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All the observed universe has contributed to life

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SUMMARY

This paper presents evidence that virtually all electrons and nuclei of the atoms that are or have been part of living matter on Earth came from almost all stars in our and nearby galaxies and even from all other galaxies in the Universe that have produced observed high-energy gamma rays. However, a standard 70 kg human is always making about 7 ^{3}He, 600 ^{40}Ca, and 3000 ^{14}N nuclei every second by radioactive decay of ^{3}H, ^{40}K, and ^{14}C, respectively.

1. INTRODUCTION

Scales of selected structures in the Universe that are useful for this paper appear in table 1. The table is intended to emphasize the paths connecting the Universe to humans and to the atoms of hydrogen (H), the simplest element.

At least 36 of the chemical elements are known to be necessary for the totality of terrestrial organisms; at least 27 of these are required for humans and 17 for the microorganism, *E. coli*. It is commonly accepted that, apart from H (the protyle of the ancients), the elements found in organisms were synthesized from H and helium (He) in the interiors of stars and then ejected by quiescent and explosive events, such as stellar winds, planetary nebulae, novae, and supernovae. After many episodes of turbulent mixing, these processes seeded, *inter alia*, the particular gas and dust cloud from which the Solar System collapsed about 5×10^9 years ago. This paper presents evidence and calculations which show that the Sun is not a 'second or third generation' star but that about 3×10^9 supernovae were necessary to form the Solar System and our human chemistry. Further, virtually every star in the Milky Way Galaxy existing at or before about 8×10^9 years ago has made some material contribution to Earth and us. In fact, even the Andromeda Galaxy (M31) and every other member of the Local Group of galaxies have provided some of the atomic nuclei and electrons now existing in the molecules in the body of a human being, each of which contains about 6×10^{27} atoms. In addition, high-energy gamma rays from all old and new stars and even from all galaxies observable from Earth have, by pair production and by transmutation in Earth's atmosphere, made matter presently in human beings. In each human there is about 1 H atom from every average milligram of all species of organisms that existed earlier than about 10^3 years ago. The very non-uniform distribution of the elements throughout Earth's crust, sea, and air make it likely that Life originated from matter at or near the interfaces of these terrestrial reservoirs. The elements phosphorous (P) and potassium (K) are cosmically in shortest supply and the quantities of them necessary to make a human can only have come from a minimum average galactic volume of about 2×10^7 that of Sun.

The history and evolution of the chemical elements comprising living systems continues to be of great interest (e.g. Cox 1989; Mason 1991). From nucleosynthetic theory (e.g. Burbidge & Burbidge 1958) and

Table 1. *Ages, etc. of selected structures in the Universe*

(The values and units of these relevant basic quantities are those used in the text or in subsequent tables.)

assumed age of the Universe	2×10^{10} years
age of Sun and the Solar System	5×10^9 years
age of terrestrial Life	4×10^9 years
age of *Homo*	5×10^6 years
mass of the observed Universe	10^{54} g
mass of the Milky Way Galaxy	2×10^{45} g
galactic stars	9×10^{44} g
galactic ISM	10^{44} g
galactic dark matter	10^{45} g
mass of Sun	1.99×10^{33} g
mass of Earth	5.98×10^{27} g
crust	1.5×10^{25} g
ocean	1.7×10^{24} g
atmosphere	5.1×10^{21} g
mass of human biomass	3×10^{14} g
mass of a standard lean human male	7.0×10^4 g
mass of a hydrogen atom	1.66×10^{-24} g
diameter of the observed Universe	10^{29} cm
diameter of Local Group of galaxies	3×10^{24} cm
diameter of Milky Way Galaxy	10^{23} cm
diameter of Sun	1.39×10^{11} cm
mean diameter of Earth	1.27×10^9 cm
mean density of observed Universe	2×10^{-31} g cm^{-3}
mean density of Milky Way Galaxy	10^{-23} g cm^{-3}
mean density of Sun	1.41 g cm^{-3}
mean density of Earth	5.52 g cm^{-3}
mean density of a standard lean human male	1.0 g cm^{-3}
number of atoms in a standard lean human male	6.3×10^{27}

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many observational analyses (e.g. Cameron 1970, 1982; Grevesse & Anders 1989; Penzias 1979) it is accepted that 29.3% of the mass of the primordial H has been transmuted into heavier elements. Most of this transmutation was into He (present mass fraction about $Y = 27.4\%$) and occurred within the first 3 min after the Big Bang. Since that epoch, later transmutations formed the nuclei of all other elements from lithium (Li) to uranium (U). The present mass fraction of this ensemble is about $Z = 1.9\%$. Thus, the present mass fraction (X) of H is about 70.7%.

The history of our H atoms themselves has been very complicated, because at different times some of them have resided serially in many different stars. About half (Weaver *et al.* 1978; Woosley & Weaver 1982) of all H in a large-mass star survives the subsequent supernova explosion to be incorporated eventually into many other stars yet to be born. In addition, there are many other stellar mass-loss episodes (Boothroyd & Sackmann 1988; Stenholm 1987; Tout & Eggleton 1988) in single red giants and mildly interacting close binaries. In all of these stars much more than half of their ejecta survives as H and subsequently becomes well-mixed in the interstellar medium (ISM). For the large number of cataclysmic variables in the Galaxy, processing of H into the carbon–nitrogen–oxygen (CNO) species occurring in the nova events is very efficient (Kato & Hachisu 1988; Sparks *et al.* 1978) so that nova ejecta are greatly depleted in H. However, the amount of mass ejected by a nova is negligible compared to that lost in the three other types of stellar events.

At present, about 95% of the H known in the Milky Way exists in stars (Bloemen *et al.* 1986; Solomon & Rivolo 1987). Because the Initial Mass Function favours low-mass star formation (Yoshii & Saio 1985), much of the mass will remain in low-mass stars for a very long time albeit partially transmuted to He, etc. However, at some times in their lives all stars have significant stellar 'winds' (Boothroyd & Sackmann 1988; Stenholm 1987; Tout & Eggleton 1988) which blow some of their least-processed, H-rich layers into space. For example, Sun emits about 10^{20} grams per year – i.e. about 10^{44} protons per year – into the Solar System (Allen 1973). As may be calculated from table 1, this number, 10^{44}, is the number of H atoms in about 10^{16} humans, more than 10^{6} greater than the present population of Earth.

If it is accepted that the Big Bang occurred 20×10^{9} years ago and formation of the Solar System occurred 5×10^{9} years ago (Borrow & Silk 1980), then about 98% of the H remaining 15×10^{9} years after the Big Bang formation of He had not yet been synthesized into other elements. However, most of this H had already been part of at least one star. Because of the statistics of such quasi-random events, it is clear that some of the presently non-stellar H atoms had already been incorporated into large numbers – even millions – of stars. It is known that there is only a small galactocentric iron-to-hydrogen [Fe/H] gradient (Lambert 1989), and it is generally believed that stars of comparable cosmic ages and masses had similar initial chemical compositions. This has occurred, in part, by mixing of the ejecta from all the mass-loss events described above and, in part, by means of galactic shear via the non-rigid-body, short-period (2×10^{8} years) rotation of the Galaxy (Allen 1973). As a consequence of all these processes, it follows that all galactic stars existing earlier than about 8×10^{9} years ago have actually contributed to the mass of every human.

Ejection velocities (about 2500 km s^{-1}) (Chuvenkov & Vainer 1989) from supernovae exceed escape velocity (250 to 700 km s^{-1}) anywhere from the visible rim to the centre of the Galaxy (Allen 1973). On the basis of depletion of deuterium in the intergalactic medium (IGM), it has been calculated that exchange between the Milky Way Galaxy and the IGM occurs at a rate of 3% of the galactic mass per 10^{9} years (Chuvenkov & Vainer 1989). For the galactic masses and the distance and timescales within the Local Group of galaxies (Allen 1973), it is possible that as much as 10% of the H in every average 70 kg human could be nuclei previously ejected from M31 (the Andromeda Galaxy) and a smaller percentage could have come from all other members of the Local Group of galaxies.

