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Chronology of the Galaxy

Ages obtained by radioactivity studies and spectroscopy are not necessarily in conflict.

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There are two well-established observational techniques for determining the age of our galaxy. The first of these delineates one of the most active areas of contemporary astronomy—determination of the ages of clusters of stars having a common origin. The ages of stellar clusters place a lower limit on the age of the galaxy, since the galaxy is, by definition, at least as old as its oldest member object. The electromagnetic spectrum of the stars within a cluster reveals, moreover, the relative abundances of metals and hydrogen in the composition of the cluster. Correlation of the metal content of clusters with the ages of the clusters then provides an indication of the rate at which the synthesis of the metals has occurred throughout the history of our galaxy. This interpretation of the metal-age correlation is based on two important assumptions that are now widely believed to be valid: (i) that the composition of the surfaces of stars reveals the composition of the gas out of which the stars formed, and (ii) that the heavy elements in our galaxy have been synthesized in the interiors of stars in our own galaxy by nuclear reactions. I return to the results of this method later.

In the second technique use is made of the systematic nuclear properties of radioactive decay and of nucleosynthesis to determine the time of formation of the heavy elements that eventually condensed and formed our solar system and the duration of the process. Radioactive species of very long half-life occur naturally in the material of our solar system. Some of these long-lived radioactive species are clearly the remnants of processes of nucleosynthesis that occurred earlier in the history of our galaxy. These particular species were synthesized at the same time and in the same nucleosynthetic events as the more common elements of our solar system. By examining the present-day abundances of both the parent and the daughter nuclei of these radioactive species we may use the techniques of radioactivity dating to ascertain the time at which these elements were synthesized. Most of this article is concerned with the results of this technique.

To apply this second method one must have accurate measurements of the isotopic abundances of relatively rare nuclear species. This information can be obtained only from objects in our solar system, primarily from the earth's crust and from meteorites. Thus, the only history we may attempt to trace by this method is the history of the gas that eventually condensed to form our solar nebula and the rate at which heavy metals were added to that gas. The resulting history of nucleosynthesis applies only to our solar system. Some other object in some other part of our galaxy could, conceivably, have an entirely different history of heavy-element enrichment. Whether or not the composition of the galaxy became uniform, with time, would have depended upon whether the rate of star formation was uniform and upon the extent of mixing in the interstellar medium—questions that are themselves unsettled. On the other hand, because of our powerful telescopes, the first or astronomical method can be used to ascertain ages of objects throughout our galaxy. It is important that we keep in mind this fundamental distinction between the two methods.

There are three important conditions that must be met in using a radioactive-decay scheme to date any nucleosynthesis event. First, it is clear that both the present abundances and the abundances of the radioactive species at the time of the event must be known. Second, the intervening history must be known in order that we may be sure that no physical effect other than radioactive decay has altered the relative abundances of the radioactive species in question. Third, in order that the radioactivity method may have sensitivity, the half-life of the radioactive species used must be of the same order of magnitude as the age to be measured. This last restriction is a severe one, for the ages involved are long indeed. For example, the age of our earth is known from radioactivity dating techniques to be almost 5 billion years. Furthermore, the ages of the oldest clusters of stars appear to be in excess of 20 billion years. It would seem, then, that this technique is limited to species having half-lives in the range of 1 billion to 100 billion years. Only four radioactive species meeting these requirements have been shown to be useful. The most important characteristics of those decay modes are listed in Table 1. The question mark after the half-life of Re^{187} indicates that considerable doubt remains as to the exact value. We will examine how each of these decay modes may be used to ascertain the time and duration of nucleosynthesis.

The uncertainty in the intervening

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history between the time of formation of the radioactive species in stellar nucleosynthesis and the incorporation of those elements into the solar system offers no sizable problem. We need only assume that no chemical differentiation occurs in the gas in the interstellar medium. Since it is difficult to imagine any physical process for separating elements in the interstellar medium, this last assumption is quite justified. For each decay mode there *are* a number of problems concerning determination of the initial solar-system abundances, however. I mention briefly the problems associated with each decay mode when considering the chronology.

