Title
Origin of the biologically important elements.

Journal
Origins of life and evolution of the biosphere : the journal of the International Society for the Study of the Origin of Life, 27(1-3)

ISSN
0169-6149

Author
Trimble, V

Publication Date
1997-06-01

DOI
10.1023/a:1006561811750

ORIGIN OF THE BIOLOGICALLY IMPORTANT ELEMENTS

VIRGINIA TRIMBLE
Astronomy Department, University of Maryland, College Park, MD 20742, U.S.A., and Physics Department, University of California, Irvine, CA 92697, U.S.A.

(Received 18 January 1996)

Abstract. The chemical elements most widely distributed in terrestrial living creatures are the ones (apart from inert helium and neon) that are commonest in the Universe – hydrogen, oxygen, carbon, and nitrogen. A chemically different Universe would clearly have different biology, if any. We explore here the nuclear processes in stars, the early Universe, and elsewhere that have produced these common elements, and, while we are at it, also encounter the production of lithium, gold, uranium, and other elements of sociological, if not biological, importance. The relevant processes are, for the most part, well understood. Much less well understood is the overall history of chemical evolution of the Galaxy, from pure hydrogen and helium to the mix of elements we see today. One implication is that we cannot do a very good job of estimating how many stars and which ones might be orbited by habitable planets.

1. Introduction

Life on Earth is very complex, carbon-based chemistry. (Us reductionists would say *just* very complex, carbon-based chemistry.) Would anything else do instead of carbon? Apparently not. A quick glance at the periodic table sets you to thinking about silicon, possibly boron, phosphorus, or germanium. But each has a much less rich array of stable compounds and possible linkages with itself. And you know what a large assemblage of molecules based on silicon looks like – it is piled over every beach.

The next essential, and perhaps the limiting factor for life on any other earthlike planet, is water. That such a light substance as H_2O is a liquid at any reasonable temperature and pressure is remarkable in itself, but I will be concerned here only with the need for hydrogen and oxygen to make it. Nitrogen for proteins and DNA comes next, then perhaps phosphorus (often the least available vital element in fresh water ecologies, hence the extreme effects of phosphate-bearing detergents washed into them).

Beyond these come substances whose biological importance is obvious, but whose irreplaceability is not. We would all feel floppy without our calcium, anemic without our iron, and are used to having a good deal of sodium chloride around. But one can imagine other structural materials, other ways of transporting oxygen, and other salts that could regulate water concentration and conduct weak electric currents.

The elements that appear only as traces in our bodies are still more mysterious. Why is element 34 (selenium) now a standard ingredient in multivitamins and mineral tablets, while element 33 (arsenic) definitely is not? Why should compounds

Origins of Life and Evolution of the Biosphere **27:** 3–21, 1997.

of element 83 (bismuth) be recommended for travelers' diarrhea, while compounds of element 82 (lead) are clearly inappropriate? These questions have, of course, detailed answers known to biochemists. I suspect, however, that while having a range of heavy elements around may be generally good for complex chemical systems, no one particular such element is essential in the way that carbon is.

Finally one comes to elements that interact interestingly with ourselves without being natural parts of us. The use of lithium in mental illness, mercury-silver amalgam for stuffing teeth, gold salts as a palliative for rheumatism, and fluoride toothpaste come to mind.

The following sections address (2) the observed abundances of the elements and isotopes in the solar system, (3) the nuclear reactions and sites that produce them, and (4) the chemical evolution of the Galaxy and its 10^{11} stars over the past 10–20 Gyr and implications for numbers of earthlike planets and their locations. A historical approach to these topics appears in Trimble (1996) and many more technical details in Trimble (1975, 1991).

2. Abundances of the Elements

Our inventory of stable elements was completed only in 1925, with the separation of rhenium (75) from platinum (78). Chemists and geologists had long before noticed that some elements were a lot easier to find on Earth than others, and serious efforts to tabulate abundances and spot interesting patterns in them go back more than a century. Important early discoveries were the dominance of the light elements (carbon to iron roughly) over all the heavier ones; the preponderance of even-numbered elements over nearby odd ones (oxygen vs. fluorine, magnesium vs. sodium, etc.); and a corresponding effect in even and odd isotopes (carbon 12 is common, carbon 13 rare, and similarly for iron 56 vs. 55 and 57). These are now all well understood.

That the most abundant elements of all are hydrogen and helium, in which the Earth is greatly deficient, was the discovery of a young English astronomer, Cecilia Payne, working on a Ph.D. dissertation at Harvard/Radcliffe (Payne, 1925). So unlikely seemed this result at the time that it had to be confirmed by an older, more famous, male astronomer (Russell, 1929) before it was believed. Modern compilers of abundances now fully recognize that the gaseous elements – hydrogen, helium, oxygen, neon, argon, and others – can be measured meaningfully only in the Sun, stars, and interstellar gas, while the best data for the solar system on elements that are normally solid, from lithium to uranium, come from the subset of meteorites called chondrites. Meteoritic data are more informative than the composition of earthrocks because some of them have undergone almost no chemical differentiation or processing since the solar system formed, while the Earth has been through the separation of its metallic core from its rocky mantle and many other traumatic events.

A particularly influential compilation of elemental and isotopic abundances in the solar system was that of Hans Suess and Harold Urey (1956), because these were the data available to Burbidge *et al.* (1957, universally known as B^2FH, for E. M. Burbidge, G. R. Burbidge, W. A. Fowler, and F. Hoyle), when they put together their landmark discussion of ‘Synthesis of the Elements in Stars’. A similar synthesis by Cameron (1957) was much less readily available, and he is perhaps best known in this field as the inheritor, from Suess and Urey, of the task of maintaining the tables of solar system abundances (Cameron, 1968, 1973). The most recent such complete summary is that of Anders and Grevasse (1989).

You might think (given the widely-advertised, exponentially speeding progress of science) that it is time and past for a new such compilation. In fact, however, for our purposes, it hardly matters whether we look at Suess and Urey (1956), Cameron (1968), Anders and Grevasse (1989), or the intermediate points in time represented by Figures 1 and 2 (from Trimble, 1975) and Table I (expanded from Trimble, 1991). The reason is that only beryllium has changed by as much as a factor of 10 in the interim, and most changes are factors of 2–3 or less. Abundances, especially isotopic abundances, of very high precision are important to nuclear physicists and astrophysicists seeking to test whether they have understood which processes produce each nuclide, and the density and temperature conditions under which the processes operate. But I suspect that the biological choice of calcium rather than silicon for vertebrate support structures does not depend on whether the Ca/Si ratio (by number) is 0.049 (Suess and Urey, 1956) or 0.061 (Anders and Grevasse, 1989).

The images and numbers in Figures 1 and 2 and Table I are meant to make as conspicuous as possible (a) the enormous range of abundances from common to rare substances, (b) the major patterns that guide us toward picking out the important nucleosynthetic processes and sites, and (c) the correlation of biological importance with commonness. As an example of (a), consider a representative glob of solar system material that has enough iron to fill a backyard swimming pool. It will have a sizeable lake of hydrogen, but less than a sugar-cube volume of Ytterbium. Important patterns of type (b) include the odd-even effects in atomic number and isotope masses previously mentioned, and the bulges in relative abundance vs. atomic number or weight that occur around 50 and 82 protons (tin, lead) and 50, 82, and 126 neutrons. These last are most conspicuous when isotopes are separated according to their dominant production processes (Figure 3).

