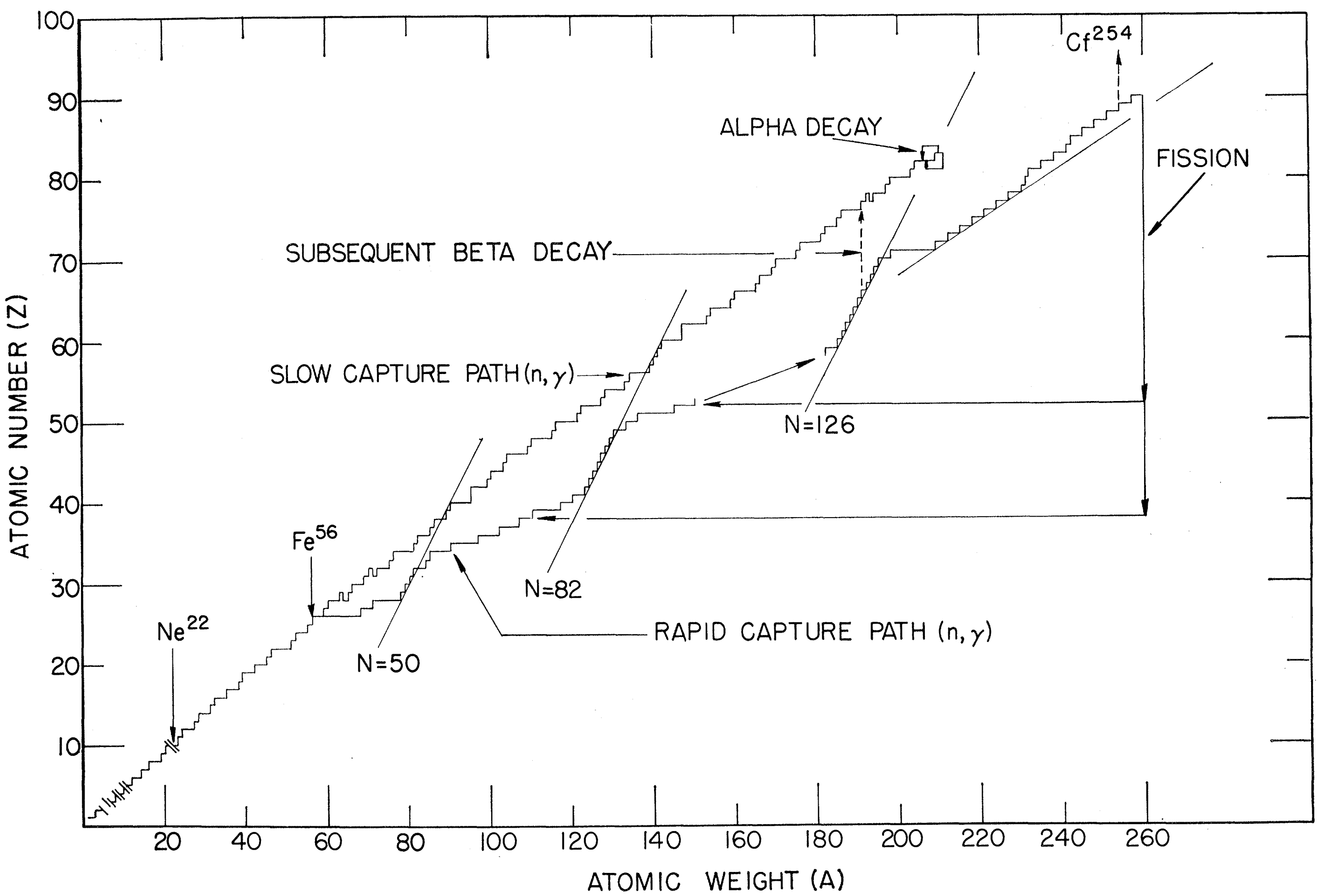

Fig. 8. Schematic plot showing how heavier nuclei are built from lighter ones by neutron capture on either a slow (*s*-process) or a rapid (*r*-process) time scale. The atomic number Z (charge of the nucleus) is plotted against the atomic weight A. The build-up goes from the bottom left-hand corner upward and to the right. Capture of a neutron moves a nucleus one unit to the right, and β-decay moves it one unit upward. At the closed shells of neutrons ($N = A - Z = 50$, 82, and 126) addition of a further neutron is more difficult, and excess abundances build up at these points. [Courtesy *Reviews of Modern Physics* (*19*)]

