5.4.3 Astrogeology

While the skies and seas of alien worlds are fascinating subjects for discussion, it is mainly upon the surface of a planet (its crust, or lithosphere) that life evolves and flourishes. Scientists who study mountain-building (orogeny), tectonic and seismic activity, and the construction of worlds generally, call themselves “astrogeologists” or “astrogeophysicists.”[598,2144]

As Dole has pointed out, our knowledge of the forces responsible for earthquakes, volcanoes, and mountain-building is still incomplete.[214] One suggestion is that quakes and volcanoes are more likely on planets with higher gravitational compression and more internal heat generation due to radioactive decay. Planets smaller than Earth would tend to have less gravitational contractive force, relatively larger surface areas (compared to total mass) across which to radiate heat off to space,[1237] and relatively smaller volumes of heat-producing radioactive substances. Small worlds will thus tend to have lower internal temperatures,[1237] thicker and more solid crusts, and therefore much less volcanism and seismic activity.

Larger planets have relatively great volumes of radioactive material, higher gravitational compressive energy, and comparatively smaller surface-to-volume ratios (so it’s harder to get rid of heat).[1237] They should have larger molten cores, mantles that rise closer to the surface, and thinner crusts that can buckle and slip around more easily. If these suppositions are true in general for high-mass terrestrial worlds, more frequent and more severe quakes might be predicted, as well as higher levels of volcanic activity.

This theory squares with the reported characteristics of planets in our own solar system. The lightest world that has been intensively investigated is the Moon, within which only the faintest tremors have been detected deep below the surface.[2056] The lunar lithosphere has solidified down to a depth of roughly 1000 kilometers.[1291,2043] When the core loses heat and contracts, the mantle is so thick and rigid it cannot buckle. Consequently, there is no real geologic surface activity on the Moon.[1291,2043]

Mercury, the next most massive world examined by astrogeologists, is believed to have no surface tectonic activity at this time - although various surface migrations and volcanism a few eons ago are evident.[1565,2040] Mars apparently has seismic activity. The red planet also seems to have some lithospheric collapse due to mantle contraction, but there is no clear and convincing evidence for horizontal plate movements across the surface. It has been suggested that on Mars we may be seeing *“incipient plate tectonics...where one plate is beginning to break away...like the Earth, about two hundred million years ago.”*[598] The towering Olympus Mons (formerly “Nix Olympica”[1323]), at 26 kilometers high the largest mountain in the solar system, bears mute testimony to the presence of extensive and fairly recent volcanism on Mars.[2072]

Earth has well-developed tectonic activity, plenty of active volcanoes, and a crust only about 30 kilometers thick.[367] Radar probes of Venus, our sister world, have found low mountain chains suggestive of at least a moderately active lithospheric environment.[1214,2041]

Presumably, the core of a still larger terrestrial planet would be more massive and hotter, pushing the mantle closer to the surface. The thinner crustal sheet would buckle, slip and shake far more readily than does Earth’s rocky skin. Quakes would probably be more violent and more numerous, and breakthroughs in the crust by hot magma (volcanoes) should be widespread and commonplace.

What kinds of mountains are alien worlds likely to possess ? The building of mountains is an extremely complex process, depending on planetary mass, gravity, composition, heat flow rate through minerals, air pressure and wind velocity, and a host of other factors. For instance, on larger worlds rivers may flow downhill faster because of the higher gravity, which may cut deeper valleys and canyons.

Perhaps one of the most significant astrogeological advances in this century has been the development and elaboration of the theory of continental drift. Continents are now known to be small plateaus of granite embedded in much larger “tectonic plates.” The entire Earth’s crust is believed to be fragmented into a mosaic of perhaps eight of these plates, rigid shifting masses of solidified lithosphere which have been described as great tabular “icebergs” of rock floating on the surface of a “sea” of denser subjacent mantle material.[2140,2141]

Plates are believed to be about 100 kilometers thick,[2140] and may move literally thousands of kilometers across the surface of the planet in only 100 million years or so.[2142] Convection currents in the deep mantle have been proposed as the prime mover of the plates, circulating the viscous magma in localized “cells” much like the currents of water in a flat pan which is heated from below.[2141]