Looking outside the solar system, we find three kinds of departures from the solar system norm. First, some stars (galaxies, etc.) contain slightly larger, slightly smaller, or very much smaller fractions of the elements other than hydrogen and helium. (These are called heavy elements or metals, though carbon and the rest are very much included.) Second, there are systematic correlations of relative abundances of various heavies, especially where the total is small. Good examples are anomalously low ratios of iron to oxygen and barium to iron in metal poor stars. The third category is ‘other’. It is quite broad and includes stars and stellar ejecta

Table I

Significance and abundances of some interesting elements. Abundances are by number, normalized to $N(\mathrm{Si}) = 10^6$

Z	Element	Interaction with living systems	N
1	Hydrogen	Water, carbohydrates	27 900 000 000
2	Helium	Inert	2 720 000 000
3	Lithium	Psychoactive	57.1
4	Beryllium	Tastes sweet; berylliosis	0.73
5	Boron	*Boric acid eyewashes; borax	21.2
6	Carbon	Organic chemistry	10 100 000
7	Nitrogen	Proteins, DNA	3 130 000
8	Oxygen	Aerobic processes, carbohydrates	23 800 000
9	Fluorine	Tooth enamel, bones	843
10	Neon	Inert	3 440 000
11	Sodium	Fluid regulator	57 400
12	Magnesium	**Chlorophylls	1 074 000
13	Aluminum	Brain tissue contaminant (?), Alzheimer's disease	84 900
14	Silicon	*Diatoms, cell walls, plant cells, bone, silicosis	1 000 000
15	Phosphorus	**Fertilizers, DNA, lake eutrophication	10 400
16	Sulfur	Fats, rotten eggs, purple bacteria	515 000
17	Chlorine	*Chlorination, electrolyte	5 420
18	Argon	Inert	101 000
19	Potassium	**Plant growth, fertilizers, bananas	3 770
20	Calcium	**Bones, electrical signal transmitter	61 100
21	Scandium	???	34.2
22	Titanium	Bone prostheses (inert)	2 400
23	Vanadium	*Toxic	293
24	Chromium	*Toxic, leather tanning	13 500
25	Manganese	*Utilization of vitamin B1	9 550
26	Iron	**Hemoglobin	900 000
27	Cobalt	*Essential nutrient for grazing animals	2 250
28	Nickel	*Catalyst for hydrogenation of vegetable oils	49 300
29	Copper	**Essential nutrient; algicide	522
30	Zinc	**Needed for growth	1 260
33	Arsenic	Generally regarded as undesirable	6.56
34	Selenium	*Locoweed	62.1
35	Bromine	Soporifics	11.8
36	Krypton	Superman, otherwise inert	45
40	Zirconium	Poison ivy lotion	11.4
42	Molybdenum	*Probable essential nutrient	2.55
47	Silver	Germicide, argyria (silver poisoning)	0.486
50	Tin	Biocides, tin cans	3.82
51	Antimony	Tartar emetic	0.309
52	Tellurium	Tellurium breath (garlicky)	4.81

Table I
Continued

Z	Element	Interaction with living systems	N
53	Iodine	**Thyroxins, bactericides; heaviest (and rarest) element known to be essential in humans	0.90
56	Barium	Intestinal imaging	4.49
73	Tantalum	Surgical appliances; rarest stable element	0.0207
78	Platinum	Dental fillings	1.34
79	Gold	Dental fillings, arthritis amelioration	0.187
80	Mercury	Dental fillings, bactericides, calomel	0.34
82	Lead	Insecticides, radiation shielding	3.15
83	Bismuth	Pink Pills for Pale People	0.144
90	Thorium	Bombs and reactors	0.0335
92	Uranium	More bombs and reactors	0.0090

* Present in standard commercial multivitamin and mineral products.
** Recommended daily allowance established.

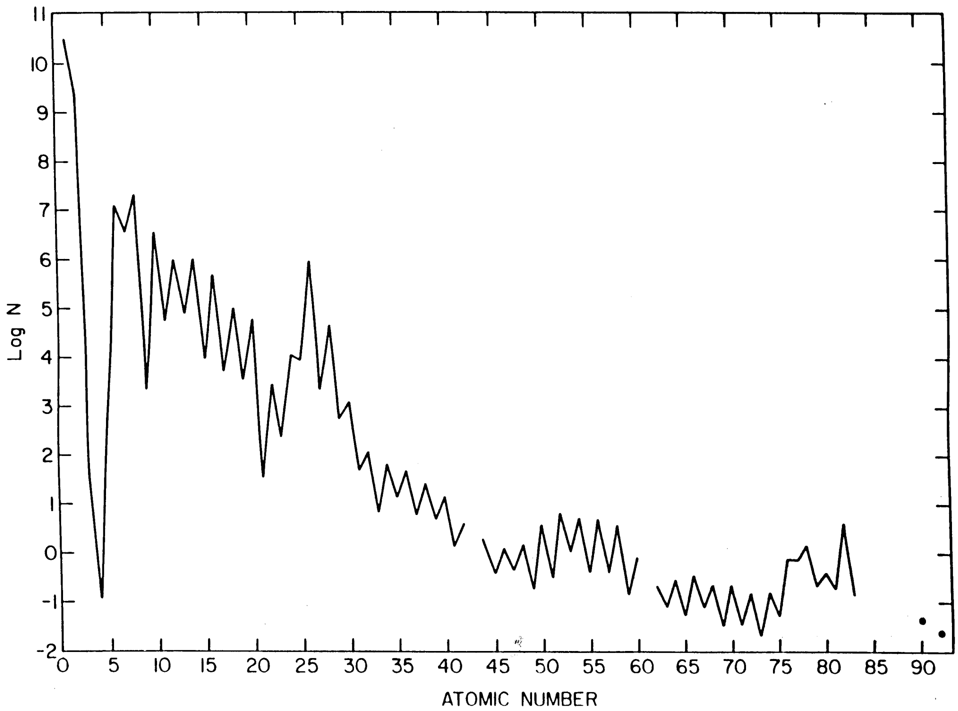

Figure 1. Logarithms of the relative abundances of the chemical elements as a function of atomic number (Z, the number of protons in the nucleus), normalized to $N(\mathrm{Si}) = 10^6$. The numbers are those given in Trimble (1975), but have not changed enough to affect the appearance of such a plot since the time of Suess and Urey (1956). Conspicuous features are the overwhelming dominance of hydrogen and helium, the preponderance of even Z elements over neighboring odd Z elements, the relative peak around iron ($Z = 26$), and the breaks representing elements with no stable isotopes.