r-process is triggered in the following way. If the core of a star continues to shrink until a temperature of between 7 and 8×10^9 degrees is reached, the equations of statistical equilibrium show that the material will be broken up from Fe^{56} to He^4. The energy required for this to happen can come only from the gravitational energy which will practically all be used, so that mechanical equilibrium cannot be maintained and the core will implode. Now the material in the outer regions of the star normally possesses a thermal energy which is far less than its gravitational potential energy. If, therefore, any abnormal process leads to the thermal energy suddenly increasing to a value comparable with the gravitational energy, this means that the material is suddenly heated. This is what will happen when the core implodes. It has been estimated that as the outer regions fall inward temperatures of 10^8 degrees will be reached. This sudden heating will be sufficient to generate much energy by (p,γ) reactions and a large flux of neutrons through the (α,n) reactions described earlier. What fraction of these neutrons will be available to generate the *r*-process chain is not certain, but an additional supply of neutrons will have been provided a few seconds earlier in the conversion of Fe^{56} to He^4. The energy release triggered by this sudden heating leads to the ejection of matter and to the sudden increase in brightness of the star.

Calculation shows that the observed abundances of the *r*-process isotopes can be well reproduced when such a model is assumed. A further point of interest is that it is possible to calculate the initial ratio of the abundances of U^{235} and U^{238} which are built. Then, by using the abundance ratio of these isotopes found in the earth and the meteorites today and their decay rates, it is possible to determine the time which has elapsed since the isotopes were made in a supernova explosion, or in a number of such explosions. The minimum age is about 6.6×10^9 years. It does not follow, of course, that the solar system was formed at that time.

Remainder of the Heavy Elements: the p-Process

The neutron capture processes account satisfactorily for the great majority of the heavy elements, but there remain a few isotopes which are in all cases *proton-rich* nuclei, and which cannot be produced by either the *s*- or the *r*-processes. All these isotopes are less abundant than the adjacent nuclei in the solar system material by factors of 100 or more (see Fig. 1). Such nuclei could be produced by the modifying processes of proton capture (p,γ) or the ejection of neutrons by γ-rays, (γ,n), acting upon nuclei already made by the *s*- or *r*-processes. The relative abundances of these isotopes show that (p,γ) reactions are more probably responsible; hence we have called this the *p*-process. It might take place in those supernova explosions involving stars that still have considerable hydrogen left in their envelopes. There is some evidence suggesting that the more massive stars explode while there is still some hydrogen left. Alter-