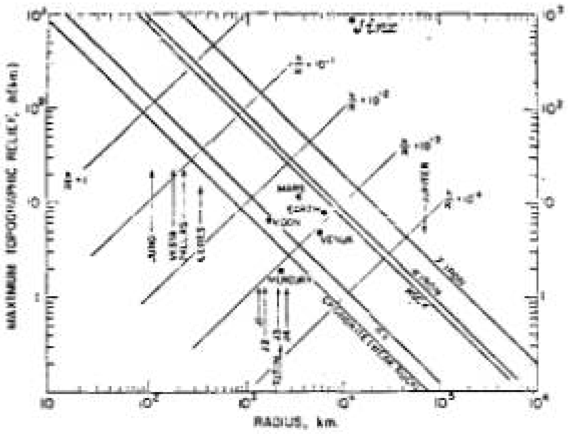
Because the continents are always on the move (though they change shape very little as they travel piggyback around the world[2142]), each has a trailing edge and a leading edge. The trailing edge is tectonically stable, so mountain-building is minimal. But the leading edge is forced downward with the descending mantle currents; the lighter, more siliceous materials that comprise the continents pile up at the site of subduction.[2141] Great mountains are born. (One of the clearest examples of this process occurred during the Cenozoic Period, when the Indian Plate smashed into and dove under the Eurasian Plate, throwing up the mammoth Himalayan ranges.[2140])

From the arguments presented earlier, it is at least plausible to advance the hypothesis that more massive planets will have more internal energy available to drive the thermal convection currents in the mantle, and should therefore produce greater tectonic thrusting and more extensive mountain chains.

Like all material bodies, mountains are subject to the Square-Cube Law. This principle is, quite simply, that volume increases faster than area as size increases. For a mountain to remain standing and not collapse, it must be strong enough to support its own weight. This weight is distributed over an area. The weight that must be supported, however, increases with the volume. (For example, mountains with eight times more mass have only about four times more base area to support that mass.) Consequently, a mountain should be less capable of sustaining its own bulk as it increases in size.

The maximum height of rocky ranges is therefore proportional to their weight, the product of the mass and the force of gravity (Figure 5.10). Higher gravity planets will have smaller, squatter mountains, because the limits of compressive strength of rock are reached much sooner. At least down to about 0.1 Mearth or so, smaller worlds should tend to have taller formations. As has been discovered with craters on the bodies in our solar system,[1277] the height of mountains should statistically vary inversely as the force of surface gravity.*

Figure 5.10 Maximum Size for a Planet's Mountains[1279]



The graph above gives the “maximum statically loaded topography” supportable by a range of different materials. The curves are based on the assumption that if the interior pressure created by building the mountain exceeds the compressive strength of the materials, then the mountain will “fall down.” Planetary radius R is the horizontal axis, and h, the maximum height of mountains (or depth of depressions), is the vertical axis, both in kilometers. For weaker materials - such as water-ice - the topographic relief must be far less than if rock is used. No materials are expected to have much greater strength than taenite, so all planets should be found below this line. (Note the extreme position of Jinx, a hypothetical egg-shaped planet devised by science fiction writer Larry Niven.451) Note the relative weakness of the ices - if Titan has only ammonia-ice mountains, they cannot be larger than two or three kilometers.

Maximum mountain heights in our solar system are roughly as follows : Mercury -- 3 km,1563 Venus - from 1-2 km,2041 Earth - from 8-11 km, Luna - highest peak is 6.8 km high (Theophilus). Mars - highest peak is 26 km high (the volcano Olympus Mons).2072

Mountain size will also be related to the compressive and shear strength of the building materials used.1233,1279 The maximum height of ranges will vary approximately linearly with the compression strength (Table 5.12). For Earth mountains, rock is the usual orogen** with a maximum sustainable load of about 107 kilograms/meter2. However, were we to find mountains of carbon dioxide on another planet, the greatest height would be far lower. This is because the compressive strength of “dry ice” is less than 10-30% that of rock.1569