For the Virgo and more distant galaxy clusters, velocities of ejecta after escape are too small and distances too great for matter yet to have mixed into the Milky Way. However, gamma photons have been observed from the quasar horizon of the Universe (Ramaty & Lingenfelter 1986). These highly energetic photons, created originally from nuclear matter in quasars, themselves created matter and anti-matter in Earth's atmosphere. The anti-matter then annihilated and some of the matter (mainly electrons and protons) must have been incorporated into humans. Clearly and remarkably because of the ubiquity of energetic gamma rays, at least parts of atoms have actually been contributed to the totality of the biomass on Earth from all parts of the observable Universe.

After the formation of the Solar System and the appearance of Life on Earth, the history of our H atoms became even more complicated because they became repeatedly incorporated into many individual molecules, such as water, glucose, etc. Most of the approximately 6×10^{27} atoms in a 70 kg lean human are hydrogen combined with oxygen as water. With a mixing time of about 10^{3} years for virtually all of the hydrosphere (Broecker 1963; Stuiver *et al.* 1983), each human contains about 1 H atom from every average milligram from all species of organisms that existed over 10^{3} years ago. (This, of course, includes every dinosaur and most of our own ancestors.)

Particularly in partially closed environments, such as rooms, humans continually re-inhale part of the same H_2O and CO_2 which they all have recently exhaled and some atoms from these molecules once again become part of their structural proteins, etc. even in a few hours.

2. SUN IN THE COSMIC TIME SCALE

Sun has been described as a Nth ($N > 1$, but not much larger) generation Population I star (Wood & Chang 1985). The concept of 'generations' of stars is intertwined with that of stellar populations (Carney *et al.* 1989). This latter term was founded on kinematical and luminosity criteria which were then ramified into chemical ones. Thus, Pop. I stars are 'low' velocity, solar-chemistry, 'young' ones whereas Pop. II are 'high' velocity, much lower-than-solar Z, 'old' objects. The concept of stellar population continues to develop beyond its primitive description. For instance, much attention is now given to the 'original' stellar population of the Milky Way Galaxy, the presumed Pop. III of nearly pure H-plus-He stars (Carney *et al.* 1989; Iben 1983). An approximation to this early chemistry is represented by the very old, low-mass star CoD-38°245 for which $Z = 5 \times 10^{-4}$ (Bessell 1983), a factor of 0.026 that of Sun. All of the many high-mass stars formed at the same time as CoD-38°245 must have exploded as supernovae, a process contributing to the subsequent formation of Pop. II stars. It is interesting to note the recent discovery of a proto-galaxy (Haynes & Giovanelli 1989) without detected stars.

Even as a Population endures, its composition must change because X continually decreases and Z increases. A recent study (Sarajedini & King 1989) shows persuasive evidence for the increase of Z over the interval -17×10^9 years to -10×10^9 years for the Milky Way globular clusters. Even though 'Population' terminology is of limited quantitative resolution, it continues to be convenient, but the term 'stellar generation' is not satisfactory. Consider low-mass stars (e.g. Sun) that have long (at least 10^{10} years) H-burning lifetimes. In fact, low-mass stars are not 'generated' mainly from older low-mass stars, even though they do contain some ejecta from the stellar winds or flares of most of the older stars. Virtually all the matter originally in these stars is composed of (Cox 1989; Mason 1991) H and He, and (Burbidge & Burbidge 1958) that part of the primordial H and He previously synthesized into heavier elements by and ejected from higher-mass stars. The heavy-element content of stars, such as Sun, was condensed largely from the ejecta of about 10^9 short-lived (e.g. 10^6 years), high-mass stars. From detailed analyses of the elements in the cosmic radiation, there is evidence for substantial enhancement of r(rapid)-process elements synthesized in supernovae and red giants (Binns *et al.* 1989; Mewaldt 1989). This very large number of 10^9 stars is derived directly from the value of Z, which was 1.9% for the epoch (about -5×10^9 years) of formation of the Solar System and the total mass (3×10^{11} $M_{\odot}$, where $M_{\odot}$ is the equivalent of the mass of Sun) of galactic stars. However, this does not mean that from -10×10^9 years to -5×10^9 years there had been 5000 serial stellar 'generations', as the term is used biologically.

3. THE CONCEPTS OF STELLAR AND BIOLOGICAL GENERATIONS

The cores of high-mass stars have extreme temperatures and pressures which cause nucleosynthesis. This nucleosynthesis leads to the formation of higher-mass nuclides: in effect, an evolution of H into the more complex nuclei of the higher-mass elements. The continuation of this process through nuclear burning of more massive nuclides develops the ageing process that astronomers call stellar evolution. These large-mass stars live brief lives and, when they become supernovae, form the shock waves which can help form new stars partly from a local density enhancement and partly from seed material which these exploding stars themselves contribute (Shu *et al.* 1987). The new stars therefore possess a newer, richer nuclear chemistry than their progenitors, and this altered chemistry causes young, high-mass stars to generate energy at a different rate as a result of reactions catalyzed by the C, N, and O made by these progenitors (Cox 1989; Mason 1991). New mechanisms of nuclear burning therefore appear after the first ($Z = 0$) stars have lived; thus, true evolution has occurred in both stellar composition, structure, and reactions. As time has progressed, existing stars have incorporated material from increasing numbers of stellar progenitors rather than only from the original H clouds. Another consequence has been the secular lowering of temperature. The early, large, $Z = 0$ stars could form only from hot gas clouds wherein the Jeans mass (Jeans 1902; Lang 1980) for initiating gravitational collapse is larger than in the cool clouds existing at later time, which could initially form only small stars.

Despite these changes, there has been only a small increase of 'information' content from earlier to later stars. It is true that more than 2500 nuclides of the more than 100 elements have been synthesized but most of these are in such low abundances that they hardly contribute to further stellar evolution. A star as a natural site for nuclear fusion, however, is very nearly a unique structure despite the numerous conventional codings for photospheric temperature, pressure, and composition (Allen 1973). Even accounting for collapsed objects leads to the recognition of only three other generically different structures (white dwarfs, neutron stars, black holes).

Biological generation is generally characterized by transmission of unique genetic information from parents to offspring (and from mitochondrion to mitochondrion, etc.). This lineage is unbroken back to the origin of present Life. In the case of an adult multicellular organism, only a trifling fraction of the mass is actually derived from the parent(s). This is akin to the situation in stars. An important difference does occur in that, for the biological case, the original fertilized cell came entirely from the parents whereas for recent stars there were more than 10^9 stellar progenitors. Thus, stellar and biological generations and evolution are similar but not identical. The most conspicuous difference is the very large amount of information transmitted genetically by organisms which, following interaction with the environment, determines form and function in the next generation. Stars themselves are significantly affected by their environments, both during formation and as they age, but they do not generate and propagate the diversity and quantity of information that organisms create and transmit.