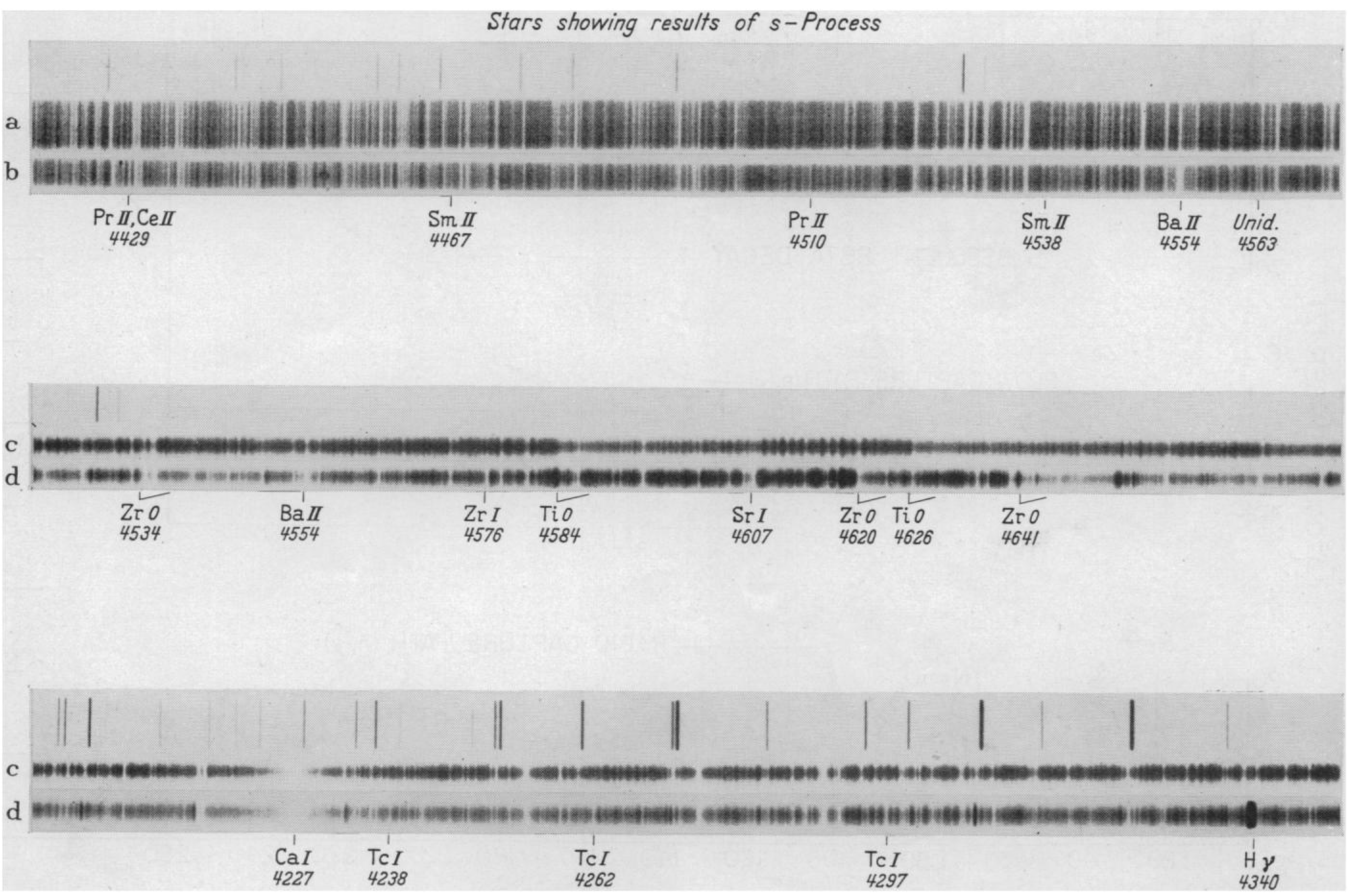

Fig. 9. Portions of the spectra of stars showing the results of the *s*-process. Top: (*a*) Normal star, κ Geminorum. (*b*) Peculiar star, HD 46407, showing the strengthening of the lines due to the *s*-process elements barium and some rare earths. Middle: (*c*) M-type star, 56 Leonis, showing TiO bands at λ 4584 and λ 4626. (*d*) S-type star, R Andromedae, showing ZrO bands which replace the TiO bands. Lines due to strontium, zirconium, and barium are all strengthened. Bottom: (*c*) Another spectral region of the M-type star, 56 Leonis; note that technetium lines are weak or absent. (*d*) R Andromedae; note the strong lines of technetium. The spectrum of R Andromedae was obtained by P. W. Merrill, the upper two spectra by E. M. and G. R. Burbidge.

natively, the *p*-process might occur in the outer parts of the supernovae thought to be responsible for the *r*-process.