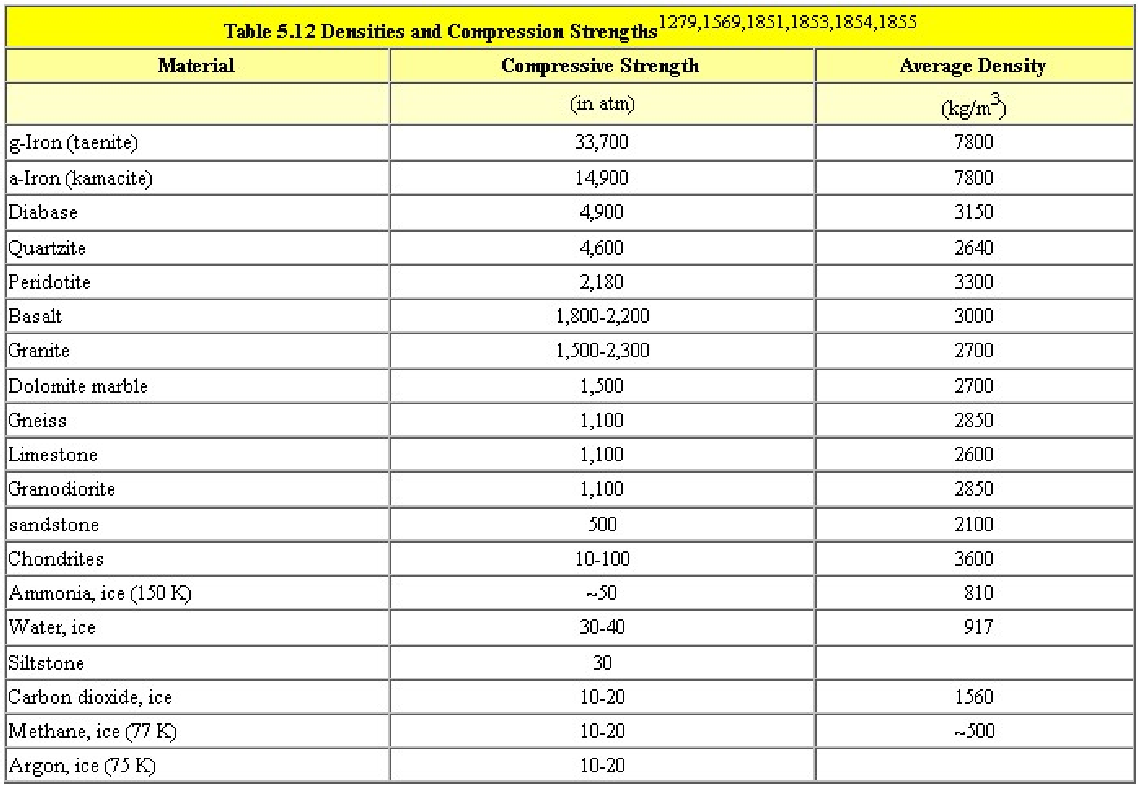


Table 5.12 Densities and Compression Strengths[1279,1569,1851,1853,1854,1855]

Material	Compressive Strength	Average Density
	(in atm)	(kg/m^3)
g-Iron (taenite)	33,700	7800
a-Iron (kamacite)	14,900	7800
Diabase	4,900	3150
Quartzite	4,600	2640
Peridotite	2,180	3300
Basalt	1,800-2,200	3000
Granite	1,500-2,300	2700
Dolomite marble	1,500	2700
Gneiss	1,100	2850
Limestone	1,100	2600
Granodiorite	1,100	2850
sandstone	500	2100
Chondrites	10-100	3600
Ammonia, ice (150 K)	~50	810
Water, ice	30-40	917
Siltstone	30	
Carbon dioxide, ice	10-20	1560
Methane, ice (77 K)	10-20	~500
Argon, ice (75 K)	10-20	

Volcanism could be a peculiar affair on other worlds. On a planet as cold as Titan, for instance, water could be an orogen instead of a thalassogen. If sufficient crustal radioactivity exists, and if the planet is roughly terrestrial-sized, we might observe cold volcanoes spewing forth molten water instead of lava.[1947] Dr. Donald M. Hunten, a physicist at the Kitt Peak National Observatory, believes that Titan may possess just such a subsurface magma of liquid water.[2046] The magma would lie atop a rocky mantle and would contain large amounts of dissolved ammonia. The relatively thin crust should then be a mixture of methane and water-ice, frozen solid.

A curious phenomenon is the flowing of glaciers (mountains of water-ice). There is some evidence that this may be virtually a unique property of H_2O “mountains,” One of the more unusual characteristics of water is its ability to drop its melting point when subjected to pressure. Underneath a glacier pressures rise to hundreds of atmospheres. A lubricating layer of melted ice can form at the base, and the object proceeds to slide downhill on this thin, slippery film of water.

While ice exhibits the freezing point depression effect up to pressures of more than 2500 atm, solid carbon dioxide and other ices cannot duplicate this behavior. Only water-ice will flow rapidly down valleys like rivers. One Alpine formation, the Quarayaq Glacier, is known to flow between 20 and 24 meters per day.[1850] (Of course, CO_2 glaciers are still subject to slow creep,[1569] but this is far less dramatic.)