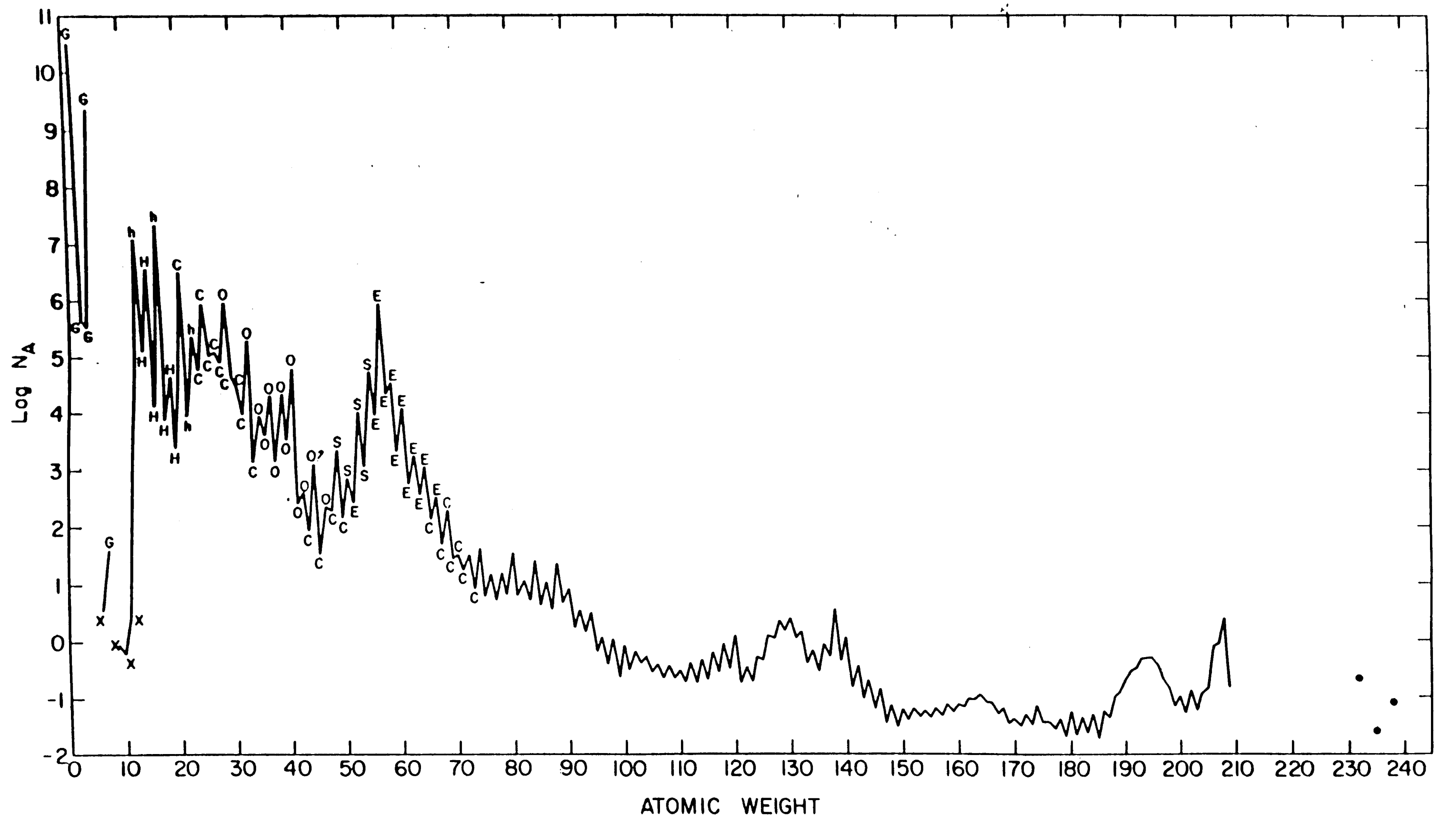

Figure 2. Logarithms of the relative abundances of the stable nuclides as a function of atomic weight (A, the sum of the numbers of protons and neutrons in the nucleus), normalized to $N(\mathrm{Si}) = 10^6$. The numbers are those of Cameron (1973) as modified in Trimble (1975). Letters indicate production processes: G = early Universe; H = hydrogen burning; h = helium burning; C, O, S, E = heavy element burning reactions; x = cosmic ray spallation (etc.). Conspicuous features are the preponderance of even A nuclides over neighboring odd A nuclides and the broad relative peaks around $A = 130$, 140, 165, 195, and 208.

with more carbon than oxygen, with 10^5 times the normal amount of europium, and even a few with technetium, whose most stable isotope lives less than a million years.

In general, the first two kinds of anomalies reflect events that happened before the particular stars showing them were born. Variations in total heavy element abundance (correlated with stellar ages and locations) demonstrate that the metals have been gradually synthesized from primordial hydrogen and helium, at different rates in different places, so that the centers of large galaxies are somewhat more metal-rich than the Milky Way (by factors up to two or three at most), while the outskirts of large galaxies, most small galaxies, and all very old stars are metal-poor (by factors ranging from 0.5 down to 10^{-4}). We return to these patterns in Section 4. Anomalies of the second type, like the ratios of oxygen, iron, and barium in metal-poor stars, are signatures of products of different processes with different time scales.

Anomalies in the third category, on the other hand, result from processes, not always nuclear, that have happened in the star that displays them. We comment on odd results of in-situ nuclear processing (including carbon and technetium) in Section 3. And this is probably as good a time as any to mention, and dismiss, the chemically peculiar stars whose remarkable surface abundances result from radiative levitation, gravitational settling, and wind expulsion, often in the presence of strong magnetic fields, rather than from nuclear reactions. At least half a dozen types are known. They include stars with greatly enhanced or deficient helium (a few with very large He^3/He^4 ratios), others with excess manganese and mercury, strong or weak spectral lines of silicon, calcium, scandium, and so forth, and, weirdest of all, occasional stars with large enhancements of europium and other lanthanides, accompanied by anomalous isotope ratios in mercury, platinum, and other elements. Such stars present interesting problems, but are irrelevant here, if only because they are all fairly massive stars that probably do not live long enough to host habitable planets.

At this point, the contributions of observational astronomy to the present topic are largely complete, and we hand over to nuclear physics and theoretical astrophysics to explain which nuclear reactions are responsible for each of the important elements, where and when they occur, and the numbers and locations of stars likely to have enough heavy elements to form earthlike planets.

3. Nucleosynthetic Processes and Sites

Speculations on how one might build up heavy elements from lighter ones, or break down heavy ones into lighter ones, are about as old as the first, turn-of-the-century, attempts at compiling tables of abundances. The first speculators had in mind processes that might have occurred throughout the Universe, long ago. ‘Building up’ quickly won out over ‘breaking down’, and, in the years just after the first world war, J. Perrin, H. N. Russell, and A. S. Eddington recognized some sort of connection between accounting for the abundances of the elements and accounting for the sources of stellar energy. The focus of attention swung back and forth between reactions in the early Universe and reactions in stars several times over the decades, until it was recognized that you really need both, and a few other minor sites as well.