Light Elements

In a comprehensive theory the production of the light elements deuterium, lithium, beryllium, and boron must be accounted for. The latter three are rare in the solar system, as is shown by Fig. 1, but deuterium comprises about one part in 6000 of the hydrogen in the oceans on earth. All these elements are readily destroyed by reactions with protons at fairly low temperatures, so that in the center of the sun, for example, deuterium can have an equilibrium abundance of only 10^{-17} that of hydrogen. In a stellar origin theory, therefore, these light elements constitute a problem.

One solution may lie in the fact that nuclear reactions sometimes take place in the atmospheres of stars, as has been studied observationally by us (*25*), and theoretically by W. A. Fowler and us (*26*). The energy source necessary to accelerate the reacting nuclei to high enough energies is electromagnetic. Although the sun has an average surface magnetic field of only about 1 gauss, sunspots have fields of several thousand gauss, and small localized high-temperature disturbances (flares), which appear to have the nature of discharge phenomena, sometimes occur. The so-called magnetic stars have average surface fields of 1000 to 10,000 gauss, and it is possible that localized areas on such stars might have even larger fields.

Since stellar atmospheres usually contain abundant hydrogen, the particles accelerated by the magnetic fields will mostly be protons. Interactions with light nuclei, for example, N^{14} (p,n)O^{14}, will free neutrons, which, in the presence of hydrogen, will almost all be captured by it in the first instance to form deuterium. In fact there is some evidence that deuterium is present in considerable quantities in solar flares (*27*).

The problem of understanding how nuclear reactions can take place in the atmosphere of a star is rather similar to the problem of understanding the conditions under which a plasma in the laboratory can be heated to such a degree that nuclear reactions take place—that is, the problem of controlled fusion. The main differences are that the star's atmosphere is a hydrogen plasma while in the laboratory a deuterium plasma is used, and, secondly, in the star we are interested in the synthesis that can occur, while the problem in the laboratory is that of getting the maximum energy release possible. In the laboratory there is much interest in force-free magnetic fields, while in the atmospheres of magnetic stars, since there is no evidence for any undue pressure effects despite the large fields, they may take up a force-free form, in some way that we do not yet understand.

If deuterium is made locally in magnetic stars, some of it may escape into the interstellar gas out of which new stars will be formed. We do not yet know what the deuterium concentration is in the interstellar gas, but if it is as high as it is on earth, it may soon be measured by radio-astronomical techniques, by means of the radiation at 327 megacycles per second, which is analogous to the 21-centimeter radiation from neutral atomic hydrogen in interstellar space.

Another possibility for the production of deuterium is that it might be made in the expanding shells of those supernovae whose envelopes still contain abundant hydrogen, if a flux of neutrons reaches the envelope. However, the large abundance of deuterium on the earth, if it turns out to be universal, may present some difficulty in either of these mechanisms. The suggestion was made earlier that possibly deuterium can be produced in the ylem if this type of cosmological model is correct, but this would mean that we would not have a *complete* stellar synthesis theory.