If mountains are subject to the Square-Cube Law, are not worlds as well ? Small, mountain-sized hunks of matter may be very irregular in shape, because the internal stresses are relatively low. But as mass increases, pressures build: Inside any terrestrial planet rock begins to flow and seek a spherical shape -- energetically the most stable configuration.

Stephen Dole has estimated that the largest mass of a body that can maintain a highly irregular shape is on the order of 10^{-5} to 10^{-4} Mearth.[214] To get some idea of the degree to which an object may deviate from sphericity, Table 5.13 gives the largest size of a body whose mountains are as tall as the planetary radius itself (e long axis is twice the short). These worlds must be very small to retain their egg-shape.

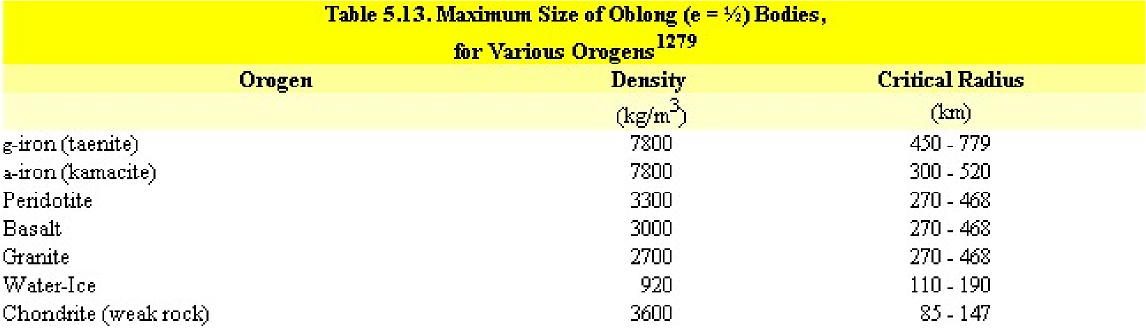


Table 5.13. Maximum Size of Oblong (e = ½) Bodies, for Various Orogens[1279]

Orogen	Density (kg/m^3)	Critical Radius (km)
g-iron (taenite)	7800	450 - 779
a-iron (kamacite)	7800	300 - 520
Peridotite	3300	270 - 468
Basalt	3000	270 - 468
Granite	2700	270 - 468
Water-Ice	920	110 - 190
Chondrite (weak rock)	3600	85 - 147

Finally, returning once again to peculiar surface effects, the astrogeologists may have some real surprises in store for us on other worlds. For example, we know that Venus' air is deficient in oxygen, and one explanation is that the surface rocks have all been well-oxidized. But at temperatures beyond 620 K and pressures above 50 atm, superheated steam dissolves alumino-silicate rocks. If the oxygen depletion theory is correct, Venus might once have been molten to considerable depths and served as a factory for huge, exquisite gemstones.[1293] The surface of the Morning Star may well be studded with garnets, sapphires, rubies and topaz !

* Astrogeologists will recognize that I have made a gross oversimplification here. The mountains of large differentiated planets are actually supported by isostatic forces. Only small bodies can accurately be considered to have statically loaded topography.[1279]

** Derived from the Greek roots, meaning, literally, "something that produces mountains." I use the word to signify "any substance capable of forming planetary mountains."