The weekend historian's minimal kitbag of classic papers has to include at least the following:

1. Atkinson and Houtermans (1929) and Atkinson (1931), who first included barrier penetration in their calculations of stellar nuclear reactions (greatly reducing the required temperature). They had in mind a catalytic recycling process, in which an atom of moderate weight would sequentially capture 4 protons and 2 electrons and spin off a helium nucleus; but, with no knowledge of neutrons, they could not quite see where the first catalyst nuclei were to come from.
2. Von Weizsäcker (1937, 1938), who pointed out that you simply have to start with proton + proton, plus Bethe and Critchfield (1938) and Bethe (1939), who wrote down the correct details for the proton-proton chain and for the cyclic process using carbon and nitrogen as catalysts.
3. Öpik (1951) and Salpeter (1952) on the only possible next stage, the fusing of three helium nuclei into a carbon (called the triple-alpha process).
4. Hoyle (1946, 1954) and Salpeter (1953) on processes that can carry you as far as the elements around iron (the 'iron peak', since they are commoner than their neighbors on either side in Z; Figure 1).
5. Explorations of what are now regarded as minor sites and processes, including pycnonuclear reactions on white dwarfs in nova explosions (Schatzman, 1947), cosmic ray spallation (Gurevich, 1954), and reactions on active stellar surfaces (Biermann, 1956).
6. The pioneering work on cosmological nucleosynthesis (processes in the early, hot, dense phase of an expanding universe) by Gamow (1946) and his colleagues (Alpher and Hermann, 1950, 1953), as modified by Hayashi (1950) to start from the correct initial conditions of a proton-electron-neutron soup in thermal equilibrium, rather than the pure neutron ylem postulated by Gamow *et al.*

The apparent advantage of the Gamow type model over stellar processes was that the abundant supply of neutrons meant you could progress beyond the iron peak and build up elements 31–92 by successive neutron captures and beta decays. The fatal disadvantage was that you really couldn't get past helium, because there are no stable nuclides with atomic weight $A = 5$ (He + H) or $A = 8$ (He + He). Stellar interiors overcome this barrier by providing such high densities that three alpha particles can get together (rarely, briefly, and with difficulty, as you know if you have ever tried to schedule a committee meeting with more than two participants, but enough). The problem of providing neutrons to get beyond iron was solved

Table II
Nuclear processes and products as proposed by B^2FH and Cameron

	Processes	Products
hydrogen burning		He^4, C^{13}, N, $O^{16,17}$, F, $Ne^{21,22}$, Na
helium burning		C^{12}, O^{16}, Ne^{20}, Mg^{24}
	Hydrogen and helium thermonuclear reactions in orderly evolution of stellar interiors	He, C, N, O, Ne
alpha process		Mg^{24}, Si^{28}, S^{32}, Ar^{36}, Ca^{40}, Ca^{44}, Ti^{48}
	Heavy-ion thermonuclear reactions in orderly evolution of stellar interiors +	
	Neutron captures on slow time scale +	Ne to Ca
	Hydrogen and helium thermonuclear reactions in supernova explosions	
e-process	Statistical equilibrium in pre-supernovae and supernovae	Fe peak
r-process	Neutron capture on fast time scale in Type I supernovae	unshielded isobars $A > 62$ including actinides
s-process	Neutron capture on slow time scale in orderly evolution of stellar interiors	most stable isobars $A > 62$
p-process	Proton capture and photonuclear reactions in Type II supernovae + Photonuclear reactions on slow time scale in orderly evolution of stellar interiors	excluded/bypassed isobars $A > 62$
x-process	Possibly made by nuclear reactions in stellar atmospheres	D, Li, Be, B

by Greenstein (1954) and Cameron (1954, 1955), who pointed out that C^{13}, made by CN-cycle hydrogen burning, will experience the reaction $C^{13}\,(\alpha, n)\,O^{16}$ in a helium-burning zone*.

Table II is a snapshot of nucleosynthesis in stars as it appeared to B^2FH (left-hand column) and Cameron (middle column) in 1957. Notice that there are two main neutron-capture processes, on rapid and slow time scales, that make the double peaks (Figure 3) at neutron numbers 50, 82, and 126. A rare process to make neutron-poor isotopes of heavy elements and a mysterious x-process were also needed.

The basic structure shown in Table II has held up remarkably well. A modern compilation of sites and processes includes the items in the following paragraphs. These are arranged in roughly chronological order, starting with the early Universe and ending with supernova explosions and cosmic ray processes. Items 2 to 8 can be associated with major phases in the lives of massive stars as shown in Table III. All stars eventually burn hydrogen and helium; only those more massive than about 8 times the mass of our Sun go on to fuse heavier elements at higher temperatures.

Table III
The seven ages of a 20 $M_\odot$ star (from Arnett *et al.*, 1989)

Energy Source	Central density (g/cm^3)	Central temperature (K)	Photon luminosity (erg/sec)	Neutrino luminosity (erg/sec)	Duration
Hydrogen fusion	5.6	4×10^7	3×10^{38}	small	10^7 yr
Helium fusion	940	2×10^8	5×10^{38}	small	10^6 yr
Carbon burning	3×10^5	8×10^8	4×10^{38}	7×10^{39}	300 yr
Neon burning	4×10^6	1.7×10^9	4×10^{38}	1×10^{43}	0.38 yr
Oxygen burning	6×10^6	2.1×10^9	4×10^{38}	7×10^{43}	0.50 yr
Silicon burning	5×10^7	4×10^9	4×10^{38}	3×10^{45}	2 days
Core collapse	$10^9 \to 10^{15}$	4×10^{10}	$10^{42} - 10^{44}$	10^{52}	10 sec
(Gravitational potential energy)					

1. *Big Bang Nucleosynthesis.* Expansion of the Universe from thermal equilibrium at $T \sim 10^{10}$ K leaves about 75% hydrogen and 25% helium. H^2 (deuterium) and He^3 are also made at a level of a few parts in 10^5, and Li^7 at about 10^{-10} by number of the total. The precise product ratios are sensitive both to the density of normal baryonic material in the Universe (which cannot be high enough to stop the current expansion) and to the number of species of low mass, stable neutrinos. Whether we can understand the precise ratios seen is currently under discussion (Copi *et al.*, 1995; Hata *et al.*, 1995).

* $C^{13}\,(\alpha, n)\,O^{16}$ indicates a reaction in which a C^{13} nucleus and an α-particle (He^4 nucleus) fuse to form an O^{16} nucleus and a neutron (n) with release of energy; similarly for other examples in the text.

2. *Hydrogen fusion to helium in stars (hydrogen burning).* Goes by the proton-proton chain in the cores of low mass stars (producing only helium) and by the CN or CNO cycle in cores of massive stars and shells of evolved (red giant) low mass stars. The main product is helium, but some carbon is also turned into nitrogen (its only known source). Nitrogen is, therefore, a secondary nucleus, produced only after there is some carbon or oxygen made by helium burning in earlier star generations; it is, therefore, particularly rare in stars of low total metallicity. Hydrogen burning is the main source of energy for all stars for more than 90% of their lives. A universe in which the Big Bang did not leave lots of hydrogen behind would not have long-lived stars to provide stable environments for life on planets. A $1\,M_\odot$ (one solar mass) star lives 10^{10} years on hydrogen fusion, a $30\,M_\odot$ star only 10^7 years.

2a. *Hot hydrogen burning.* An extension of the CNO cycle upwards to Ne–Na and perhaps Mg–Al at high temperatures in novae and massive stars produces fluorine and the rarer isotopes of Ne and Mg. Another probable product is Al^{26}, which decayed to Mg^{26} after the solar system solidified, leaving its signature in meteorite composition anomalies.