Table 2. *The stable elements by cosmic abundance*

(Stability is defined by a half-life greater than 10^9 years and the abundances are normalized to each set of 10^6 Si atoms. The sum of the individual cosmic abundances multiplied by the appropriate atomic masses is 3.978×10^{10} daltons per 10^6 Si atoms. With conventional astronomical nomenclature, $X = \mathrm{H} = 70.7\,\%$, $Y = \mathrm{He} = 27.4\,\%$, $Z = (\mathrm{Li}-\mathrm{U}) = 1.9\,\%$. The ranking (rank(mass)) by mass percentage is not identical to the ranking (rank(number)) by numerical cosmic abundance.)

rank (number)	name	symbol	date of discovery	atomic number	atomic mass	abundance in cosmic material	cosmic abundance × atomic mass	percentage by mass	rank (mass)
1	hydrogen	H	1766	1	1.00794	$\underline{2.79\times10^{10}}$	28.12×10^{9}	70.7	1
2	helium	He	1895	2	4.00260	$\underline{2.72\times10^{9}}$	10.89×10^{9}	27.4	2
3	oxygen	O	1774	8	15.9994	2.38×10^{7}	3.81×10^{8}	9.58×10^{-1}	3
4	carbon	C	Old	6	12.011	$\underline{1.01\times10^{7}}$	1.21×10^{8}	3.04×10^{-1}	4
5	neon	Ne	1898	10	20.179	3.44×10^{6}	6.94×10^{7}	1.74×10^{-1}	5
6	nitrogen	N	1772	7	14.0067	3.13×10^{6}	4.38×10^{7}	1.10×10^{-1}	7
7	magnesium	Mg	1775	12	24.305	1.07×10^{6}	2.61×10^{7}	6.56×10^{-2}	9
8	silicon	Si	1823	14	28.0855	$\underline{1.00\times10^{6}}$	2.81×10^{7}	7.06×10^{-2}	8
9	iron	Fe	Old	26	55.847	9.00×10^{5}	5.03×10^{7}	1.26×10^{-1}	6
10	sulphur	S	Old	16	32.06	5.15×10^{5}	1.65×10^{7}	4.14×10^{-2}	10
11	argon	Ar	1894	18	39.948	$\underline{1.01\times10^{5}}$	4.03×10^{6}	1.01×10^{-2}	11
12	aluminium	Al	1827	13	26.98154	8.49×10^{4}	2.29×10^{6}	5.76×10^{-3}	14
13	calcium	Ca	1808	20	40.08	6.11×10^{4}	2.45×10^{6}	6.16×10^{-3}	13
14	sodium	Na	1807	11	22.98977	5.74×10^{4}	1.32×10^{6}	3.32×10^{-3}	15
15	nickel	Ni	1751	28	58.69	4.93×10^{4}	2.89×10^{6}	7.26×10^{-3}	12
16	chromium	Cr	1797	24	51.996	1.35×10^{4}	7.02×10^{5}	1.76×10^{-3}	16
17	phosphorus	P	1669	15	30.97376	$\underline{1.04\times10^{4}}$	3.22×10^{5}	8.09×10^{-4}	18
18	manganese	Mn	1774	25	54.9380	9.55×10^{3}	5.25×10^{5}	1.32×10^{-3}	17
19	chlorine	Cl	1774	17	35.453	5.24×10^{3}	1.86×10^{5}	4.68×10^{-4}	19
20	potassium	K	1807	19	39.0983	3.77×10^{3}	1.47×10^{5}	3.70×10^{-4}	20
21	titanium	Ti	1791	22	47.88	2.40×10^{3}	1.15×10^{5}	2.89×10^{-4}	22
22	cobalt	Co	1735	27	58.9332	2.25×10^{3}	1.33×10^{5}	3.34×10^{-4}	21
23	zinc	Zn	1746	30	65.38	$\underline{1.26\times10^{3}}$	8.24×10^{4}	2.07×10^{-4}	23
24	fluorine	F	1771	9	18.998403	8.43×10^{2}	1.60×10^{4}	4.02×10^{-5}	25
25	copper	Cu	Old	29	63.546	5.22×10^{2}	3.32×10^{4}	8.35×10^{-5}	24
26	vanadium	V	1830	23	50.9415	2.93×10^{2}	1.49×10^{4}	3.75×10^{-5}	26
27	germanium	Ge	1886	32	72.59	$\underline{1.19\times10^{2}}$	8.64×10^{3}	2.17×10^{-5}	27
28	selenium	Se	1817	34	78.96	6.21×10^{1}	4.90×10^{3}	1.23×10^{-5}	28
29	lithium	Li	1817	3	6.941	5.71×10^{1}	3.96×10^{2}	9.95×10^{-7}	43
30	krypton	Kr	1898	36	83.80	4.5×10^{1}	3.77×10^{3}	9.48×10^{-6}	29
31	gallium	Ga	1875	31	69.72	3.78×10^{1}	2.64×10^{3}	6.64×10^{-6}	30
32	scandium	Sc	1879	21	44.9559	3.42×10^{1}	1.54×10^{3}	3.87×10^{-6}	32
33	strontium	Sr	1790	38	87.62	2.35×10^{1}	2.06×10^{3}	5.18×10^{-6}	31
34	boron	B	1808	5	10.81	2.12×10^{1}	2.29×10^{3}	5.76×10^{-7}	46
35	bromine	Br	1826	35	79.904	1.18×10^{1}	9.43×10^{2}	2.37×10^{-6}	34
36	zirconium	Zr	1789	40	91.22	$\underline{1.14\times10^{1}}$	1.04×10^{3}	2.61×10^{-6}	33
37	rubidium	Rb	1861	37	85.4678	7.09×10^{0}	6.06×10^{2}	1.52×10^{-6}	39
38	arsenic	As	Old	33	74.9216	6.56×10^{0}	4.91×10^{2}	1.23×10^{-6}	40
39	tellurium	Te	1782	52	127.60	4.81×10^{0}	6.14×10^{2}	1.54×10^{-6}	38
40	xenon	Xe	1898	54	131.29	4.7×10^{0}	6.17×10^{2}	1.55×10^{-6}	36=
41	yttrium	Y	1794	39	88.9059	4.64×10^{0}	4.12×10^{2}	1.04×10^{-6}	42
42	barium	Ba	1808	56	137.33	4.49×10^{0}	6.17×10^{2}	1.55×10^{-6}	36=
43	tin	Sn	Old	50	118.69	3.82×10^{0}	4.53×10^{2}	1.14×10^{-6}	41
44	lead	Pb	Old	82	207.2	3.15×10^{0}	6.53×10^{2}	1.64×10^{-6}	35
45	molybdenum	Mo	1778	42	95.94	2.55×10^{0}	2.45×10^{2}	6.16×10^{-7}	45
46	ruthenium	Ru	1844	44	101.07	1.86×10^{0}	1.88×10^{2}	4.73×10^{-7}	47
47	cadmium	Cd	1817	48	112.41	1.61×10^{0}	1.81×10^{2}	4.55×10^{-7}	48
48	palladium	Pd	1803	46	106.42	1.39×10^{0}	1.48×10^{2}	3.72×10^{-7}	50
49	platinum	Pt	1735	78	195.08	1.34×10^{0}	2.61×10^{2}	6.56×10^{-7}	44
50	cerium	Ce	1803	58	140.12	$\underline{1.14\times10^{0}}$	1.59×10^{2}	4.00×10^{-7}	49
51	iodine	I	1811	53	126.9045	9.0×10^{-1}	1.14×10^{2}	2.87×10^{-7}	54
52	neodymium	Nd	1885	60	144.24	8.28×10^{-1}	1.19×10^{2}	2.99×10^{-7}	53
53	beryllium	Be	1798	4	9.01218	7.3×10^{-1}	6.58×10^{0}	1.65×10^{-8}	79
54	niobium	Nb	1801	41	92.9064	6.98×10^{-1}	6.48×10^{1}	1.63×10^{-7}	56
55	osmium	Os	1803	76	190.2	6.75×10^{-1}	1.28×10^{2}	3.22×10^{-7}	51
56	iridium	Ir	1803	77	192.22	6.61×10^{-1}	1.27×10^{2}	3.19×10^{-7}	52
57	silver	Ag	Old	47	107.8682	4.86×10^{-1}	5.24×10^{1}	1.32×10^{-7}	59
58	lanthanum	La	1839	57	138.9055	4.46×10^{-1}	6.20×10^{1}	1.56×10^{-7}	58
59	dysprosium	Dy	1886	66	162.50	3.94×10^{-1}	6.41×10^{1}	1.61×10^{-7}	57