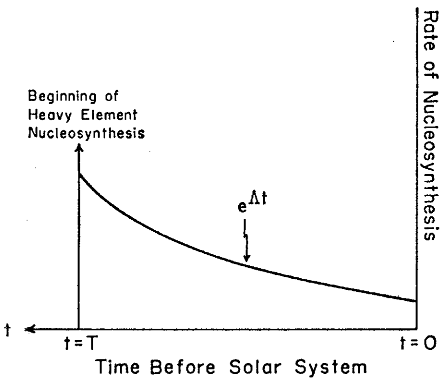

Fig. 1. The chronological model of the rate of nucleosynthesis used to compute the abundances of radioactive nuclei and of their daughter nuclei in the interstellar medium at the time of formation of the solar system.

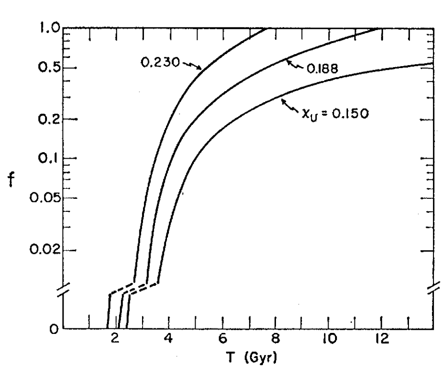

Fig. 2. Loci of points in the f,T plane which give the specified values of χ_U at the time of formation of the solar system. T, Time at which the synthesis of heavy elements began, measured backward in billions of years (Gyr) from the time of formation of the solar system; f, the ratio of the rate of nucleosynthesis at $t = 0$ to the initial rate of nucleosynthesis in the galaxy; χ_U, the initial ratio of U^{235} to U^{238} in the solar nebula divided by the ratio for the rates of production of those two nuclei in the single events of nucleosynthesis.

Even if all the other difficulties can be resolved, a galactic age can be calculated only on the basis of a specific model of the average rate of nucleosynthesis as a function of time and place. Here I use a very simple model of the rate of nucleosynthesis to estimate the chronology of the solar-system elements (see Fig. 1). The origin of time, $t = 0$, represents the time of formation of the solar system, and time is measured into the past from that point. I assume that the synthesis of the neutron-rich heavy elements, which include the long-lived radioactive nuclei of Table 1, began at a time T before the formation of the solar system and decreased exponentially as $e^{\Lambda t}$. (Note that t is measured backward in real time.) It follows that the rate of nucleosynthesis at the time of formation of the solar system is $e^{-\Lambda T}$ times the initial rate of nucleosynthesis in the galaxy.

The use of the simple model of Fig. 1 is based on some uncertain physical assumptions. If the site of some nucleosynthesis event is a supernova explosion or any other common stellar event, we may cite the large number of such events that occur as justifying the replacement of points representing discrete events by a curve representing a smooth and continuous rate of nucleosynthesis. For instance, there are some millions of supernovae events per billion years per galaxy. If the interstellar gas in a galaxy is at all well mixed, this large number of events must produce something closely approximating a continuous rate of nucleosynthesis. If the rate of nucleosynthesis is also proportional to the rate of star formation, and if the rate of star formation is proportional to the gas density, an exponential decline in the rate of nucleosynthesis is a logical result.

Uranium-Isotope Chronology

The first of the radioactivity chronologies depends upon the difference in the rates of decay of the two isotopes of uranium. Due to its much shorter half-life, U^{235} is considerably less abundant than U^{238}, the accepted (*1*) present-day ratio, or $(U^{235}/U^{238})_{\rm now}$, being 0.00723. By exponential extrapolation from this abundance ratio backward in time, we may compute the value of this ratio at the time the solar system formed, $(U^{235}/U^{238})_{\rm o}$. For instance, if we take the age of the solar system to be 4.6×10^9 years (*2*), then $(U^{235}/U^{238})_{\rm o} = 0.31$. The exact value depends upon the age taken for the solar system—that is, for the logistics of this problem, the length of time since the solar nebula withdrew from the products of fresh nucleosynthesis in the interstellar medium. I will tentatively take this time to be somewhat greater than the geological age of the earth. If all the uranium had been synthesized in one event, we could extrapolate from the present abundance ratio back even farther in time until we reached the value for the abundance ratio for the uranium isotopes at the time of this initial event. Of course, all of the uranium was not produced in one event; its production was distributed in some undetermined manner throughout galactic history. I will denote by R the ratio of the abundances of U^{235} and U^{238} produced in each single event of nucleosynthesis. Using the model for the rate of nucleosynthesis shown in Fig. 1, we may easily integrate the ratios for abundances of uranium remaining at $t = 0$ from the amounts produced in each single event of nucleosynthesis and obtain the following equation:

$$\chi_U = \frac{1}{R}\left(\frac{U^{235}}{U^{238}}\right)_{\rm o}$$
$$= \frac{\Lambda - \lambda_{238}}{\Lambda - \lambda_{235}} \frac{\exp[(\Lambda - \lambda_{235})T] - 1}{\exp[\Lambda - \lambda_{238})T] - 1}$$
$$= \frac{\ln f + \lambda_{238}T}{\ln f + \lambda_{235}T} \frac{\exp(-\lambda_{235}T) - f}{\exp(-\lambda_{238}T) - f} \qquad (1)$$

I have defined the quantity χ_U as the ratio of the abundances of the uranium isotopes remaining at the time of formation of the solar system normalized with respect to the ratio of the abundances of the isotopes produced in each single event. I have also introduced the quantity f, which is the ratio of the rate of nucleosynthesis at the time of formation of the solar system to the initial rate of nucleosynthesis in the galaxy—that is, to the rate at time T. This quantity f is related to Λ and T by the expression $f = \exp -\Lambda T$.

Let us examine Eq. 1. Presumably the ratio $(U^{235}/U^{238})_{\rm o}$, which represents the relative primordial abundances of the two isotopes in the solar system (the "primordial isotope ratio"), and the ratio R, which represents the relative abundances of these two isotopes in any single event of nucleosynthesis (the "production ratio"), may be somehow determined. The ratio χ_U of the primordial isotope ratio to the production ratio is a pure number to be determined without regard to galactic chronology. The right-hand side of Eq. 1, on the other hand, is a function of the two parameters f and T. We may view the equation as a relationship between T and f. This relationship is plotted in Fig. 2 for three different values of χ_U: 0.230, 0.188, and 0.150. Figure 2 has the following meaning: If χ_U has the value given for any one of the three curves, then all possible values of f and T are given by all the possible points lying on the curve.

The evaluation of χ_U is fraught with minor uncertainties. The value for the primordial isotope ratio depends upon the time taken as the time of formation of the solar system, and the production ratio for the two uranium isotopes in each single nucleosynthesis event cannot be experimentally determined at all. It is necessary that R be computed from the theory of nucleosynthesis. In the latest theoretical calculations of this production ratio, Fowler and Hoyle (*3*) conclude that $R = 1.65 \pm 0.15$, whereas Cameron (*4*) estimates that $R = 1.45 \pm 0.15$. The difference in these two estimates reflects the uncertainty involved in the theoretical calculations. Using Fowler's "most-probable" production ratio $R = 1.65$ and the primordial isotope ratio $(U^{235}/U^{238})_o = 0.31$ given above, I calculate a "most-likely" value for χ_U of 0.188 (the middle curve of Fig. 2). The two other curves, $\chi_U = 0.230$ and $\chi_U = 0.150$, delineate the range of values thought to be at all reasonable. I expect, on this basis, that the most-likely values for f and T will fall on the middle curve of Fig. 2.

Thorium-Uranium Chronology

We may interpret the Th^{232}/U^{238} abundance ratio in much the same manner. In fact, a completely analogous equation is obtained:

$$\chi_{Th} \equiv \frac{1}{R'}\left(\frac{Th^{232}}{U^{238}}\right)_o = \frac{\ln f + \lambda_{238}T}{\ln f + \lambda_{232}T}\,\frac{\exp(-\lambda_{232}T) - f}{\exp(-\lambda_{238}T) - f} \quad (2)$$

where R' is the production ratio for Th^{232} and U^{238} in the single nucleosynthesis events. As is apparent, the symbol χ_{Th} stands for the primordial isotope ratio, $(Th^{232}/U^{238})_o$, divided by R', the production ratio for the two nuclei. The other symbols have obvious and consistent meanings. The values for f and T that satisfy this equation for various values of χ_{Th} are shown in Fig. 3.