5.5 Planetary Habitability

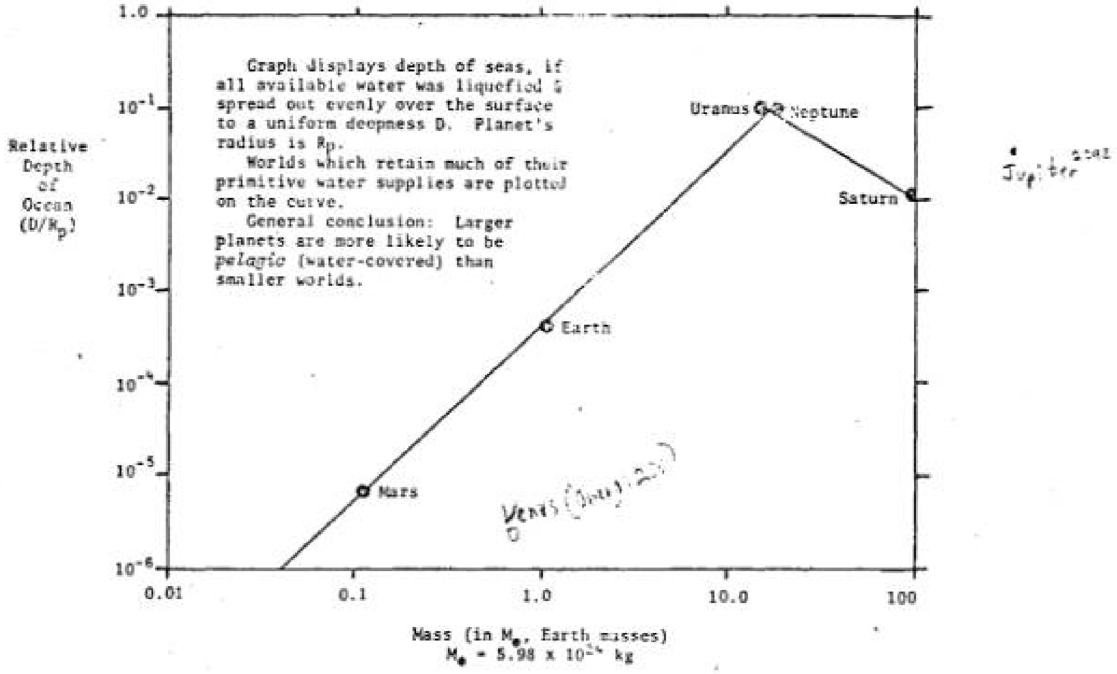
We have barely scratched the surface of the total field of general planetology in this brief survey, and most if not all of the discussions have been simplifications of vastly more complicated processes. The concept of habitable zones, for instance, is a very old and respected idea but one which should not be engraved in stone and rendered sacred. Countless ways can be imagined to "beat the heat." Some of the more obvious of these are surface effects on the planet itself and have nothing to do with the stellar class of the primary.

For example, the greenhouse effect adds about 30 K to Earth's temperature, and about 500 K to that of Venus. In Titan's air, methane and hydrogen might trap solar energy and heat the planet significantly. Calculations indicate that if the surface pressure is on the order of 0.1-0.4 atm, the greenhouse effect could easily add 60-110 K. This would raise the temperature at the surface of Titan to 150-200 K.[1280,1281] Were Titan at the distance of Jupiter instead of Saturn, another 30 K or so increase could probably be arranged -- putting it very close to Mars, temperature-wise. There are indications that even chilly Neptune may have a greenhouse amounting to some 80-90 K.[2046]

A second warming factor is the presence of small-particle smog suspended in the air of Titan. These darkened organic dust motes can absorb sunlight and transfer still more heat to the surrounding atmosphere.[2046] So we see that perfectly valid arguments may be made to extend the outer reach of the habitable zone of Sol as far Jupiter and possibly even Saturn !

What are the limits of mass for habitable planets ? Again, the answers don't come easily. In selecting worlds that might be habitable for human life, Dole set forth the following values: Mass should be greater than 0.4 M_{earth}, to ensure that a heavy enough atmosphere can evolve and remain trapped, and should be less than 2.35 M_{earth}, to keep the force of gravity below 1.5 Earth-gees.[214] Planetary mass will also affect the likelihood of finding planetwide oceans (Figure 5.11).

Figure 5.11 Planetary Mass and Pelagic Worlds[367,2044,2046]

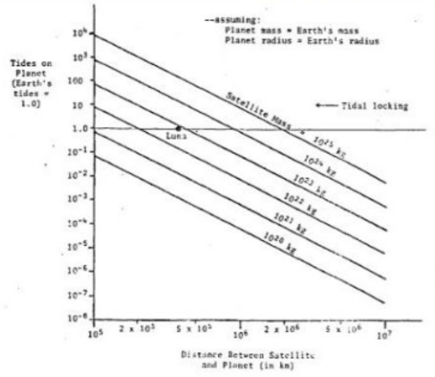


While these are useful estimates, they are clearly rather conservative when applied to all ET lifeforms instead of just to humans. Rasool expects that in a few eons, Mars' atmosphere will thicken sufficiently for it to begin evolving towards a more Earth-like clime.[2065] The mass of Mars, however, is only 0.11 Mearth. And while human life may be uncomfortable at more than 1.5 gees, there is absolutely no rationale for using this as the cutoff for all carbon-based intelligent life. Accretion models suggest that terrestrial worlds may form with masses as high as 5-10 Mearth,[1258] with surface gravity reaching at least 2.2 gees.

Another factor we have not really considered is the tides caused by satellites (or by the primary). Tides may occur in the lithosphere and atmosphere, but are most effective when they arise in the hydrosphere - the ocean. A moon which is very massive, or quite close, will tug at its primary much more insistently and raise higher tides (Figure 5.12).