Table 2 (*cont.*)

rank (number)	name	symbol	date of discovery	atomic number	atomic mass	abundance in cosmic material	cosmic abundance × atomic mass	percentage by mass	rank (mass)
60	caesium	Cs	1860	55	132.9054	3.72×10^{-1}	4.94×10^{1}	1.24×10^{-7}	61
61	rhodium	Rh	1803	45	102.9055	3.44×10^{-1}	3.54×10^{1}	8.90×10^{-8}	68
62	mercury	Hg	Old	80	200.59	3.4×10^{-1}	6.82×10^{1}	1.71×10^{-7}	55
63	gadolinium	Gd	1880	64	157.25	3.30×10^{-1}	5.19×10^{1}	1.30×10^{-7}	60
64	antimony	Sb	Old	51	121.75	3.09×10^{-1}	3.76×10^{1}	9.45×10^{-8}	65=
65	samarium	Sm	1879	62	150.36	2.58×10^{-1}	3.88×10^{1}	9.75×10^{-8}	64
66	erbium	Er	1843	68	167.26	2.51×10^{-1}	4.19×10^{1}	1.05×10^{-7}	63
67	ytterbium	Yb	1878	70	173.04	2.48×10^{-1}	4.29×10^{1}	1.08×10^{-7}	62
68	gold	Au	Old	79	196.9665	1.87×10^{-1}	3.68×10^{1}	9.25×10^{-8}	67
69=	indium	In	1863	49	114.82	1.84×10^{-1}	2.11×10^{1}	5.30×10^{-8}	73
69=	thallium	Tl	1861	81	204.383	1.84×10^{-1}	3.76×10^{1}	9.45×10^{-8}	65=
71	praseodymium	Pr	1879	59	140.9077	1.67×10^{-1}	2.35×10^{1}	5.91×10^{-8}	72
72	hafnium	Hf	1923	72	178.49	1.54×10^{-1}	2.75×10^{1}	6.91×10^{-8}	70
73	bismuth	Bi	1753	83	208.9804	1.44×10^{-1}	3.01×10^{1}	7.56×10^{-8}	69
74	tungsten	W	1781	74	183.85	$\underline{1.33 \times 10^{-1}}$	2.45×10^{1}	6.16×10^{-8}	71
75	europium	Eu	1896	63	151.96	9.73×10^{-2}	1.48×10^{1}	3.72×10^{-8}	74
76	holmium	Ho	1879	67	164.9304	8.89×10^{-2}	1.47×10^{1}	3.70×10^{-8}	75
77	terbium	Tb	1843	65	158.9254	6.03×10^{-2}	9.58×10^{0}	2.41×10^{-8}	77
78	rhenium	Re	1925	75	186.207	5.17×10^{-2}	9.62×10^{0}	2.42×10^{-8}	76
79	thulium	Tm	1879	69	168.9342	3.78×10^{-2}	6.39×10^{0}	1.61×10^{-8}	80=
80	lutetium	Lu	1907	71	174.967	3.67×10^{-2}	6.42×10^{0}	1.61×10^{-8}	80=
81	thorium	Th	1828	90	232.0381	3.35×10^{-2}	7.77×10^{0}	1.95×10^{-8}	78
82	tantalum	Ta	1802	73	180.9479	$\underline{2.07 \times 10^{-2}}$	3.75×10^{0}	9.43×10^{-9}	82
83	uranium	U	1789	92	238.0289	9.0×10^{-3}	2.14×10^{0}	5.38×10^{-9}	83

4. THE DEVELOPMENT OF KNOWLEDGE CONCERNING THE CHEMICAL ELEMENTS

Many people (e.g. Brock 1985) have summarized thinking and experiments concerning the intrinsic nature of matter from Hellenic times into the 17th century. Natural philosophers considered that the four alchemical elements – earth, air, fire and water – were derived from a more fundamental substance, protyle (Brock 1985). By the end of the 18th century, many real chemical elements had already been discovered and investigated quantitatively. Dalton (1808–1810) produced compelling evidence for the existence of atomic elements but rejected the concept of protyle as it had originally been put forward by Empedocles and Democritus (Brock 1985). Prout (1815, 1816) was the first to suggest that protyle, the building block of all the elements composing matter, is actually H. This conclusion was based on the belief that the atomic masses of all known elements are integral multiples of that of H. However, by 1833, Turner (1833) showed that at least barium (Ba), chlorine (Cl), and lead (Pb) did not conform to this rule and many other exceptions soon were discovered. The confused history leading to rejection of Prout's Hypothesis is summarized in Benfey (1952).

The discoveries of the electron, proton, neutron, isotopes, and radioactive transmutation of elements cover the interval from about 1896 to 1932. The almost exactly integral atomic masses of all the isotopes of the chemical elements follow from their equal numbers of protons and electrons and dissimilar numbers of neutrons. Deviations from exactly integral isotopic atomic masses are due to the very small mass difference between the proton and neutron and mass defects due to net nuclear binding energies. In an unexpected manner and at least for chemists, Prout's Hypothesis has actually been validated: all elements have been and continue to be synthesized by processes starting with H, identifiable as the protyle of the ancients.

5. THE CHEMICAL ELEMENTS

Quite recently there has been a very large increase of knowledge regarding the cosmic abundances of the chemical elements. The content of table 2, (adapted from Cameron 1982; Grevesse & Anders 1989), presents a rank ordering by abundance of the elements. This information derives largely from Sun and meteorites and therefore refers to an epoch of about -5×10^{9} years. Because the abundances by mass involve multiplication by atomic masses, abundance rankings by mass and number are not identical.

6. THE CHEMICAL COMPOSITIONS OF THE UNIVERSE, SUN, EARTH, AND BIOMASS

To assess the sources and limitations of supply of the common and trace elements found in the biomass, their availabilities in cosmic and assorted terrestrial pools were calculated. Table 3 gives the cosmic rank ordering by mass for the stable elements as well as the orderings of these elements for the terrestrial crust, sea water, and atmosphere (Demayo 1991 *a*, *b*). It is well known that virtually all elements heavier than He with even atomic numbers are more abundant in the universe than adjacent odd-numbered ones. Table 3 gives 36 elements known (Gottschalk 1986; Guillemin & Larson 1922; Hunter 1972; Ingraham *et al.* 1983; Miller 1974; Neidhardt 1987; Underwood 1981;

Table 3. *The stable elements in rank order of percentage by mass*

(Rankings appear for the cosmic abundance and each of the three major subdivisions of Earth and for two organisms. For the real atmosphere, ranking for hydrogen (H) depends upon relative humidity. For instance, at a temperature of 20 °C and for relative humidities of 50 % and 100 %, the mass percentages of H are 7.8×10^{-2} and 1.6×10^{-1}, respectively. For these cases, H would rank fourth. The 'hash' mark (#) signifies elements with a known role in some form of life on Earth. The asterisks (*) signify elements with no known role for human life as of 1991. For *E. coli* the last 5 elements are ranked by atomic number because their individual percentages by mass are not known.)