As in the case of the uranium isotopes, the application of this method depends upon determination of the value for χ_{Th}. The production ratio for Th^{232} and U^{238} for each single event of nucleosynthesis has the same fundamental uncertainty as has the corresponding ratio for the two isotopes of uranium. From theoretical considerations, Fowler and Hoyle conclude that $R' = 1.65 \pm 0.15$, whereas Cameron concludes that $R' = 1.65$ is a lower limit for this particular production ratio and its most-probable value as well. The primordial isotope ratio $(Th^{232}/U^{238})_o$, on the other hand, depends critically on the value determined for the ratio of the present-day abundances of thorium and uranium. Because of the long half-life for differential decay (*5*) between Th^{232} and U^{238}, 6.68 billion years, the primordial abundance ratio is relatively insensitive to the time assumed for the time at which the solar system formed. This last fact means that the uncertainty in $(Th^{232}/U^{238})_o$ is due almost entirely to uncertainties in the ratio for present-day abundances of thorium and uranium, the relationship being $(Th^{232}/U^{238})_o = 0.62\ (Th/U)_{now}$. Since the ratio for the present-day abundances (*6*) is generally believed to be 3.8, we see that the most-probable value for χ_{Th} is 2.35/1.65, or 1.42. The curve corresponding to this value of χ_{Th} is the middle curve of Fig. 3; the outer curves represent the maximum uncertainty to be expected for χ_{Th}.

Osmium-Rhenium Chronology

As I have recently shown (*7*), a chronology of nucleosynthesis may also be calculated from the isotopic composition of the element osmium and the ratio of the abundance of osmium to that of rhenium. This calculation is based on the supposition that the beta decay of the nucleus Re^{187}—which is made in the same events of nucleosynthesis as are the isotopes of uranium and thorium—increased the abundance of Os^{187} during the interval between the creation of Re^{187} and the formation of the solar nebula. I denote that portion of the solar-system abundance of Os^{187} that is due solely to the decay of Re^{187} *during this interval* by $Os^{187}{}_c$ (which stands for cosmoradiogenic Os^{187}). The primordial Os^{187} in the solar nebula had two distinct components: (i) the Os^{187} due to the normal mechanisms of heavy-element nucleosynthesis, and (ii) the cosmoradiogenic $Os^{187}{}_c$ due to the decay of Re^{187} in the interstellar medium. The whole idea of using the Re^{187} beta decay as a measure of the chronology of nucleosynthesis depends crucially upon the ability to obtain a value for $Os^{187}{}_c$—that is, to be able to say what fraction of the primordial Os^{187} actually resulted from the decay of Re^{187} in the interstellar medium.

Table 1. Long-lived radioactive nuclei.

Parent nucleus	Type of decay	Half-life ($\times 10^9$ yr)	Daughter nucleus
U^{235}	Alpha	0.7	Pb^{207}
U^{238}	Alpha	4.5	Pb^{206}
Th^{232}	Alpha	13.9	Pb^{208}
Re^{187}	Beta	40 (?)	Os^{187}

The key to this division of the primordial abundance of Os^{187} lies in realizing that, in the processes of stellar nucleosynthesis, Os^{187} and Os^{186} are synthesized only by a process of neutron capture at a slow rate, the so-called *s* process (*7, 8*). It has now been experimentally demonstrated (*9*) that nuclei synthesized only by the *s* process have abundances that are inversely proportional to their neutron-capture cross sections. It must be true, therefore, that the amount of Os^{187} synthesized by the *s* process is given by

$$Os^{187}{}_s = \frac{\sigma(186)}{\sigma(187)}\,Os^{186} \quad (3)$$

By subtraction we may obtain an expression for the amount of cosmoradiogenic Os^{187}:

$$Os^{187}{}_c = (Os^{187})_o - Os^{187}{}_s \quad (4)$$

where $Os^{187}{}_o$ is the primordial abundance of Os^{187} in the solar nebula. For purposes of chronology a more useful quantity is the ratio of the abundance

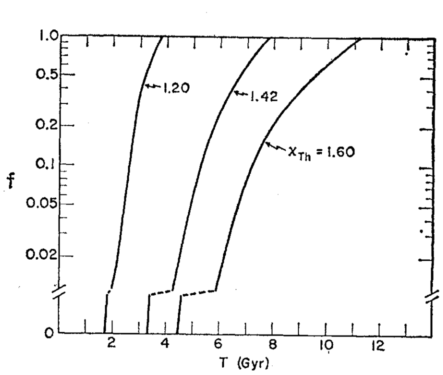

Fig. 3. Loci of points in the f,T plane which give the specified values of χ_{Th} at $t = 0$.