The tides are important because they will alter the erosion of continents, wave motions in the sea, the weather, and so forth. Larger tides will slow the rotation of the planet, depending on the distribution of land masses, and may have enormous implications in the emergence of life from the sea.

Figure 5.12 Tides Raised on an Earthlike Planet by Satellites of Various Masses and Distances



Assuming a very homogenous pair of fluid bodies, the tidal height H may be expressed mathematically as:

$$H = \text{constant} \times \frac{M_{sat} RP^4}{M_P r^3}, \text{ or}$$

$$H = \text{constant} \times \frac{r_{sat} R_{sat}^3 R_P}{r_P r^3}$$

where M_P and M_{sat} are planetary & satellite mass, R_P and R_{sat} are planetary and satellite radius, r_P and r_{sat} are the respective densities, and r is the average distance between the two bodies.[1980] (Those equations are based on a highly oversimplified model -- for fuller treatment see Alfvén and Arrhenius[1980] or Goldreich and Soter.[1243])

There are additional complicating factors. Peculiar tidal resonances are known to occur. For instance, we now know that Mercury is not a one-face planet as was once thought. Instead, it turns on its axis exactly three times for every two trips around the sun. (A case of "spin-orbit coupling."[2048]) Venus also appears to be "tidally locked" -- but to Earth.[2041] The sun must similarly be taken into account. Sol is responsible for only about one-third of Earth's oceanic tides, but a planet in the habitable zone of a K2 star would experience far greater tides even if it had no moon.

The tilt of the planet's axis is likewise significant with respect to habitability.* All of the ecospheres computed in this and the previous chapter were based on the assumption of a relatively low inclination to the orbital plane. (Earth is about 23°, which is fairly typical.) A planet with high inclination will have more extreme seasonal temperature variations across its surface. Large tracts of land may become totally uninhabitable, although marginal livability apparently can be retained for tilts as high as 81°.[214]

The tilt of a world is responsible for its seasons. Planets with 0° inclination should have relatively humdrum, monotonous climates all year long (although an especially eccentric orbit might produce season like effects). With no seasons, there would be no regularly changing weather patterns, no cycles of autumnal death and vernal rebirth in the plant kingdom, no migrations of fish and fowl. The entire rhythm of existence would be lacking, and the influence on culture, religion, philosophy, and the agricultural sciences must necessarily be enormous.

Many rare and exotic environments for life may exist in our Galaxy.[214] A "superjovian orbiter" might derive life-giving heat from the gas giant it circled. Inhabitants of this terrestrial world on the side that permanently faced away from the superjovian would scoff at tales of a giant Thing in the sky and reports of strange native religions brought back by intrepid explorers who had visited the other side. (The auroras there should be fantastic, if Io turns out to have beautiful yellow displays as many believe.[2047,2090])

The Earth-Moon system is for all practical purposes a double planet, and it is not unreasonable to suppose that in many stellar systems across the Galaxy two Earths orbit one another. A world with two habitable belts, which might be found nearer the inside edge of the stellar ecosphere, is also a distinct possibility. Only the polar regions could be livable - the tropics would be unbearably hot.

There may be starless worlds, as the late astronomer Harlow Shapley suggested, bodies which lie alone out in the cold of interstellar space.[816] Life is possible only if these planets are self-heating.[18,2061] (Hal Clement used this idea in his science fiction story entitled "The Logical Life.")

Perhaps we will find pelagic worlds, or terrestrials with Saturn-like (or Uranus-like) rings, or planets with large liquid bodies at the surface maintained near the triple point of the thalassogen.

The ocean would boil furiously while gleaming icebergs floated and tossed on the frothy sea. The possibilities are as limitless as the imagination.

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* Orbital eccentricity is also important -- e must be less than 0.2 if at least 10% of the surface is to remain human-habitable.[214]

Chapter 6. A Definition of Life

"Is life a disease of matter ?"
- Minas Ensanian (1975)[1585]

"A hen is only an egg's way of making another egg."
- Samuel Butler, in Life and Habit (1877)

"Life is more a matter of relationships and organization than of material."
- Dr. Manfred Clynes (1960)[92]

"The tumult of the time disconsolate
To inarticulate murmurs dies away
While the eternal ages watch and wait."
- Henry Wadsworth Longfellow (1807-1882)

In earlier chapters we considered the astronomical environment which extraterrestrial lifeforms must cope with. Other galaxies, stars, and countless planets appear amenable, if not perfectly hospitable, to life.