rank	symbol	cosmic	rank crust (no water, no air)			rank ocean (no gases)			rank atmosphere (1 bar, dry)			rank human (lean)			rank *E. coli*		
1	H#	70.7	1	O	46.6	1	O	85.99	1	N	73.52	1	O	64	1	O	68
2	He	27.4	2	Si	27.7	2	H	10.75	2	O	23.19	2	C	19	2	C	15
3	O#	9.58×10^{-1}	3	Al	8.13	3	Cl	1.898	3	Ar	1.28	3	H	9	3	H	10.2
4	C#	3.04×10^{-1}	4	Fe	5.00	4	Na	1.0561	4	C	1.24×10^{-2}	4	N	5	4	N	4.2
5	Ne	1.74×10^{-1}	5	Ca	3.63	5	Mg	1.272×10^{-1}	5	Ne	1.24×10^{-3}	5	Ca	1.5	5	P	0.83
6	Fe#	1.26×10^{-1}	6	Na	2.83	6	S	8.8×10^{-2}	6	Kr	2.9×10^{-4}	6	P	8×10^{-1}	6	K	0.45
7	N#	1.10×10^{-1}	7	K	2.59	7	Ca	4.0×10^{-2}	7	He	7.3×10^{-5}	7	S	6×10^{-1}	7	Na	0.40
8	Si#	7.06×10^{-2}	8	Mg	2.09	8	K	3.8×10^{-2}	8	Xe	3.6×10^{-5}	8	K	3×10^{-1}	8	S	0.30
9	Mg#	6.56×10^{-2}	9	Ti	4.4×10^{-1}	9	Br	6.5×10^{-3}	9	H	3.5×10^{-6}	9=	Na	1.5×10^{-1}	9	Ca	0.25
10	S#	4.14×10^{-2}	10	H	1.4×10^{-1}	10	C	3.0×10^{-3}	10	Rn	4.5×10^{-17}	9=	Cl	1.5×10^{-1}	10	Cl	0.12
11	Ar	1.01×10^{-2}	11	P	1.18×10^{-1}	11	Sr	1.3×10^{-3}				11	Mg	4.5×10^{-2}	11	Mg	0.097
12	Ni#	7.26×10^{-3}	12	Mn	1.0×10^{-1}	12	Si	$7\text{–}0.05\times10^{-4}$				12	Fe	8×10^{-3}	12	Fe	0.05
13	Ca#	6.16×10^{-3}	13	S	5.2×10^{-2}	13	B	4.6×10^{-4}				13=	Zn	3×10^{-3}	13	Mn	0.09
14	Al#	5.76×10^{-3}	14	C	3.2×10^{-2}	14	Al	$1.9\text{–}0.16\times10^{-4}$				13=	Cu	3×10^{-3}	14	Co	
15	Na#	3.32×10^{-3}	15	Cl	3.14×10^{-2}	15	F	1.4×10^{-4}				15	Rb	1×10^{-3}	15	Zn	
16	Cr#	1.76×10^{-3}	16	Rb	3.1×10^{-2}	16	N	$7\text{–}0.1\times10^{-5}$				16	Si	5×10^{-4}	16	Cu	
17	Mn#	1.32×10^{-3}	17=	F	3.0×10^{-2}	17	Rb	2×10^{-5}				17=	Br*	3×10^{-4}	17	Mo	
18	P#	8.09×10^{-4}	17=	Sr	3.0×10^{-2}	18	Li	1×10^{-5}				17=	Zr*	3×10^{-4}			
19	Cl#	4.68×10^{-4}	19	Ba	2.5×10^{-2}	19=	P	5×10^{-6}				19=	Mo	1×10^{-4}			
20	K#	3.70×10^{-4}	20	Zr	2.2×10^{-2}	19=	Ba	5×10^{-6}				19=	Ge*	1×10^{-4}			
21	Co#	3.34×10^{-4}	21	Cr	2.0×10^{-2}	19=	I	5×10^{-6}				19=	Pb*	1×10^{-4}			
22	Ti#	2.89×10^{-4}	22	V	1.5×10^{-2}	22=	As	2×10^{-6}				19=	Hg*	1×10^{-4}			
23	Zn#	2.07×10^{-4}	23	Zn	1.32×10^{-2}	22=	Fe	2×10^{-6}				23=	Ni	5×10^{-5}			
24	Cu#	8.35×10^{-5}	24	Ni	8.0×10^{-3}	24	Zn	1×10^{-6}				23=	Al*	5×10^{-5}			
25	F#	4.02×10^{-5}	25	Cu	7.0×10^{-3}	25=	Cu	5×10^{-7}				25=	Cd*	4×10^{-5}			
26	V#	3.75×10^{-5}	26	W	6.9×10^{-3}	25=	Mn	5×10^{-7}				25=	F	4×10^{-5}			
27	Ge	2.17×10^{-5}	27	Li	6.5×10^{-3}	27=	Pb	4×10^{-7}				25=	Ti*	4×10^{-5}			
28	Se#	1.23×10^{-5}	28=	N	4.6×10^{-3}	27=	Se	4×10^{-7}				28	Sn	3×10^{-5}			
29	Kr	9.48×10^{-6}	28=	Ce	4.6×10^{-3}	29	Sn	3×10^{-7}				29	Se	2×10^{-5}			
30	Ga#	6.64×10^{-6}	30	Sn	4.0×10^{-3}	30=	Cs	2×10^{-7}				30=	I	1×10^{-5}			
31	Sr	5.18×10^{-6}	31	Y	2.8×10^{-3}	30=	Mo	$2\text{–}0.3\times10^{-7}$				30=	V	1×10^{-5}			
32	Sc	3.87×10^{-6}	32=	Nb	2.4×10^{-3}	32	U	$\mathrm{I}\times10^{-7}$				30=	Mn	1×10^{-5}			
33	Zr	2.61×10^{-6}	32=	Nd	2.4×10^{-3}	33=	Ga	5×10^{-8}				30=	B*	1×10^{-5}			
34	Br#	2.37×10^{-6}	34	Co	2.3×10^{-3}	33=	Ni	$5\text{–}1\times10^{-8}$				30=	Sr*	1×10^{-5}			
35	Pb	1.64×10^{-6}	35	La	1.8×10^{-3}	33=	Th	5×10^{-8}				35	Cr	9×10^{-6}			
36=	Xe	1.55×10^{-6}	36	Pb	1.6×10^{-3}	36	Ce	4×10^{-8}				36	As	5×10^{-6}			
36=	Ba#	1.55×10^{-6}	37=	Ga	1.5×10^{-3}	37=	V	3×10^{-8}				37=	Co	1×10^{-6}			
38	Te	1.54×10^{-6}	37=	Mo	1.5×10^{-3}	37=	La	3×10^{-8}				37=	Ba*	1×10^{-6}			
39	Rb#	1.52×10^{-6}	39	Th	1.2×10^{-3}	37=	Y	3×10^{-8}									