In the surfaces of magnetic stars, in an acceleration process, there will be a

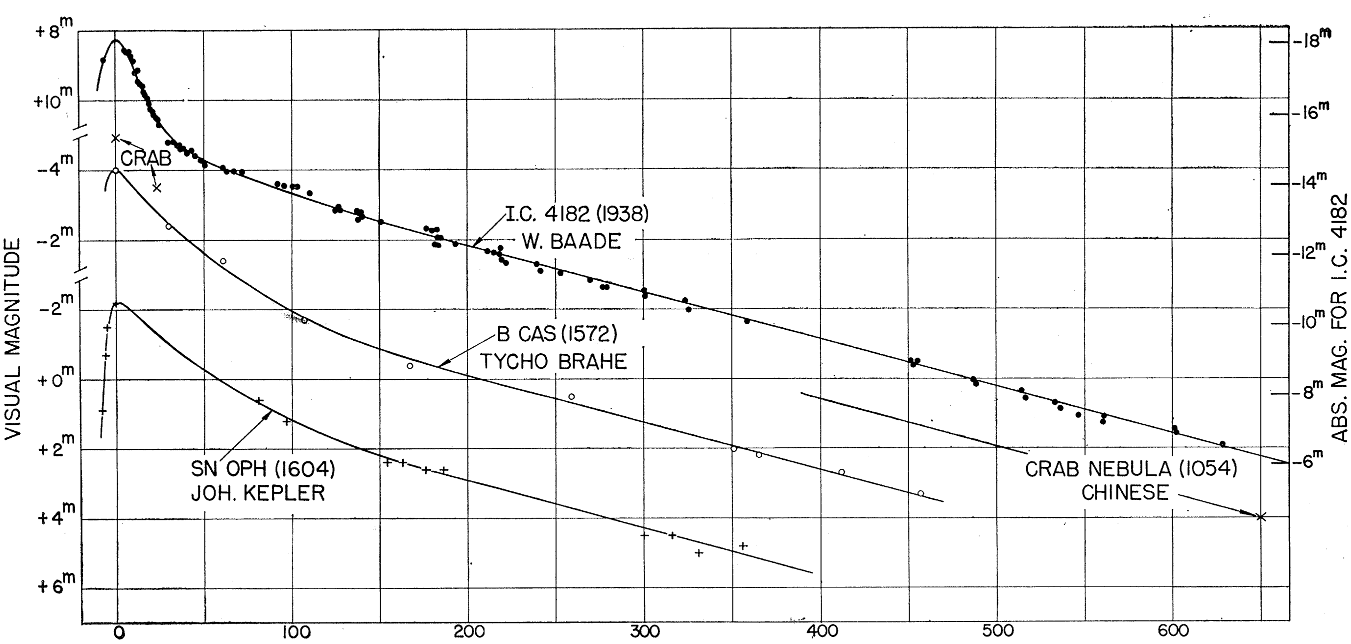

Fig. 10. Light curves of supernovae by Baade. Measures for the supernovae in IC 4182 are by Baade; those for B Cassiopeiae (1572) and SN Ophiuchi (1604) have been converted by him to the modern magnitude scale from the measures by Tycho Brahe and Kepler. The three points for the supernova of 1054 are uncertain, being taken from the ancient Chinese records. The abscissa gives the number of nights after maximum; the left-hand ordinate gives the apparent magnitude which is a logarithmic scale (separate scale for each curve); the points for the Crab Nebula belong on the middle scale—that is, that for B Cassiopeiae. The right-hand ordinate gives the absolute magnitude for SN IC 4182 derived by using the current distance scale. [Courtesy *Reviews of Modern Physics* (*19*)]

small fraction of the particles that will reach sufficiently high energies to break up heavier nuclei. In such break-up processes, lithium, beryllium, and boron are frequent products. It is not hard to account for the abundance of these elements by postulating their production and escape from the atmospheres of stars if magnetic activity, as seems probable, is widespread in the numerous red dwarfs on the main sequence below the sun. For the sake of completeness, we should mention that it is possible also that lithium is built under special conditions of mixing in certain red-giant stars.

Interchange of Matter between Stars and the Interstellar Medium

We have seen that the chemical evolution of the stars is a necessary consequence of their very existence. Thus the building of heavier elements from hydrogen must be continually going on inside stars. Whether this can account for the observed abundances of all of the elements is another matter, depending upon the *rate* of star formation and death, and upon the efficiency of the various ways in which matter, processed in stars, can return to the interstellar gas. It is impossible at present to make better than very sketchy and approximate computations of the balance between observed abundances and the rate of production of the elements. The most spectacular way of spreading the products of nuclear processes back into space is by supernova explosions, but these are not very common. There are apparently two types of supernovae, and the statistics, which are rather uncertain, indicate that they occur, per galaxy, about once every 300 years and once every 50 years, respectively. From these figures it can be estimated that they can account for the observed relative abundances of the α-, *e*-, *r*-, and *p*-process nuclei.