3. *Helium burning* produces carbon by the triple-alpha process ($3He^4 \rightarrow C^{12}$) and oxygen by the reaction $C^{12}\,(\alpha,\gamma)\,O^{16}$ in the cores of all stars more massive than about $0.5\,M_\odot$ (which is all the ones that have had time to evolve in the age of the Universe). It is clearly essential for life as we know it that both of these occur and that roughly equal amounts of C and O result. Both processes are very dependent on a detailed balance between nuclear forces pulling protons and neutrons together and electromagnetic forces pushing the protons apart. The triple alpha process occurs primarily through an excited level of carbon with quantum mechanical properties that enhance the rate. Without this level, helium could not burn at stellar temperatures. The rate at which $C^{12}\,(\alpha,\gamma)\,O^{16}$ occurs is still not very well measured (because it is dominated by a level that cannot be studied in the laboratory). The large amount of oxygen expelled by Supernova 1987A is, however, consistent with the most recent, rather high, published values for the reaction rate (Buchmann *et al.*, 1993; Zhao *et al.*, 1993). That our existence is dependent on this sort of fine tuning has seemed profound to some astronomers (but not all). Stars with large excesses of carbon are evolved ones of intermediate mass, such that their cores are hot enough for vigorous triple alpha processing, but not quite hot enough for $C^{12}\,(\alpha,\gamma)\,O^{16}$. They must, of course, also have experienced mixing between their nuclear burning cores and cool surface layers. This also happens only in rather late evolutionary stages. Excess nitrogen from CN hydrogen burning is common in these stars.

4. *Carbon burning* produces neon and sodium (and smaller amounts of other things) in cores of stars more massive than about $8 \pm 2\,M_\odot$. B^2FH and Cameron had thought that production of heavier elements would proceed through capture of successive helium nuclei by O^{16}, Ne^{20}, Mg^{24}, etc. This

does not happen because there is no quantum-mechanically suitable level of Ne^{20} to give $O^{16}\,(\alpha, \gamma)\,Ne^{20}$ a large cross-section. Their 'alpha process' therefore divides up into several successive stages of heavy element burning, beginning with carbon.

5. *Neon burning* makes the most abundant isotopes of Mg, Al, and P (and smaller amounts of other things) in cores of massive stars.
6. *Oxygen burning* makes Si, S (etc.) in massive stars.
7. *Silicon burning, or nuclear statistical equilibrium,* in which Si^{28} nuclei, alpha particles, and some free neutrons and protons come into near equilibrium at high density and a temperature of a few billion Kelvin, makes Fe, Co, Ni, Cu, Zn (etc.). The dominant immediate product is Ni^{56}, but this will eventually decay to Fe^{56} via Co^{56} (as seen in the ejecta of SN 1987A; Arnett *et al.*, 1989). Production of iron peak elements continues until the core mass reaches the maximum that can be supported by pressure of degenerate electrons (essentially the Chandrasekhar mass). The core then collapses in a few seconds, releasing about 10^{53} ergs, mostly in the form of neutrinos (Arnett *et al.*, 1989). The 1% or so of this energy that is converted into outgoing kinetic energy and photons is seen from outside as a supernova explosion of Type II (the kind with hydrogen lines in the optical spectrum, because the stars still have a hydrogen-rich envelope).
8. *Explosive nucleosynthesis*, the fine tuning of the products of C, Ne, O, and Si burning by the outgoing shock during Type II supernova explosions, makes the dominant isotopes of Cl, Ar, K, Ca, Sc, Ti, V, Cr, and Mn. A different sort of explosive nucleosynthesis occurs in the other main kind of supernova, Type Ia. These are not core collapse events, but nuclear deflagrations in which a Chandrasekhar mass of degenerate carbon and oxygen burns, partly to iron peak elements, returning 1.0–1.5 $M_\odot$ of highly processed material to the interstellar medium. Their contribution to nucleosynthesis is relatively modest because they are rare (though very bright, so that they tend to dominate catalogues of observed supernova). A signature of Type Ia supernovae starting to contribute to nucleosynthesis $\sim$ 1 Gyr after the Galaxy formed is the gradual disappearance of anomalously low Fe/O ratios as you look from very metal-poor stars to ones of solar composition.
9. *s-process.* Slow capture of neutrons by iron-peak seeds during helium burning in intermediate mass stars contributes to most elements from Ga to Bi. 'Slow' means that the time between successive captures is longer than the time scale for beta decays of unstable nuclides. Thus the s-process makes the most stable nuclide at each value of $A = Z + N$. It cannot, however, bridge the gap of unstable elements from $Z = 84$ to 89. Elements that come mostly (more than 50%) from the s-process include Ga, Ge, Se, Y, Zr, Nb, Sn, Ba, La, Ce, Hg, and Tl. Excesses of Y, Zr, and Ba in the spectra of some highly evolved stars (often carbon-rich ones, as per paragraph 3) have been known for many years. They are the result of s-process products being mixed to the surface (or occasionally

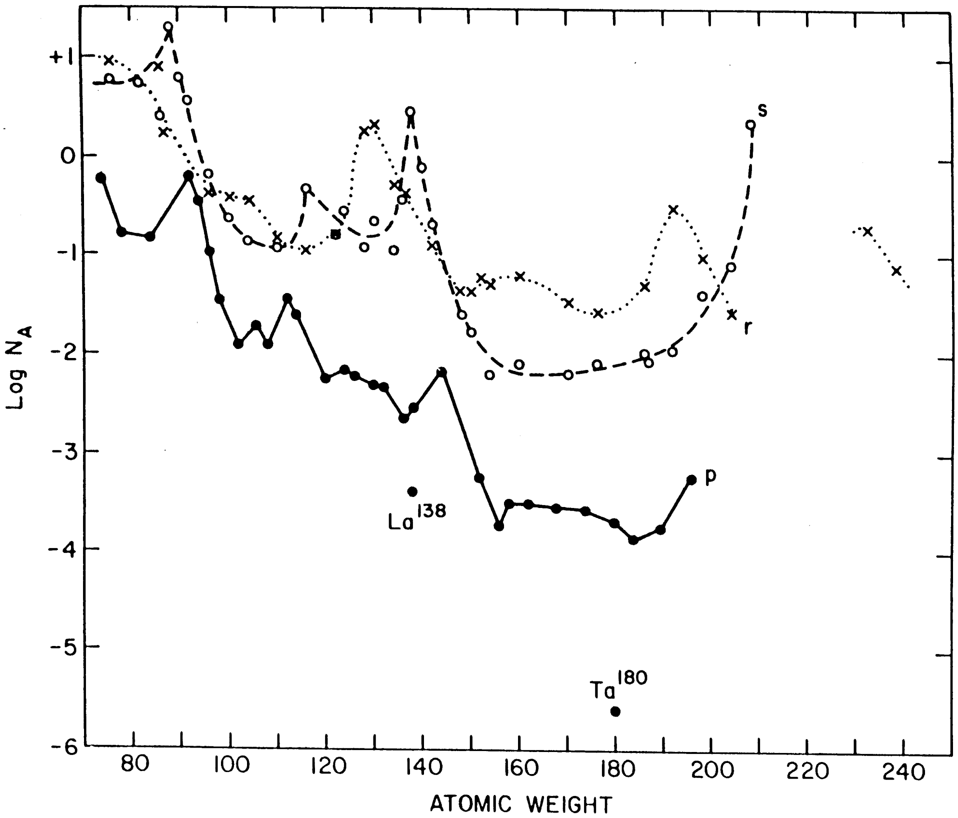

Figure 3. Logarithms of the relative abundances vs. atomic weight of nuclides heavier than the iron peak that can be attributed to a single one of the r (crosses and dotted line), s (circles and dashed line), and p (dots and solid line) processes. The closed neutron shells at neutron number $N = 50$, 82, and 126 are responsible for the three peaks in the s and r product abundances. The r peak occurs at lower A for each because the nuclides were produced with an excess of neutrons which decayed to yield stable daughters. The peaks are present also in the p abundances, but no element is primarily a p product, so we know nothing about it outside the solar system.

of dumping of material from a companion star with active s-processing). The s-process products are, like nitrogen, secondary nuclides, dependent on previously-existing iron for their production. Thus they are over-deficient in metal-poor stars. Tc is an s-product, and its discovery in a few Ba-rich stars (Merrill, 1952) was the first direct proof that nuclear reactions really do occur in stars. The neutrons come primarily from the C^{13} source mentioned above, though other production chains are possible (Lambert *et al.*, 1995).