Table 3 (*cont.*)

rank	symbol	cosmic	rank crust (no water, no air)			rank ocean (no gases)			rank atmosphere (1 bar, dry)	rank human (lean)	rank *E. coli*
40	As#	1.23×10^{-6}	40=	Ge	7×10^{-4}	37=	Ag	3×10^{-8}			
41	Sn#	1.14×10^{-6}	40=	Cs	7×10^{-4}	41	Bi	2×10^{-8}			
42	Y	1.04×10^{-6}	42	Sm	6.5×10^{-4}	42	Co	1×10^{-8}			
43	Li	9.95×10^{-7}	43	Gd	6.4×10^{-4}	43	Sc	4×10^{-9}			
44	Pt	6.56×10^{-7}	44	Be	6×10^{-4}	44	Hg	3×10^{-9}			
45	Mo#	6.16×10^{-7}	45	Pr	5.5×10^{-4}	45	Au	5×10^{-10}			
46	B#	5.76×10^{-7}	46=	Sc	5×10^{-4}	46	Ra	1×10^{-11}			
47	Ru	4.73×10^{-7}	46=	As	5×10^{-4}	47=	Ti	present in very tiny amounts			
48	Cd	4.55×10^{-7}	48=	Dy	4.5×10^{-4}	47=	Cr				
49	Ce	4.00×10^{-7}	48=	Hf	4.5×10^{-4}	47=	Ge				
50	Pd	3.72×10^{-7}	50	U	4×10^{-4}	47=	Zr				
51	Os	3.22×10^{-7}	51	B	3×10^{-4}	47=	Cd				
52	Ir	3.19×10^{-7}	52	Yb	2.7×10^{-4}	47=	Sb				
53	Nd	2.99×10^{-7}	53	Er	2.5×10^{-4}	47=	W				
54	I#	2.87×10^{-7}	54	Ta	2.1×10^{-4}	47=	Pt				
55	Hg	1.71×10^{-7}	55	Br	1.6×10^{-4}	47=	Tl				
56	Nb#	1.63×10^{-7}	56	Ho	1.2×10^{-4}						
57	Dy	1.61×10^{-7}	57	Eu	1.1×10^{-4}						
58	La	1.56×10^{-7}	58	Sb	1×10^{-4}						
59	Ag	1.32×10^{-7}	59	Tb	9×10^{-5}						
60	Gd	1.30×10^{-7}	60	Lu	8×10^{-5}						
61	Cs	1.24×10^{-7}	61	Tl	6×10^{-5}						
62	Yb	1.08×10^{-7}	62	Hg	5×10^{-5}						
63	Er	1.05×10^{-7}	63	I	3×10^{-5}						
64	Sm	9.75×10^{-8}	64=	Tm	2×10^{-5}						
65=	Sb	9.45×10^{-8}	64=	Bi	2×10^{-5}						
65=	Tl	9.45×10^{-8}	66	Cd	1.5×10^{-5}						
67	Au	9.25×10^{-8}	67=	Ag	1×10^{-5}						
68	Rh	8.90×10^{-8}	67=	In	1×10^{-5}						
69	Bi	7.56×10^{-8}	69	Se	9×10^{-6}						
70	Hf	6.91×10^{-8}	70	Ar	4×10^{-6}						
71	W#	6.16×10^{-8}	71	Pd	1×10^{-6}						
72	Pr	5.91×10^{-8}	72=	Pt	5×10^{-7}						
73	In	5.30×10^{-8}	72=	Au	5×10^{-7}						
74	Eu	3.72×10^{-8}	74	He	3×10^{-7}						
75	Ho	3.70×10^{-8}	75	Te	$2? \times 10^{-7}$						
76	Re	2.42×10^{-8}	76=	Ru	$1? \times 10^{-7}$						
77	Tb	2.41×10^{-8}	76=	Rh	1×10^{-7}						
78	Th	1.95×10^{-8}	76=	Re	1×10^{-7}						
79	Be	1.65×10^{-8}	76=	Os	$1? \times 10^{-7}$						
80=	Lu	1.61×10^{-8}	76=	Ir	1×10^{-7}						
80=	Tm	1.61×10^{-8}									
82	Ta#	9.43×10^{-9}									
83	U	5.38×10^{-9}									

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Wetherell & Robinson 1973; Williams 1981) to be important to some form of Life. Only 16 of these are even and 20 are odd. This distribution reflects unique chemical properties found in these odd-numbered elements (mainly the uni- and trivalent ones) compared with these even-numbered (mainly the di- and tetravalent) elements.

The measured biological abundances of these elements may be seen in table 3, which presents information for the human body and *E. coli*. In table 4 there are shown the ratios (by mass concentration) of the significant elements found in humans relative to their presence in the sources of table 3. For *E. coli* the ratios are quite comparable to those for humans. Note, however, that the calcium (Ca) content of *E. coli* is much lower than for humans because this prokaryote has no mineralized skeleton. Because every human (table 1) contains about 6×10^{27} atoms, it is expected that some atoms of every stable element (and most unstable ones) will actually be present in each person. For example, atoms of all the noble gases must be dissolved in body fluids of every human.

Additionally, each human contains atoms of ^{14}C and ^{3}H. These atoms are actually made by cosmic ray proton spallation from the N in Earth's atmosphere generating atmospheric neutrons. These neutrons then interact with more N to form both radioactive species. These radioactive atoms are about 1.2×10^{-12} ^{14}C and 3.8×10^{-18} ^{3}H of the stable species. Direct calculation shows that the average human must contain more than 10^{14} ^{14}C and 10^{9} ^{3}H atoms. The decays of these species then generate about 3000 ^{14}N and 7 ^{3}He atoms each second in the body. The very long-lived isotope, ^{40}K, although made in stars, still exists as 0.00118 % of total K in the human body. By its decay path it makes about 600 ^{40}Ca per second in the body. The amusing and

Table 4. *Human concentration factors*

(The ratios of percentages by mass are derived from the entries in table 2. Because the concentrations of Ge, Ti, Cr, Zr, and Cd are 'very tiny' in seawater, the ratios of their human-to-seawater percentages are recorded here as 'very large'. The asterisks (*) signify elements with no known role for human life as of 1991.)

rank	symbol	human/ cosmic abundance	rank	symbol	human/ earth's crust	rank	symbol	human/ seawater	rank	symbol	human/ atmosphere (dry)
1	P	1000	1	N	1000	1=	Zr*	very large ratios	1	H	2500000
2	K	800	2	C	600	1=	Ge*		2	C	1500
3	Rb	650	3	H	65	1=	Cd*		3	O	3
4	Hg*	600	4	S	10	1=	Ti*		4	N	0.065
5	Cl	300	5	P	7	1=	Cr				
6	Ca	250	6	Cl	5	6	P	150000			
7=	Br*	150	7	Cd*	2.5	7	N	70000			
7=	Mo	150	8=	Br*	2	8	Hg*	35000			
9=	Zr*	100	8=	Hg*	2	9	C	6500			
9=	Cd*	100	8=	Se	2	10	Cu	6000			
11=	O	65	11	O	1.5	11	Fe	4000			
11=	C	65	12	Cu	0.45	12	Zn	3000			
13	Pb*	60	13	Ca	0.4	13	Ni	1000			
14=	N	45	14	I	0.35	14	Mo	500			
14=	Na	45	15	Zn	0.25	15	V	350			
16=	Cu	35	16	Ge*	0.15	16	Pb*	250			
16=	I	35	17	K	0.1	17=	Sn	100			
18	Sn	25	18=	Mo	0.065	17=	Co	100			
19=	S	15	18=	Pb*	0.065	19=	Rb	50			
19=	Zn	15	20	Na	0.05	19=	Se	50			
19=	B*	15	21	B*	0.035	21	Ca	40			
22	Ge*	4.5	22	Rb	0.03	22	Mn	20			
23	As	4	23	Mg	0.02	23	K	8			
24	Sr*	2	24	Zr*	0.015	24	S	7			
25	Se	1.5	25	As	0.01	25	As	2.5			
26	F	1	26	Sn	0.0075	26	I	2			
27	Mg	0.7	27	Ni	0.0065	27	Si	1.5			
28	Ba*	0.65	28	Fe	0.006	28	H	0.85			
29	V	0.25	29	F	0.0015	29	O	0.75			
30	Ti*	0.15	30	V	0.00065	30	Br*	0.45			
31	H	0.13	31=	Cr	0.00045	31	Mg	0.35			
32	Fe	0.065	31=	Co	0.00045	32	F	0.3			
33	Al*	0.01	33	Mn	0.0004	33	Al*	0.25			
34	Mn	0.0075	34	Sr*	0.00035	34	Ba*	0.2			
35	Cr	0.005	35	Ti*	0.00009	35	Na	0.15			
36=	Si	0.007	36	Ba*	0.00004	36	Cl	0.08			
36=	Ni	0.007	37	Si	0.00002	37	B*	0.02			
38	Co	0.003	38	Al*	0.000006	38	Sr*	0.0075			

surprising net effects of these processes are that the body turns more than 10^{12} C atoms into N atoms during a 70-year lifetime, it exhales more He than it inhales, and, at constant mass, its output of Ca is greater than its intake of the atom.