On the other hand, evidence is accumulating (*28*) that giant and supergiant stars steadily eject matter. This may be a more efficient process than explosive ejection simply because it involves a much greater number of stars. In this way the products of hydrogen-burning, helium-burning, and the *s*-process may be returned to interstellar space. Counts of the number of stars of a given brightness per unit volume of space, together with knowledge of how long a star of a particular brightness can last on the main sequence, enable one to estimate how many stars pass through a giant stage. Taking into account the fact that the rate of star births must have been greater in the early history of the galaxy than it is today, as we shall discuss in the next section, it has been calculated that in a time of order 10^{10} years there has been enough ejection to account for the observed abundances of the products of hydrogen-burning, helium-burning, and the *s*-process.

Thus the stellar synthesis theory can certainly account qualitatively, and can probably account quantitatively, for the observed abundances of all of the elements.

Evolution of Galaxies

During the life history of a galaxy there should be a steady enrichment in elements heavier than hydrogen. In an explosive cosmology combined with the stellar synthesis theory, a galaxy would consist at first of pure hydrogen, while in the steady-state cosmology it might have a small amount of heavier elements synthesized in other, earlier, galaxies. For either model, as time passes, the succeeding generations of stars should be formed out of interstellar gas and dust containing a successively richer admixture of elements heavier than hydrogen. The final stage in the history of a galaxy will be reached when it is made up completely of white dwarfs.

Evidence of the progressive enrichment in heavier elements can be found in our galaxy. The globular clusters—dense groups of stars that are in a roughly spherical distribution about the center of our galaxy—are the oldest star groups yet known, with ages of about 6.5 billion years. Although quantitative analyses have not yet been made, the spectra of some of these clusters show that the metals must be in very low abundance relative to hydrogen. Two stars quite near the sun, HD 19445 (see Fig. 6) and HD 140283, whose velocities indicate that they do not belong in the solar neighborhood but probably are closely akin to globular cluster stars, have been found to be deficient in iron and calcium by factors of 10 and 30, respectively (*29*). Some stars with compositions intermediate between young stars and these extreme cases have also been analyzed (*29*).

We may call this the aging effect. It is an effect that is quite apart from the individual chemical evolution of a particular star. The oldest groups of stars were formed out of material whose average composition was different from that today. The observations are hard to explain in any other way than by the stellar synthesis theory, but they are a necessary consequence of it. To account for the variety of processes needed to synthesize the elements in the solar system, the sun must be at least a third-generation star, although it is about 5 billion years old. Differences in composition between the sun and young stars are not very large. Possibly in the early history of the galaxy the rate of star formation and death was much faster than it is now, so that elements were synthesized and ejected more rapidly. This is borne out by the radio-astronomical evidence that the amount of gas (which will determine the rate of star formation) is at present only about 1 percent of the mass of our galaxy, while in the beginning it must have comprised 100 percent.

This raises the question of whether an evolutionary sequence can be detected among external galaxies. Those that have recently formed would be expected to contain more interstellar gas and less heavy elements than those that have been in existence a long time. The study of galactic evolution is in its infancy at present. We do not know whether the different structural forms —irregular (youngest), barred spiral, spiral, and elliptical (oldest)—represent evolutionary stages, or whether they are determined by the initial conditions at the time of birth of a galaxy, or both. Furthermore, the study of the chemical compositions of external galaxies has barely begun and must always remain a difficult problem, because, except for the very nearest galaxies, it is impossible to look at anything other than the integrated effect of billions of stars.