10. r-process. Rapid capture of neutrons by iron peak seeds. The primary site has been disputed, but intermediate zones of Type II supernovae are the best bet (Woosley *et al.*, 1994). 'Rapid' means that successive captures occur faster than beta decays. Thus the r-process makes nuclides that are more neutron-rich than the products of the s-process (the right hand part of each of the dual peaks in Figure 3). It can also bridge the gap to make Th and U, as well as contributing to most of the stable elements between As and Bi. The Pu^{244} present when the solar system solidified, but now long gone, was also an r-product. Elements that come mostly from the r-process include As, Se, Br, Mo, Ru, Rh, Pd, Ag, In, Sn, Te, Xe, Ce, Pr, Eu, Gd, Tb, Dy, Ho, Er, Tm, Lu, Ta, W, Re, Os, Ir, Pt, Au, Pb, Bi, Th, and U. Elements above $Z = 30$ not mentioned specifically in either this paragraph or the previous one are made by both r- and s-processes in roughly equal amounts.

You might feel that we would have been better off without the ability of the r-process to jump over $Z = 84$–89 and make uranium and thorium. But the decays of these within the Earth were a major source of the heat that permitted partial melting and the separation of the liquid iron-nickel core from the solid rocky mantle. A planet without this separation would have no magnetic field to keep out cosmic rays. It would also have enough iron near its surface to make an oxygen-rich atmosphere very difficult to maintain. Both would be bad for life as we know it.

11. *The p-process*, where p stands for ‘proton’, also happens mostly in supernovae (Rayet *et al*., 1994; Lambert, 1992). The actual nuclear reactions are some combination of proton additions and neutron removals to make the (always rare) neutron-poor isotopes of the elements beyond the iron peak. No element is dominated by p-products.

12. *The x-process* of B^2FH is now thought to have several parts. Most important is the production of Li, Be, and B when CNO nuclei in the interstellar medium are broken up by passing cosmic rays (spallation). Some red giants are lithium-rich and they, as well as flares, novae, and neutrino captures in supernovae (Woosley, 1996) are probably also x-producers. All the deuterium and a bit of lithium are left from the Big Bang (paragraph 1).

Of course, the amount of each element that you get out of this moderate complexity depends on how common its production mechanism is. Notice that, of the elements most important for life, hydrogen is left in abundance by the Big Bang, while carbon, nitrogen, and oxygen are made by the hydrogen and helium burning reactions that occur in all stars. Continuing down the line, we find that the majority of other very useful elements, calcium, iron, and so forth, come from the main sequence of heavy-element-burning reactions that occur, at least, in all massive stars.

In summary, so far we are doing very well. Each element important for life – and all the others – is made in roughly the right amount by some known reaction or set of reactions; and the stars (etc.) that we see around us provide environments with the right densities and temperatures for the reactions to occur. Admittedly, some isotopes (especially rare ones) still come out a bit too low or too high in the sums of processes, and we are not very sure which stars or binary pairs are the progenitors of Type Ia supernovae. But, for the most part, stellar structure, evolution, and nucleosynthesis are solved problems. The situation is less satisfactory as we move on to the final topic.

4. Galactic Chemical Evolution and Numbers of Potentially Habitable Planets

The final task is to put all the reactions and sites together over the history of the Galaxy, add up their products, and see whether the sum as a function of time and place agrees with the data we have on heavy element abundances vs. time and place. In addition, the model galaxy must end up with luminosity, color, mass, and residual gas fraction matching those of the real Galaxy you are trying to understand. If this could be successfully accomplished, we would then be in a position to say something about the numbers and locations of stars that are both sufficiently metal-rich to have had a good chance of forming terrestrial (rocks and metals) planets and sufficiently old for chemical evolution to have progressed to biological evolution. Somewhat arbitrarily, I will set the necessary metallicity equal to one-half solar and the necessary time equal to the present age of our solar system (4.55 Gyr out of the 15 ± 3 Gyr age of the Galaxy). What fraction of potential host stars actually form planets (terrestrial, Jovian, or both) is a separate issue, insightfully discussed by Lunine (1995).

In fact, we cannot even do a good job of estimating host frequencies. What is the problem? Not the obvious one that your computer isn't big enough to keep track of 10^{11} Galactic stars at once. That was solved by Beatrice M. Tinsley in her Ph.D. dissertation (Tinsley, 1968). The trick is to treat all stars of similar mass (hence similar life time, nuclear reactions, etc.) together. Nor is there any doubt about what the dominant processes must be. Gas clouds gradually contract and fragment into stars, which do their thing and blow off smaller amounts of metal-enriched gas, thus gradually increasing the fraction of heavy elements in the remaining gas from nearly zero to about 2%. Meanwhile, metal-free gas left from the Big Bang can continue to flow into the Galaxy, and enriched gas can be blown out by supernova-driven winds.

Unfortunately, we have no real theory of any of these processes (though Galactic chemical evolution has been simulated and reviewed many, many times (Rana, 1991; Timmes *et al.*, 1995, and references therein). That is, no one knows how to calculate when a given gas cloud will turn into stars, how efficient the process will be, or how many stars of each mass will be formed. The star formation rate in a galaxy as a function of time and mass is therefore treated as an adjustable parameter (dependent on gas composition or whatever else appeals to you). Infall and outflow rates as a function of time introduce additional adjustable parameters. Indeed the big galaxies we now see may really have been assembled from large numbers of entities like dwarf galaxies over billions of years, rather than have functioned as semi-isolated systems.