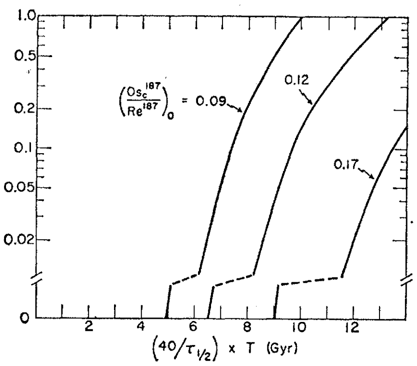

Fig. 4. Loci of points in the f,T plane which give the specified ratios for the abundance, at $t = 0$, of the cosmoradiogenic Os^{187} to the abundance of the parent Re^{187}. The time axis represents real time only if the half-life of Re^{187} is 40 billion years. If it is not, the correct age is given by $\tau_{1/2}/40$ times the values on the abscissa.

of the cosmoradiogenic daughter to the abundance of the radioactive parent at the time of formation of the solar nebula:

$$\left(\frac{Os^{187}{}_c}{Re^{187}}\right)_0 = \frac{\left(\frac{Os^{187}}{Os}\right)_0 - \left[\frac{\sigma(186)}{\sigma(187)}\right]\left(\frac{Os^{186}}{Os}\right)_0}{\left(\frac{Re^{187}}{Re}\right)_0} \times \left(\frac{Os}{Re}\right)_0 \qquad (5)$$

This ratio may be evaluated by examining the geochemical evidence for the abundance ratios involved and by evaluating the ratio of the neutron-capture cross sections of the two isotopes of osmium. Most of the geochemical evidence comes from the research of Herr *et al.* (*10*). From their work I conclude that the most-likely values for the terms of Eq. 5 are: $(Os^{186}/Os)_0 = 0.0159$; $(Os^{187}/Os)_0 = 0.0132$; $(Re^{187}/Re)_0 = 0.65$; and $(Os/Re)_0 = 11.3$. Substitution of these most-probable geochemical values in Eq. 5 gives

$$\left(\frac{Os^{187}{}_c}{Re^{187}}\right)_0 = 0.230 - 0.277\left[\frac{\sigma(186)}{\sigma(187)}\right] \qquad (6)$$

The largest uncertainty in the numerical coefficients of this expression seems to be due to their linear dependence upon the value taken for the present abundances of osmium and rhenium. I expect future geochemical research to firmly establish the abundance ratio for these two chemically similar elements, but I do not foresee a sizable error in the value I have used. The neutron-capture cross sections represented in Eqs. 5 and 6 are, in reality, *averages* of the neutron-capture cross sections over a rather extended spectrum of neutron energies, probably a Maxwell-Boltzmann distribution of velocities corresponding to a value of $kT = 30$ kev. The neutron-capture cross sections in question have not yet been measured; however, experiments are now under way at the Oak Ridge National Laboratory to measure them with high accuracy. From both nuclear theory and the systematics of those neutron-capture cross sections that have been measured, I conclude that the ratio $\sigma(186)/\sigma(187)$ must almost certainly lie in the range 0.3 to 0.5. I tentatively adopt 0.4 as the most-probable value for the cross-section ratio: it then follows from Eq. 6 that $(Os^{187}{}_c/Re^{187})_0 = 0.12$.

For the exponential models under discussion, a simple integration shows that

$$\left(\frac{Os^{187}{}_c}{Re^{187}}\right)_0 = \left[\frac{\ln f + \lambda_{187}T}{\ln f}\;\frac{1-f}{\exp(-\lambda_{187}T) - f}\right] - 1 \qquad (7)$$

The values of f and T that satisfy this equation for various values of $(Os^{187}{}_c/Re^{187})_0$ are shown in Fig. 4. I have modified the abscissa (time) of Fig. 4 to take account of the fact that the half-life of the Re^{187} beta decay is not well known at present. On the basis of several arguments that I will not repeat here, I believe the most-probable value for the half-life is 40 billion years. Therefore, instead of using true time (T) for the commencement time of heavy-element nucleosynthesis as an abscissa in Fig. 4, I have used T multiplied by the ratio $(40/\tau_{1/2})$. In other words, this abscissa represents the real commencement time for nucleosynthesis if the half-life has the expected value of 40 billion years.