Since no ETs have been detected outside the Earth to date, it might be argued that any statements regarding the ubiquity of life in the universe must necessarily be pure speculation. But this is not so. We have the incredibly good fortune to be alive at the first moment in history when this tantalizing question can be approached with rigor and in some detail.20 Not only can we draw certain tentative conclusions regarding the existence of extrasolar planetary systems, but we may also seriously discuss whether or not other worlds will possess environs which permit, encourage, or demand the emergence of life.

It is probably true that a good many planets are merely dead bodies of rock washed by sterile seas.[939] Much depends on whether life originates quickly and regularly given suitable conditions, or if it requires an event so improbable that evolution in any reasonable time is scarcely possible on any world.

The study of the origin of life, called "abiogenesis" by many researchers in the field, is highly relevant to xenology and xenologists. By determining the conditions that existed on the primitive Earth, and by duplicating them in the laboratory, scientists can attempt to recreate events that must have occurred on this planet billions of years ago. Should these experiments indicate that the fundamental chemical building blocks of life are easy to generate - perhaps even inevitable under the proper circumstances - then we might well be justified in concluding that biology is a fairly widespread phenomenon among the many worlds of the Milky Way.

Studies in abiogenesis give some clues as to the universality of those processes which lead to the emergence of life. Of course, any rigorous discussion must include a good working definition of the subject of discourse. When we say we are searching for "life," what do we really mean? The traditional wisdom that "if it wiggles, it's alive" is insufficient to deal with exotic lifeforms which may have little in common with organisms on Earth.[50]

We must also remain sensitive to yet another aspect of the problem of the origin of life. We 180-centimeter-high lifeforms with mere 70-year lifespans all too easily lose sight of the broader perspective we need to appreciate the vastness of space and time. This "chauvinism of scale" is simple to identify but almost impossible to overcome.

In one sense, life is both abundant and ubiquitous on Earth. The live weight of microscopic organisms in an acre of soil to the plow depth of 18 cm has been estimated as more than two tons.* But viewed from a slightly different perspective, life fades into obscurity. The entire Earth weighs 6 × 1024 kg, the whole atmosphere only 5 × 1018 kg. The total mass of the biosphere is no more than 1016 kg, about 0.2% as much as air or 0.0000002% of the entire planet. The mighty works of man and nature are a kind of biological rust, clinging doggedly to the surface of a small world.20

So even in terms of mere planetary spatial frames, biology is only an impurity, a trace constituent of the cosmos.

Perhaps an even more relevant problem of scale is what might be called "temporal chauvinism." Man tends to think in terms of timescales commensurate with his own puny lifespan. But if we are to comprehend the meaning and the magnitude of evolutionary processes that lead to the origin and development of life, it becomes necessary to overcome temporal chauvinism. Centuries are of little concern in this arena -- it is only the millions and billions of years that count.

Events which seem unfathomable in the usual time frame become more sensible on geological timescales. Indeed, it appears that the key to evolution is time. As one scientist puts it, "in two billion years the impossible becomes the inevitable."[702]

A proper sense of the passage of time enables us to firmly grasp, not only the origin of life and the evolution of intelligence in the universe, but also such seemingly diverse topics as comparative culturology, technology gaps and alien thought processes, suboptic communications lag times, and the mechanics of galactic colonization.

* This includes 900 kg of molds, 450 kg of bacteria, 450 kg of branching unicellular organisms (Actinomycetes), 100 kg of protozoa, 50 kg of algae, and 50 kg of yeasts. Viruses are present in great numbers, but their mass is insignificant.[38]