Conclusion: Problems Remaining

Astrophysical observations and experiments in nuclear physics in the last decade have lent increasing support to the idea that all of the elements have been built from hydrogen in stars. The next steps in developing this theory lead in several directions. Firstly, more experimental nuclear physics data are needed, in particular isotopic neutron-capture cross-sections, more accurate binding energies of nuclei in the range of $60 < A < 210$ (for improving the details of the *r*-process), and information on heavy-particle reactions (almost wholly lacking) and improved reactions rates among the light nuclei. This is all basic information without which it will be hard to refine the nuclear physics of the problem.

On the side of theoretical astrophysics, models for stellar evolution need to be taken further, and the evolutionary path of a star after it leaves the red giant configuration must be understood. This involves computational programs on the best automatic computers, such as the one devised by Hoyle for an IBM 704. The problem of handling instabilities in the evolutionary path remains to be solved. On the observational side, more work on the determination of abundances in stars is needed. At present, there has been much qualitative examination of spectra but very little spectroscopic analysis to give quantitative results. More studies of old stars, preferably members of clusters that can actually be dated by the position of the break-off from the main sequence, will be very valuable.

Galactic evolution is one of the subjects where interesting new developments may come soon. This embraces study of the structures, spectra, and distribution of galaxies, as well as theoretical work. When it is remembered that so well-known a feature as the arms in spiral galaxies are still imperfectly understood theoretically, it will be seen how much work still remains to be done in this field.

Astrophysics is the only branch of physics in which we cannot make experiments, but can only observe. It is a science also in which the conditions are always more extreme than any attainable in terrestrial laboratories and the time scales are unimaginably longer. Perhaps its fascination lies in this very aspect, that it challenges man's imagination to the utmost.