The Concordant Solution

It is my hope that future advances in the geochemical sciences and in the application of nuclear theory will make possible an unambiguous determination of the quantities χ_U, χ_{Th}, and $(Os^{187}/Re^{187})_0$. When these data are obtained, the corresponding curves of Figs. 2–4, when plotted on a single graph, should intersect in the f,T plane at a common point if the exponential family of chronological models is realistic. This intersection at a common point is called the concordant solution. The three curves based on the most-probable values [$\chi_U = 0.188$, $\chi_{Th} = 1.42$, and $(Os^{187}{}_c/Re^{187})_0 = 0.12$, with $\tau_{1/2}(Re_{187}) = 40$] are shown in Fig. 5. It is obvious from Fig. 5 that no concordant solution exists at our present state of knowledge. Although this lack of concordance may seem disappointing at first, we must view it realistically. Much work remains to be done toward establishing the correct values of the parameters which identify the three curves of Fig. 5. Accordingly, I reemphasize at this point those physical quantities upon which these three parameters most strongly depend.

The value of χ_U depends on the time we take for the time of formation of the solar nebula. It is by no means obvious that we should take the terrestrial age of the earth, or the age of meteorites, as the time appropriate for the determination of χ_U. The models of continuous nucleosynthesis that are used in this discussion suggest that the appropriate time is that time when the components of the solar nebula withdrew from the products of fresh nucleosynthesis in the interstellar medium. This time could be significantly longer ago than the time of formation of the earth. The value of χ_{Th}, on the other hand, depends strongly upon the ratio for present-day abundances of thorium and uranium. And, of course, χ_U and χ_{Th} are inversely proportional to the theoretically calculated production ratios for the three nuclear species involved. The value of $(Os^{187}{}_c/Re^{187})_0$ depends strongly upon the ratio for present-day abundances of osmium and rhenium and upon the ratio of the neutron-capture cross sections of the osmium isotopes. On the other hand, $(Os^{187}{}_c/Re^{187})_0$, like χ_{Th}, is almost insensitive to the time required in the formation of the solar nebula. Finally, the correspondence with real time in the case of the Re^{187} chronology depends upon the exact value of the half-life of Re^{187}.

In considering the question of concordance, it is also necessary to recall that the simple exponential models for the rate of nucleosynthesis that are used in this article may not be correct. If the gases of our galaxy have always been well mixed, and if the actual rate of nucleosynthesis of the neutron-rich heavy elements has proceeded in accord with any monotonically decreasing function of time, then a model based on exponentially decreasing continuous rates of nucleosynthesis must be a good approximation. However, it is now known that the gases in our galaxy have not been well mixed. As we shall see shortly, there are old clusters of stars in our galaxy that differ in metal-to-hydrogen content by almost an

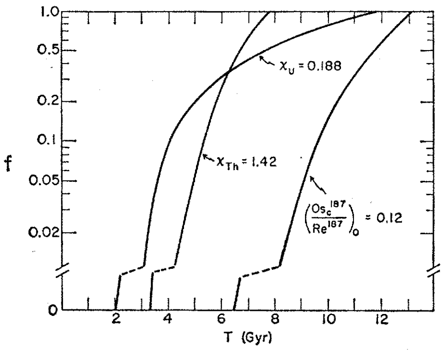

Fig. 5. The concordance test for the most likely values of χ_U, χ_{Th}, and $(Os^{187}{}_c/Re^{187})_0$. The three curves are a superposition of specific curves from Figs. 2, 3, and 4.

order of magnitude although they are of identical age. Furthermore, the present-day metal-to-hydrogen ratios vary by at least a factor of 3 in very young galactic clusters. These inhomogeneities can exist only because the gas in our galaxy has not been completely mixed. Nonetheless, the metals that were added to the interstellar medium in numerous events that occurred billions of years prior to the formation of our solar system must have had nearly the same abundances at $t = 0$ that they would have had if they had been continuously created. Whether we may assume that the rate of heavy-element nucleosynthesis never rose above the initial rate is quite a different matter. It is quite conceivable that heavy-metal formation began slowly at first, increased for a while to some maximum rate, and then decreased from that time forward. Another problem with models based on exponentially decreasing rates of nucleosynthesis becomes apparent when we think of the final additions to the presolar interstellar medium. Whereas the long-ago enrichments must merge into a continuum, the last one or two events of nucleosynthesis may appear as discrete points, particularly in the case of the uranium isotopes.