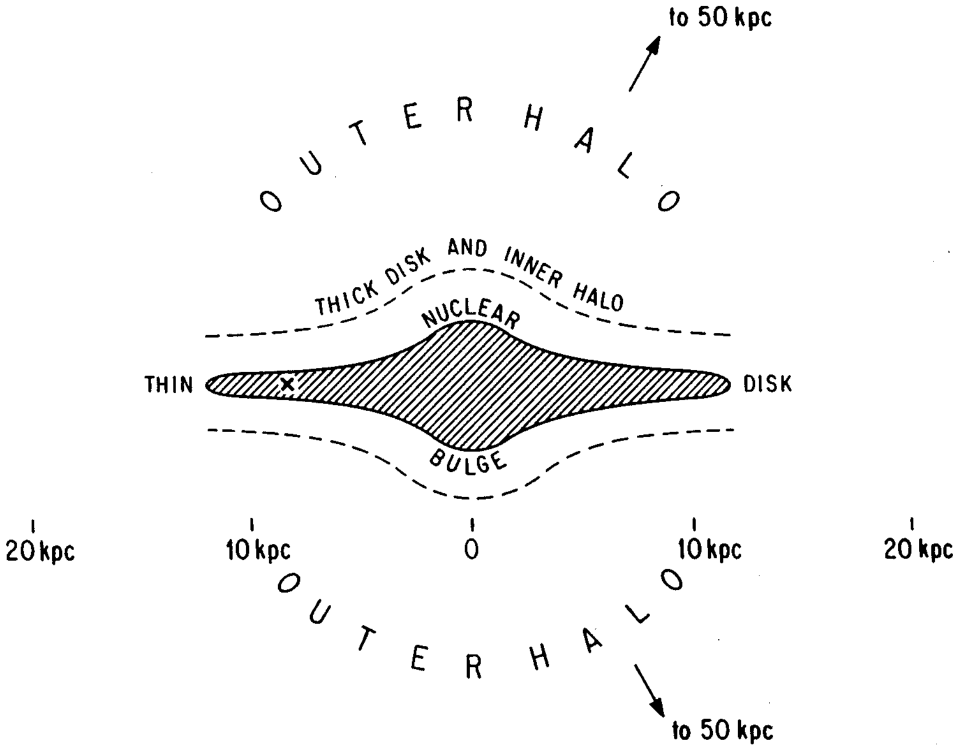

Figure 4. Author's impressionistic view of our Milky Way Galaxy, seen edge on, indicating the locations of the bulge, disk, and halo populations of stars. The Sun is in the thin disk about 8.5 kpc (2.6×10^{22} cm) out from the center (point X). Stars passing near the Sun include members of the thin and thick disk and inner and outer halo populations, but no bulge stars. The outer halo actually extends to more than twice the size of the page, as indicated by the locations of the most distant globular clusters of stars. A face-on image of the Galaxy would show spiral arms, where most star formation occurs, in the thin disk and in the distribution of atomic and molecular gas.

The result is enough parameters to fit any size pachyderm you might see (George Gamow is supposed to have said that, with five free parameters, you could fit an elephant). On the positive side, this means we can model all the galaxies that exist and lots that don't. The down side is that the models have almost no predictive power when you start asking about stellar populations at times and places that were not originally used to constrain the model. We have a couple of firm warnings that caution is needed. First, a relatively well measured quantity is the number of stars as a function of metal abundance near us. But all of the simple models predict far more stars with less than 10% of solar metallicity than we actually see (van den Bergh, 1962; Schmidt, 1963). A second puzzle is the wide range of heavy element abundances at any given time and place. The local interstellar gas is, at present, not quite as rich in heavy elements as our own solar system (Walter *et al.*, 1992). At the same time, one of the oldest nearby star clusters, NGC 6791, contains about twice the solar allotment of heavy elements (Kaluzny and Rucinski, 1995). Only when

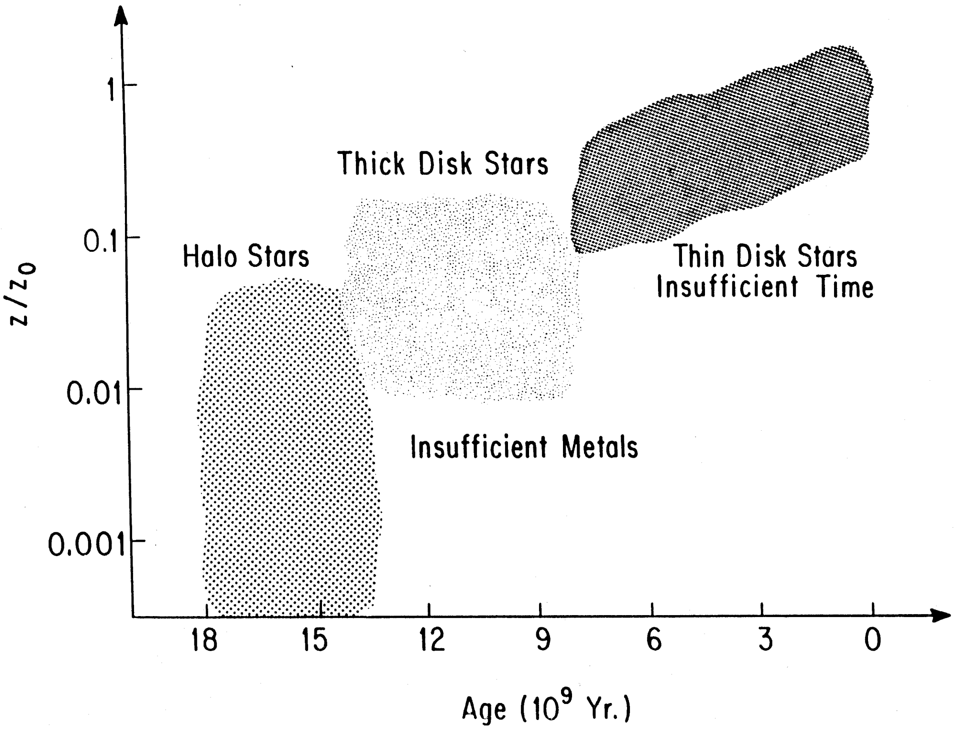

Figure 5. The range of ages and metallicities found among stars of three populations that pass through the solar neighborhood. The heavy element abundances are given as a fraction of the solar amount (1.7% heavy elements or metals). Most halo and thick disk stars are probably too deficient in heavy elements to have formed terrestrial planets, while most of the thin-disk stars are younger than the Sun, so that life has probably not had time to develop on their planets.

we look at the very oldest stars in the halo of our Galaxy do we find the expected trend of composition with age that can be explained by just about any model.

As a result of this curse of the adjustable parameter and the residual puzzles, the image of galactic chemical evolution presented in Figures 4, 5, and 6 is based partly on observations and partly on expectation, rather than on any very firm theoretical footing. I think, however, that the pictures are roughly right. In the solar neighborhood (Figures 4, 5) there are rather few stars that are both rich enough in heavy elements to have formed terrestrial planets and old enough for life to have had time to develop on them. Such stars do exist, but, apart from a few freaks like the members of NGC 6791, they are to be found much closer to the Galactic center than we are (Figures 4, 6).

The round-trip travel time between us and the Galactic Center, 8500 parsecs away, is about 50 000 years for light and considerably longer for anything of non-zero rest mass. The problems of searching for extraterrestrial life and of establishing communication thus become very long term ones indeed. I have, of course, completely neglected the point that 'inhabited' may be a very different and