The entries in table 4 for, e.g., P and K emphasize the impressive selectivity of human life with concentration factors of more than 800 compared with the cosmic values. On the other hand, most of the trace elements used in only tiny amounts are readily available cosmically and in Earth's crust and have not been evolutionary bottlenecks. However, it is also clear that the formation of Earth's crust and oceans led to selective concentrations and exclusions of many elements individually. For example, the trace element molybdenum (Mo) is quite rare in sea water and would have to be concentrated about 500 times if this were its only source for Life (Crick & Orgel 1973; Gualtieri 1977). This element is, in fact, readily available in Earth's crust and, in reality, the human body selects against it by about a factor of 15. For the biomass, the entries in table 4 show that the initial major source for O and H is water but for N it is the atmosphere. Of the elements required for Life, C, P, sulphur (S), and selenium (Se) all must be concentrated from their available sources. Some others – notably silicon (Si), aluminium (Al), Fe, titanium (Ti) – are in great abundance both cosmically and in Earth's crust yet in advanced forms in the biomass they are present only in very small quantities filling broad and major (Fe) or very minor and limited (Si, Al, Ti) roles. It is also remarkable that, for example, cadmium (Cd) and mercury (Hg) are concentrated by some organisms although the elements have no known functional activity. A number of organisms, in fact, have developed special mechanisms to detoxify these elements (Higham *et al.* 1984; Tsubaki & Irukayama 1977) for their own survival in otherwise lethal environments.

7. THE COSMIC SOURCES OF SOME ELEMENTS SELECTED BY ORGANISMS

As a result of experimental and theoretical astrophysics (cf. the first six references cited in § 1 above) the processes and sites for synthesizing nuclides are now well known (Aller 1989; Schramm 1982; Ulrich 1982).

The modes of nucleosynthesis for biologically important elements (derived from Grevesse & Anders 1989) are summarized in two different ways in tables 5 and 6. By any of a few well-known chains and cycles (Cox 1989; Mason 1991), He is generated from H sustaining a near-steady state in the stellar interior where gravitation is balanced radially by gas and radiation pressure. The process of consuming H in the stellar core and in overlying shells creates a transient red giant configuration. Eventually, He will become the major nuclear fuel for the further syntheses that produce most elements of light and intermediate mass.

The overabundance of C and O compared with N – the latter generated mainly in the CNO reactions (Cox 1989; Mason 1991) dominating in high-mass stars – is the reason why even-numbered elements are more abundant than adjacent odd-numbered ones. Up to neon (Ne) (Cox 1989; Mason 1991), heavier elements are synthesized by subsequent He burning. While consuming most of this He nuclear fuel, a star becomes, for the second time, a red giant of large radius and very low average density containing a high density, high temperature core where more diverse nuclear reactions now dominate the stellar evolution. These reactions include additional fusions, neutron captures onto existing nuclei, and radioactive decays (Aller 1989; Cox 1989; Mason 1991; Schramm 1982; Ulrich 1982). The eventual impossibility of further energy generation by fusion of Fe-peak nuclides, which are at the peak of the binding energy curve, causes the star to extract energy from its interior. This destabilizes the stellar interior. Gravitation now overwhelms gas and residual radiation pressure and causes a stellar implosion. When neutron density is attained (or surpassed if the collapse forms a black hole), the implosion is

Table 5. *Contributions from individual nucleosynthetic processes to the 38 elements found in measured amounts in humans (table 3)*

(The coding for the processes is taken from Grevesse & Anders (1989). The asterisk (*) identifies elements with no known biological role in humans as of 1991; the 'hash' mark (#) indicates an element for which more than one isotope is cosmically abundant (> 20 %).

process	element
BB = Big Bang	H
H = hydrogen burning	N
He = helium burning	O, C
C = carbon burning	Na#, Cl#, Cu#, Co#
N = hot or explosive hydrogen burning	Mg#, F
O = oxygen burning	S#, Si#
Ne = neon burning	P, Na#, Al*#
S = slow neutron-capture onto Fe-peak 'seeds'	Cl#, Rb#, Zr*, Ge*, Pb*#, Hg*, Cd*, Sn#, Sr*#, Ba*
R = rapid neutron-capture onto Fe-peak 'seeds'	Rb#, Br*, Mo, Pb*#, Cd*#, Sn#, Se, I, As
Ex = explosive burning in supernovae	Ca, P, S#, K, Na#, Cl#, Mg#, Fe#, Zn#, Cu#, Si#, Ni#, Al*#, Ti*, V, Mn#, Cr
E = nuclear statistical equilibrium	Fe#, Zn#, Ni#, Mn#, Co#
X = spallation in ISM	B*

Table 6. *The processes forming the predominant isotopes (more than 20% of a given element) for the elements found in humans and ranked in order of abundance by mass (cf. table 3)*

(The asterisk (*) identifies the elements with no known role in human life as of 1991. The process coding and, where applicable, the minor (i.e. 10%–30% as indicated by lower-case characters) contributions of s- and r- processes are taken from Grevesse & Anders (1989). For a given isotope, the contributing processes are given in rank order. Many isotopes, which appear only at intermediate nucleosynthetic stages, do not appear in the list.)

rank (mass)	atomic number	atomic symbol	isotope mass	process
1	8	O	16	*He*
2	6	C	12	*He*
3	1	H	1	*BB*
4	7	N	14	*H*
5	20	Ca	40	*Ex*
6	15	P	31	*Ne, Ex*
7	16	S	32	*O, Ex*
8	19	K	39	*Ex*
9=	11	Na	23	*C, Ne, Ex*
9=	17	Cl	35	*Ex*
			37	*Ex, C, S*
11	12	Mg	24	*N, Ex*
12	26	Fe	56	*Ex, E*
13=	30	Zn	64	*Ex, E*
			66	*E*
13=	29	Cu	63	*Ex, C*
			65	*Ex*
15	37	Rb	85	*R, s*
			87	*S*
16	14	Si	28	*O, Ex*
17=	35	Br*	79	*R, s*
			81	*R, s*
17=	40	Zr*	90	*S*
19=	42	Mo	98	*R, s*
19=	32	Ge*	70	*S, e*
			72	*S, e, r*
			74	*e, s, r*
19=	82	Pb*	207	*R, S*
			208	*R, s*
19=	80	Hg*	200	*S, r*
			202	*S, r*
23	28	Ni	58	*E, Ex*
			60	*E*
24	13	Al*	27	*Ne, Ex*
25=	48	Cd*	112	*S, R*
			114	*S, R*
25=	9	F	19	*N*
25=	22	Ti*	48	*Ex*
28	50	Sn	118	*S, r*
			120	*S, R*
29	34	Se	78	*R, s*
			80	*R, s*
30=	53	I	127	*R*
30=	23	V	51	*Ex*
32	25	Mn	55	*Ex, E*
33	5	B*	11	*X*
34	38	Sr*	88	*S, r*
35	24	Cr	52	*Ex*
36	33	As	75	*R, s*
37=	27	Co	59	*E, C*
37=	56	Ba*	138	*S*

arrested and shocks cause an explosion: the Type II supernova event expelling a significant portion of the stellar mass. During these brief terminal stages further nuclear reactions run their courses in the ejecta (Aller 1989; Schramm 1982; Ulrich 1982). Table 6 lists the various processes that form at least 10% of each individual isotope comprising more than 20% of the total mass of an element found in humans.