Since the half-life of U^{235} is only 0.7 billion years, it does seem that the value of $(U^{235}/U^{238})_0$, the abundance ratio at the time of formation of the solar system, may depend explicitly upon the time of the last event of nucleosynthesis that contributed to the interstellar medium in the neighborhood of our sun. Perhaps we may best view this problem by saying that we should reckon radioactive decay not from the time of formation of the solar nebula but from the time of the last local event of heavy-element nucleosynthesis. In that case we should assume, in addition to a continuous rate of nucleosynthesis, a sudden event exactly at the time of withdrawal of the solar nebula. A similar viewpoint has been expressed by others (*11, 4*) in an attempt to account for the extinct radioactivities Al^{26}, Pd^{107}, and I^{129}.

These are some of the difficulties in calculating the chronologies of the galaxy. I want now to return to Fig. 5 with a more positive approach, since it represents the best evaluation I can make at present of the available radioactivity data. Although the three curves nowhere intersect at a point, they do clearly show that the material of our solar nebula began receiving heavy-element enrichment long before our solar system formed. An estimate for time of initial heavy-element nucleosynthesis of something like 8 billion years before the formation of the solar system gives, roughly, the best agreement of the three curves of Fig. 5. Since the solar system itself is almost 5 billion years old, this time of initial nucleosynthesis would be close to 13 billion years ago. Studies of radioactive decay have revealed that nucleosynthesis has been occurring throughout the history of our galaxy. This is an extremely important finding and one that is entirely independent of the findings of the observational astronomer who correlates metal concentrations with ages of stellar clusters. It may seem superfluous to point out a conclusion that has been accepted for a long time, but I do so nonetheless: nucleosynthesis occurs continuously in stars.

Astronomical Evidence

I now return to the astronomical evidence relating to the rate of heavy-element nucleosynthesis in our galaxy. Figure 6 is a slight modification of figures presented by Arp (*12, 13*), in which the metal-to-hydrogen ratio of stellar clusters is correlated with the ages of the clusters. The metal concentration is determinable from the intensity in the ultraviolet region of the continuous-emission spectrum, whereas the ages of the clusters are determinable from calculations of rates of stellar evolution and from the point of departure from the main sequence in the Hertzsprung-Russell diagram of the stars of the cluster. The dashed lines in Fig. 6 are a visual aid; they outline an envelope which contains the observed variations of metal-to-hydrogen concentrations. Arp has emphasized that vari-

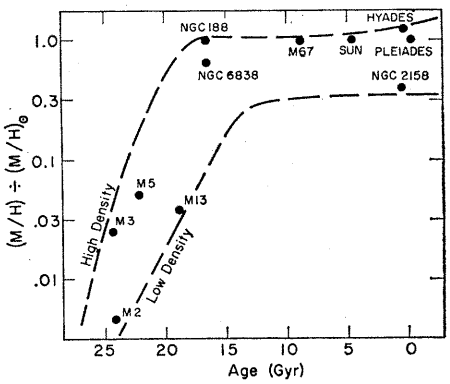

Fig. 6. The observed concentrations of metals in galactic star clusters plotted against the age of the cluster as calculated from the color-magnitude diagrams of the clusters. The dashed lines suggest envelopes for the observed points. The marked rise in concentrations of the metals with real time indicates clearly the effects of heavy-element nucleosynthesis in our galaxy. [Slightly modified from Arp (*11, 12*)]

ations in metal concentration in star clusters of the same age indicate that the rate of nucleosynthesis has not been constant in differing parts of our galaxy, and that the mixing of gases in the interstellar medium of our galaxy has not been complete. Concerning the very oldest globular clusters of our galaxy, represented in Fig. 6, Arp has also suggested that the upper envelope may perhaps correspond to the regions of high initial density in our galaxy, where nucleosynthesis would be expected to proceed at a more rapid rate, whereas the lower envelope may correspond to the regions of low initial density. I consider this to be an important working hypothesis. Even at present the metal-to-hydrogen ratio for the Hyades cluster and that for cluster NGC 2158 differ by a factor of 3. The cluster NGC 2158 is 5000 parsecs from the sun in the anticenter direction. I quote Arp (*13*):

> NGC 2158 resembles, in structure and in richness, a globular cluster more than it does a galactic cluster. With respect to age, metal richness, and structure, NGC 2158 represents the long-sought-for transition system between a galactic and a globular cluster. It is more important to stress, however, that [this] cluster appears to belong to a region beyond the sun, where the density is probably smaller. For the first time, we are beginning to get observed correlations between low density regions and low metal content as predicted by the theory of element building and star formation.