References and Notes

1. H. E. Suess and H. C. Urey, *Revs. Mod. Phys.* 28, 53 (1956).
2. R. A. Alpher and R. C. Herman, *Revs. Mod. Phys.* 22, 153 (1950).
3. *Ylem* is an obsolete word for primordial matter.
4. F. Hoyle, *Monthly Notices Roy. Astron. Soc.* 108, 372 (1948); H. Bondi and T. Gold, *Monthly Notices Roy. Astron. Soc.* 108, 252 (1948).
5. G. R. Burbidge and F. Hoyle, *Nuovo Cimento* 4, 558 (1956); M. Goldhaber, *Science* 124, 218 (1956).
6. J. L. Stebbins and A. E. Whitford, *Astrophys. J.* 108, 413 (1948).
7. A. E. Whitford and A. D. Code, "Annual Report of the Washburn Observatory," *Astron. J.* 61, 352 (1956).
8. M. Ryle and P. Scheuer, *Proc. Roy. Soc. (London)* A230, 448 (1955); B. Y. Mills and O. B. Slee, *Australian J. Phys.* 10, 162 (1957).
9. M. L. Humason, N. U. Mayall, A. R. Sandage, *Astron. J.* 61, 97 (1956).
10. A. R. Sandage, *Astrophys. J.* 127, 513 (1958).
11. It should be remembered that the age of the universe can be derived from these figures only after a particular cosmological model is specified. For example, for the Einstein-de Sitter case, the age is two-thirds of the figure given.
12. R. d'E. Atkinson, *Astrophys. J.* 73, 250, 308 (1931).
13. H. A. Bethe, *Phys. Rev.* 55, 434 (1939).
14. C. F. von Weizsäcker, *Physik Z.* 39, 633 (1938).
15. F. Hoyle, *Monthly Notices Roy. Astron. Soc.* 106, 343 (1946).
16. E. E. Salpeter, *Astrophys. J.* 115, 326 (1952); F. Hoyle, *Astrophys. J. Suppl.* 1, 121 (1954).
17. C. W. Cook, W. A. Fowler, C. C. Lauritsen, T. Lauritsen, *Phys. Rev.* 107, 508 (1957); W. A. Fowler, *Sci. Monthly,* 84, 84 (1957).
18. A. R. Sandage, in *Stellar Populations,* D. J. K. O'Connell, Ed. (Vatican Observatory, Vatican City, 1958), p. 41.
19. E. M. Burbidge, G. R. Burbidge, W. A. Fowler, F. Hoyle, *Revs. Mod. Phys.* 29, 547 (1957).
20. A. G. W. Cameron, *Phys. Rev.* 93, 932 (1954); *Astrophys. J.* 121, 144 (1955); see also J. L. Greenstein, *Modern Physics for Engineers,* L. Ridenour, Ed. (McGraw-Hill, New York, 1954), p. 267.
21. W. A. Fowler, G. R. Burbidge, E. M. Burbidge, *Astrophys. J.* 122, 271 (1955).
22. P. W. Merrill, *Science* 115, 484 (1952); *Publs. Astron. Soc. Pacific* 68, 70 (1956).
23. E. M. Burbidge and G. R. Burbidge, *Astrophys. J.* 126, 357 (1957).
24. G. R. Burbidge, F. Hoyle, E. M. Burbidge, R. F. Christy, W. A. Fowler, *Phys. Rev.* 103, 1145 (1956); W. Baade, G. R. Burbidge, E. M. Burbidge, F. Hoyle, R. F. Christy, W. A. Fowler, *Publs. Astron. Soc. Pacific* 68, 296 (1956).
25. E. M. Burbidge and G. R. Burbidge, *Astrophys. J. Suppl.* 1, 431 (1955); *Astrophys. J.* 122, 396 (1955); *Astrophys. J.* 124, 130, 655 (1956).
26. W. A. Fowler, G. R. Burbidge, E. M. Burbidge, *Astrophys. J. Suppl.* 2, 167 (1955); E. M. Burbidge, G. R. Burbidge, W. A. Fowler, *Proc. Stockholm Conf. Cosmical Magnetism 1956,* in press.
27. A. B. Severny, *Astron. Zhur.* 34, 328 (1957); L. Goldberg, O. C. Mohler, E. Muller, *Astrophys. J.* 127, 302 (1958).
28. A. J. Deutsch, *Astrophys. J.* 123, 210 (1956); J. A. Crawford, *Astrophys. J.* 121, 71 (1955).
29. J. W. Chamberlain and L. H. Aller, *Astrophys. J.* 114, 52 (1951); E. M. Burbidge and G. R. Burbidge, *Astrophys. J.* 124, 116 (1956); M. and B. Schwarzschild, L. Searle, A. Meltzer, *Astrophys. J.* 125, 435 (1957).

Long-Term Fallout

A summary of measurements made through June 1957 by the gummed-film network of the AEC is presented.

Merril Eisenbud and John H. Harley

Several papers have described the phenomena of long-range fallout and the methods by which it is routinely monitored (*1*). This paper presents estimates of strontium-90 deposition and external gamma dose which were obtained from the world-wide gummed film network of the U.S. Atomic Energy Commission through June 1957. Results for the continental United States and other stations are tabulated in Table 1; results for the worldwide network are mapped in Fig. 1. In addition, the estimates of strontium-90 deposition as obtained by the gummed-film method are compard with measured values obtained by sampling with open pots.

The authors are on the staff of the Health and Safety Laboratory, New York Operations Office, U.S. Atomic Energy Commission.

Because of their mass, it is not practical to present the detailed analytical results in this article (*2*). This presentation, therefore, is limited to a condensation of the cumulative fallout observations.

Sampling and Measurement

A primary technique in studying long-range fallout is the measurement of the rate of deposition and the cumulative deposit per unit area. For this purpose, three types of samples are currently used: soils, pots or funnels, and gummed film.

Soil samples represent the accumulated fallout at a given location, but these samples require tedious radiochemical analyses for the determination of specific isotopes. Moreover, soil sampling does not permit one to estimate the external gamma dose delivered by the isotopes because of difficulty in analysis and uncertainty in the time of fallout.

Open samplers, such as pots or fun-