For low-mass stars, timescales for each stage possible for such a star are much longer than for high-mass stars and temperatures and pressures never attain values high enough to ignite processes beyond He burning into Ne. Most of this material remains in these stars as mass loss – even through the planetary nebula episode – is modest compared with the loss from high-mass stars (Allen 1973; Bassgen *et al.* 1987; Hua 1988).

In the galactic plane near the location of Sun, the average stellar plus interstellar density is of the order of 5×10^{-24} g cm^{-3} (Allen 1973). The mean densities of Sun, Earth, seawater, the terrestrial atmosphere, and the human body are, respectively, about 1.4, 5.5, 1.0, 1.3×10^{-3}, and 1.0 g cm^{-3}. Following the great concentrating by gravity from the ISM and the proto-Solar System and then the cooling which permitted chemical bonding to form the chemical assemblages in the material that became the various parts of Earth, living cells appeared and then selected elements (and molecules) from each of the three terrestrial pools. These selections by living cells continue to be many and various. For instance, the primary reservoirs of N, Cl, and Mo available for living matter are the atmosphere, seawater, and the crust, respectively. This may be seen from the entries in table 4. Because no one single reservoir could make all elements readily available and because of the known catalytic properties of many mineral surfaces, it seems certain that Life originated with access to the interfaces among the individual phases of Earth.

8. PHOSPHORUS, POTASSIUM AND FLUORINE

The odd-numbered elements P and K are among the 20 most common ones cosmically, in Earth's crust, in seawater and in humans. Remarkably, P and K themselves determine the minimum cosmic volume necessary to make a human being.

As a nuclear species, P is synthesized mainly by Ne burning (Grevesse & Anders 1989) in high- and intermediate-mass single and binary stars. A smaller amount of P is also made in the subsequent supernova explosions. For the example of a 25 $M_{\odot}$ (Aller 1989; Schramm 1982; Ulrich 1982; Weaver *et al.* 1978; Woosley & Weaver 1982) star, some 3×10^{30} g of P is mobilized into the ISM. The average density of P in the ISM is of the order of 10^{-29} g cm^{-3}. As a consequence of repeated shockings of a cloud sample by successive supernovae, density wave passages, and low-mass star evolutions, the primitive Solar System nebula condensed some 2×10^{28} g of P. A large portion of this survives in Sun and the gaseous planets. At about 1 Astronomical Unit (1.5×10^{13} cm) from Sun, condensation processes have preserved some 2×10^{22} g of it in Earth's crust (Allen 1973). (The reservoirs of the element in the ocean and atmosphere are very much smaller.) Geophysical processes concentrated the element into assorted phosphate minerals. Weathering then made it more available for absorption by plants and bacteria. Humans obtain their necessary quantities of it from the plants and animals in their diets. A smoothed-out average density for P characteristic of the Milky Way disk (including stars, gas, dust, etc.) is of the order of 10^{-28} g cm^{-3}. For a 70 kg human with 560 g of P, we have calculated that about 2×10^6 present solar volumes of average galactic matter are required to make available the quantity of P essential for the human body.

However, about 90% of the observable galactic matter is now in the form of low-mass stars which are presumed to have the same initial composition as the ISM. These stars do not process nuclear matter quickly and do conserve their matter efficiently for very long intervals (greater than 10^{10} years) so most of their P is really sequestered and unavailable for Life. Hence, the interstellar volume really necessary to form a human becomes about 2×10^7 equivalent solar volumes.

The other limiting element, K, is made only explosively, as indicated in table 6. The same example as formerly, a 25 $M_\odot$ model, disperses about 3×10^{29} g of K (about 10% the mass of P) into the ISM. By the same argument as in the last paragraph and again to one order of magnitude precision, approximately 10^8 solar volumes of the ISM are required for K. However, it is interesting that table 2 shows that the observed cosmic abundance of K by mass is only about half (rather than 0.1) that of P and the same table also shows that the relative abundance of these elements actually inverts by about a factor of 50× in Earth's crust and reinverts in the human body to nearly the original ratio of about 2× in favour of P. Thus, from the results in table 2 for K as well as for P, the IS volume needed to form a human is about 2×10^7 solar volumes. At the level of one-figure precision then, these results from P and K resolve the apparent inconsistency by a factor of about 5× in the two ways of calculating the volumes derived from P and K separately. The explanation of this matter is in the great variety of concentrating processes which transport some P and K from the ISM gas into interstellar dust, where they are temporarily undetectable, and then to both Sun and Earth, where they can be measured (cf. table 3).

There is an interesting situation with respect to the trace element fluorine (F), which is required for teeth and bones but is not an element which humans must concentrate from the ISM, Earth's crust or sea. Virtually all of this element is made by N-burning in the surface layers of white dwarfs loaded with mass transferred from distorted companion stars locked with the white dwarfs in close binaries (Barnes 1982; Grevesse & Anders 1989; Kato & Hachisu 1988; Rodney & Rolfs 1982; Sparks *et al.* 1978). No other mechanism for generating this element is known, pointing up the contribution to nucleosynthesis from close binaries, which compose a significant fraction of all stars. Because this nova-type event occurs in and above the white dwarf photosphere, N-burning is an instance of uncommon non-core nucleosynthesis. More extravagantly, supernovae of Type I are believed to result from total deflagration of such white dwarfs whose increased masses finally exceed the Chandrasekhar limit or from the coalescence of two such stars (Mochkovitch & Livio 1989). Despite some evidence for cataclysmic variables and X-ray binaries in globular clusters, it remains true that almost all known binaries reside in the Pop. I stars of the Milky Way and of the few other galaxies which have been investigated for this distribution (Richer & Fahlman 1988).

9. THE NUMBER OF GALACTIC SUPERNOVAE THAT MADE THE ELEMENTS REQUIRED FOR HUMAN LIFE

Table 2 shows that, on average $Z = 1.9\%$ cosmically. Thus, 1.9% of the Galaxy has been converted by stellar processes into elements heavier than He, dispersed into the ISM by supernova and other events, and then concentrated into later 'generations' of stars (e.g. Sun), and planets.

The Milky Way mass, excluding the dark halo, is of the order of 10^{11} $M_\odot$ (Borges & De Freitas Pacheco 1989). Thus, about 2×10^9 $M_\odot$ arose from supernova terminations of the lives of stars. If each of these had an average mass of 15 $M_\odot$ and synthesized and ejected 5% of its mass as elements heavier than He, of the order of 3×10^9 stars had to have followed this pathway. Because the accepted age of the Milky Way is about 10^{10} years (Borrow & Silk 1980), the average rate of supernova events is about one per 3 years. This is clearly greater than the rate (about one per 200 years) (Allen 1973) observed during the past 1000 years for the Milky Way. It is reasonable to conclude that most of the necessary number of supernovae were events early in the life of the Galaxy. At that time, the interstellar clouds were much denser and hotter than currently. Thus, an initial larger incidence of high-mass, hence short-lived, stars would be expected. As it appears that the rate of supernovae (Barbon *et al.* 1984; Hunter & Gallagher 1989; Trimble 1989) is individual for each galaxy – for some being much greater and some much less than for the Milky Way – extrapolation of the evolution of Milky Way interstellar and planetary chemistry to other individual galaxies is not yet possible. Therefore, calculation of the incidence of Life in any specific part of the Universe as a whole must eventually take account of the great variability of the rate of nucleosynthesis from galaxy to galaxy.

Despite present ignorance of detail, there is no doubt that most atoms in our bodies have had origins which include the earliest and the most distant horizons of the Universe. Furthermore, once accumulated on Earth, many of these atoms have been used time and again by the same organism and even more so by different organisms since Life began. In addition, a few thousand are even now being made every second in each of our bodies.

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