It is even clearer that an increase in the metal-to-hydrogen ratio by more than two orders of magnitude over the last

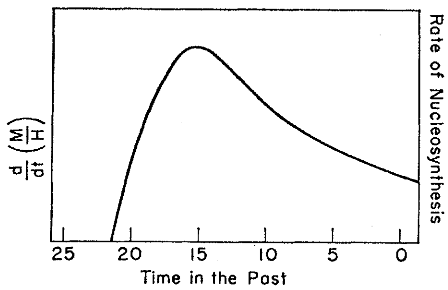

Fig. 7. The astronomically observed rate of heavy-element nucleosynthesis. The curve is a smooth derivative of Fig. 6; it represents the rate at which heavy elements were added to the interstellar medium (compare Fig. 1).

25 billion years is a demonstration of the effects of nucleosynthesis.

Let us now compare the results of the two techniques for determining the age of our galaxy: (i) studies of radioactive decay and nucleosynthesis and (ii) astronomical observation. Is there a conflict between the time of 13 billion years ago concluded from the study of schemes of radioactive decay to have been the time nucleosynthesis began and the time of nearly 25 billion years ago determined by astronomical observation to be the age of the oldest known star clusters in our galaxy? Not necessarily. The two ages do not measure the same thing. It is true that the age of the oldest star cluster may represent the age of our galaxy, and 25 billion years may, at present, be an acceptable estimate of the age of our galaxy, though there are serious objections to ages as great as 25 billion years on the basis of fuel supply (*14*). On the other hand, between 25 and 20 billion years ago the metal-to-hydrogen ratio was only a small percentage of the present ratio in the sun. It seems clear from Fig. 6 that synthesis of the heavy neutron-rich metals in stars had not really begun in earnest 20 billion years ago. It is in the suggested "knee" of the curve of Fig. 6, occurring about 15 billion years ago, that we see the real onset of heavy-element nucleosynthesis. In my mind's eye I can see a sharp increase in the rate of heavy-element nucleosynthesis between 20 and 15 billion years ago to some maximum value perhaps 15 billion years ago, followed by a slow and gradual decline from that day forward. The rate of nucleosynthesis of the heavy metals is given by the slope of the curves of Fig. 6. I have constructed this slope schematically (see Fig. 7). The details are not discernible, but the point is obvious. A time of 13 billion years ago for the large-scale commencement of heavy-element nucleosynthesis, as far as the solar nebula is concerned, is quite in agreement with the general outlines of Figs. 6 and 7. The agreement may be said to be remarkable in view of the fact that both the techniques are still relatively unrefined.

Many interesting and exciting problems for future research are suggested by these considerations. Perhaps the most puzzling of these questions is that of whether there was a long interval, of almost 10 billion years, between the formation of our galaxy some 25 billion years ago and the onset of heavy-element nucleosynthesis around 15 billion years ago. If the ages determined for the star clusters turn out to be correct, this interval will pose an important problem to be solved by the theories of star formation and nucleosynthesis. Perhaps the assumption of one generation of low-mass stars is required, or perhaps the initial interstellar density was not conducive to formation of the appropriate stars. It is too early to say. Since the concentrations of the lighter elements in the very old star clusters (Fig. 6) seem to be not so low relative to present concentrations in the sun as the concentrations of the metals, it may be that heavy-metal synthesis began only after extensive synthesis of the lighter elements. In light of the vast progress made in the last 5 years, it is stimulating to speculate on what observational findings will accrue in the next 5 years to clear up these mysteries.

Summary

I believe that the two observational methods for ascertaining galactic chronology are slowly converging to provide a common answer. My latest evaluation of radioactive decays indicates that synthesis of the heavy elements that were to condense into our solar system began about 13 billion years ago. The rate of increase in the concentrations of metals in observed star clusters, on the other hand, indicates that most of the heavy elements began to be synthesized between 20 and 15 billion years ago. Both estimates will no doubt change in the years to come, but, for the present, I would say that extensive star formation began in the galaxy about 15 billion years ago.

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