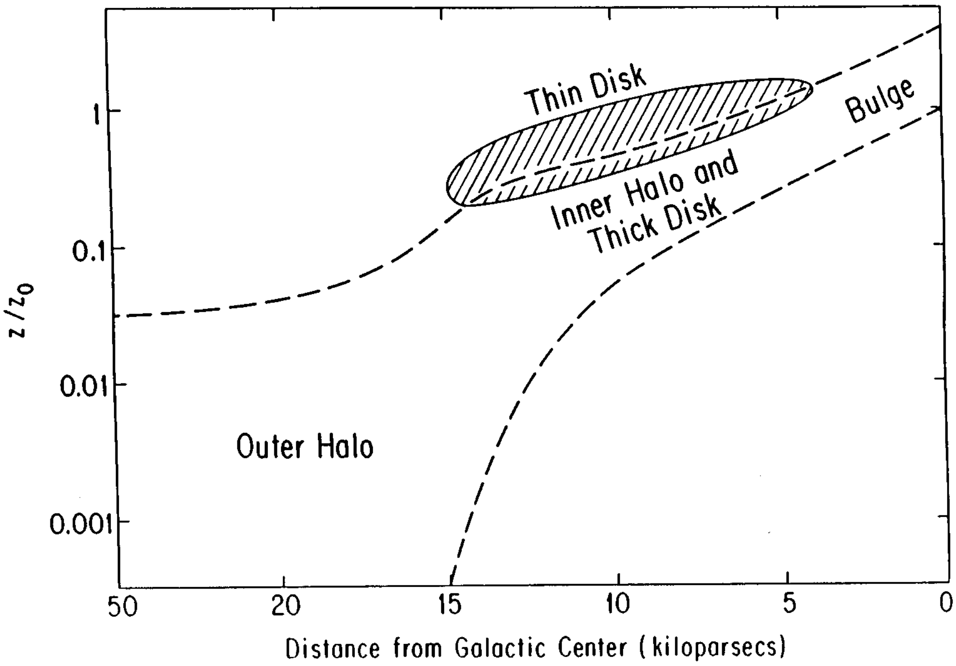

Figure 6. Heavy element abundances in the main stellar population, in units of the solar metallicity (1.7% metals for $Z/Z_o = 1$). Stars considerably older than the Sun occur in all three of the spheroidal components, inner and outer halo and nuclear bulge. Many bulge stars are also quite metal rich, and they are the ones perhaps most likely to have habitable planets orbiting them.

less likely circumstance from 'habitable'. It is widely rumored that astronomers, physicists, and chemists are the optimists about origin of life (presumably because we do not understand the difficulties), while biologists are the pessimists. In fact, a wide divergence of opinion exists even within the life sciences community, from life as we know it as a one-shot affair (Mayr, 1995) to life as a cosmic imperative (de Duve, 1995).

References

Alpher, R. A. and Hermann, R. L.: 1950, *Rev. Mod. Phys.* **22**, 153.
Alpher, R. A. and Hermann, R. L.: 1953, *Ann. Rev. Nuclear Science* **2**, 1.
Anders, E. and Grevasse, N.: 1989, *Geochim. Cosmochim. Acta* **53**, 197.
Arnett, W. D., Bahcall, J. N., Kirshner, R. P. and Woosley, S. E.: 1989, *Ann. Rev. Astron. Astrophys.* **27**, 629.
Atkinson, R. d'E.: 1931, *Astron. J.* **73**, 250.
Atkinson, R. d'E. and Houtermans, F. G.: 1929, *Z. Phys.* **54**, 656.
Bethe, H. A.: 1939, *Phys. Rev.* **55**, 434.
Bethe, H. A. and Critchfield, C. L.: 1938, *Phys. Rev.* **54**, 248.
Biermann, L.: 1956, *Z. Astrophys.* **41**, 46.
Buchmann, L. *et al.*: 1993, *Phys. Rev. Lett.* **70**, 726.
Burbidge, E. M., Burbidge, G. R., Fowler, W. A. and Hoyle, F.: 1957, *Rev. Mod. Phys.* **29**, 547 (B^2FH).

Cameron, A. G. W.: 1954, *Phys. Rev.* **93**, 932.
Cameron, A. G. W.: 1955, *Astrophys. J.* **121**, 144.
Cameron, A. G. W.: 1957, *Chalk River Report*, CRL–41.
Cameron, A. G. W.: 1968, in Ahrens, L.H. (ed.), *Origin and Distribution of the Elements*, Pergamon, Oxford, p. 125.
Cameron, A. G. W.: 1973, *Space Sci. Rev.* **15**, 121.
Copi, C. J. *et al.*: 1995, *Phys. Rev. Lett.* **75**, 3981.
de Duve, C.: 1995, *American Scientist* **83**, 423.
Gamow, G.: 1946, *Phys. Rev.* **70**, 372.
Greenstein, J. L.: 1954, in Ridenour, L. N. (ed.), *Modern Physics for the Engineer*, McGraw Hill, New York, p. 235.
Gurevich, L.E.: 1954, *Trudy 3. Soveshch. pr. Vopr. Kosmogenii* (Moscow), pp. 191–202.
Hata, N. *et al.*: 1995, *Phys. Rev. Lett.* **75**, 3977.
Hayashi, C.: 1950, *Prog. Theor. Phys.* **5**, 224.
Hoyle, F.: 1946, *Monthly Notices Roy. Astron. Soc.* **106**, 232.
Hoyle, F.: 1954, *Astrophys. J. Suppl.* **1**, 121.
Kaluzny, J. and Rucinski, S. M.: 1995, *Astron. Astrophys. Suppl.* **114**, 1.
Lambert, D.L.: 1992, *Astron. Astrophys. Reviews* **3**, 201.
Lambert, D. L. *et al.*: 1995, *Astrophys. J.* **450**, 302.
Lunine, J.: 1995, in Zuckerman, B. M. and Hart, M. (eds.), *Extraterrestrials: Where Are They?*, Cambridge Univ. Press, p. 192.
Mayr, E.: 1995, in Zuckerman, B. M. and Hart, M. (eds.), *Extraterrestrials: Where Are They?*, Cambridge Univ. Press, p. 152.
Merrill, P. W.: 1952, *Science* **115**, 484.
Öpik, E.: 1951, *Proc. Royal Irish Academy* **A54**, 49.
Payne, C. H.: 1925, *Stellar Atmospheres*, W. Heffer and Sons, Cambridge.
Rana, N. C.: 1991, *Ann. Rev. Astron. Astrophys.* **29**, 129.
Russell, H. N.: 1929, *Astrophys. J.* **70**, 11.
Salpeter, E. E.: 1952, *Astrophys. J.* **115**, 326.
Salpeter, E. E.: 1953, *Ann. Rev. Nuclear Science* **2**, 41.
Schmidt, M.: 1963, *Astrophys. J.* **137**, 758.
Suess, H. E. and Urey, H. C.: 1956, *Rev. Mod. Phys.* **28**, 53.
Timmes, F.X., Woosley, S.E. and Weaver, T.A.: 1995, *Astrophys. J. Suppl.* **98**, 617.
Tinsley, B. M.: 1968, *Astrophys. J.* **151**, 547.
Trimble, V.: 1975, *Rev. Mod. Phys.* **47**, 877.
Trimble, V.: 1991, *Astron. Astrophys. Rev.* **3**, 1.
Trimble, V.: 1996, in Holt, S. E. and Sonneborn, G. (eds.), *Cosmic Abundances*, Astron. Soc. Pacific Conf. Ser. vol. 99, p. 3.
van den Bergh, S.: 1962, *Astron. J.* **67**, 486.
Von Weizsäcker, C. G.: 1937, *Phys. Zeitschrift* **38**, 176.
Von Weizsäcker, C. G.: 1938, *Phys. Zeitschrift* **39**, 633.
Walter, D. K., Dufour, R. J. and Hester, J. J.: 1992, *Astrophys. J.* **397**, 196.
Woosley, S. E. *et al.*: 1994, *Astrophys. J.* **433**, 229.
Woosley, S.E.: 1996, in Holt, S. E. and Sonneborn, G. (eds.), *Cosmic Abundances*, Astron. Soc. Pacific Conf. Ser. Vol. 99.