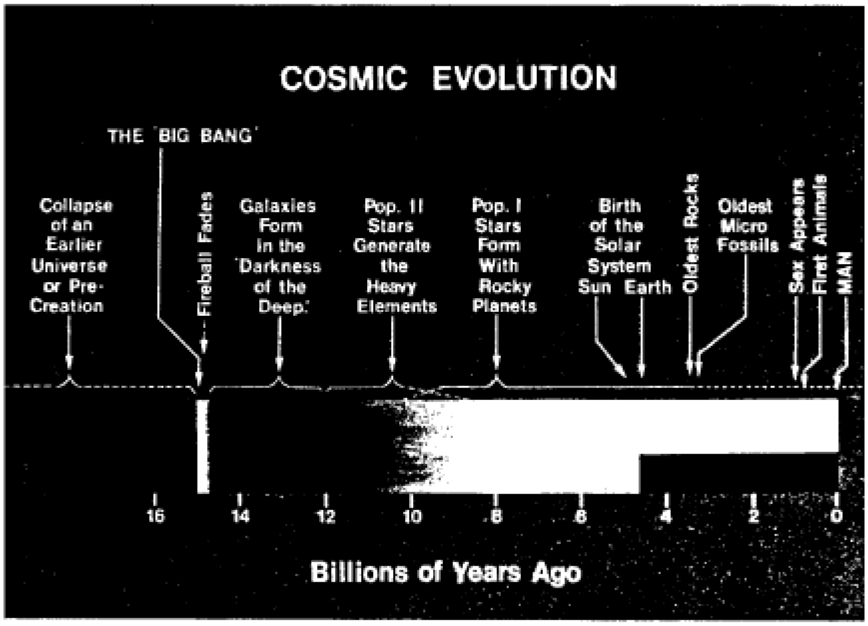
6.1 Chronology

In 1648 James Ussher, the Archbishop of Armagh, announced that the creation of Earth occurred promptly at 10 A.M., October 23, 4004 B.C. This span of roughly six thousand years was calculated in accordance with the descriptions and geneologies found in the Bible, and enjoyed wide currency until about two centuries ago.

Today we know that the material universe is far older. The primieval fireball is believed to have exploded perhaps sixteen billion years ago, the Milky Way coalescing a few eons later. Such vastness is scarcely conceivable in any meaningful terms.

How does one conveniently comprehend a span of time equal to millions of human lifetimes? Imagine that we draw a line from top to bottom of this page, a linear scale to portray the entire history of the universe. On this map, the sum total of human civilization would be represented by an invisible sliver a few hundred atoms long. On the same scale, the time man has known electricity is measured by the span of two or three atoms. Even the segment illustrating the entire Age of Mammals would hardly exceed a millimeter in length (Figure 6.1).

Figure 6.1 Timescale of Cosmic Evolution (from Barney Oliver, in Duckworth[2296])



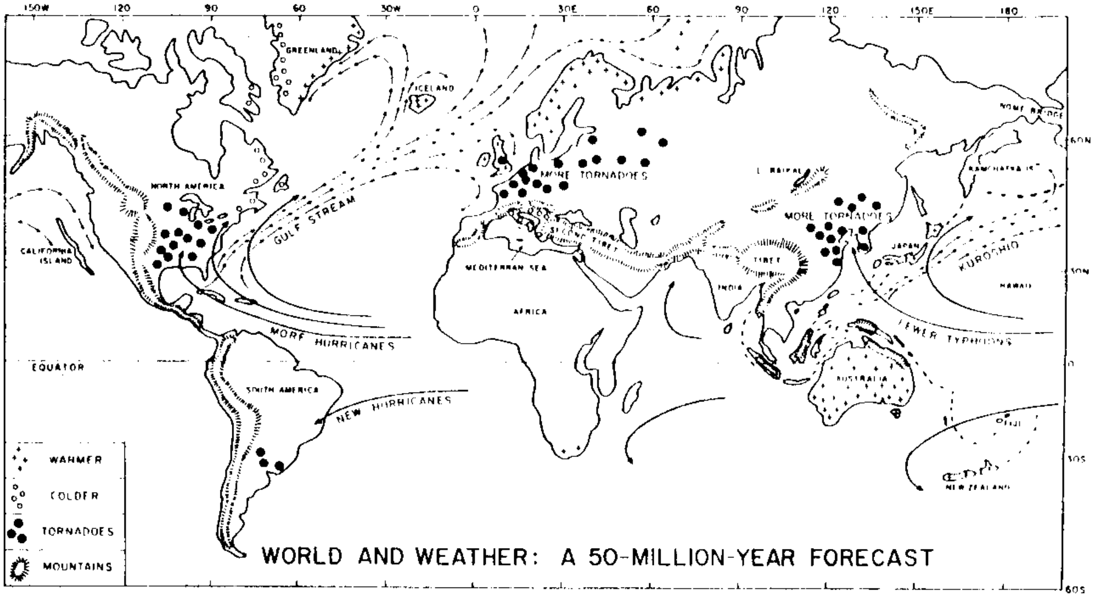
In 15 billion years the universe has evolved from the blazing inferno of the primordial fireball into galaxies of stars surrounded by planets, many of which may support intelligent life. The earth has existed for approximately one-third this time or 4.5 billion years, while man has been around for only 1.5 million years or one ten thousandths the estimated age of the universe.

One rather well-known visualization was set forth by the famous British astronomer Sir James Jeans many decades ago. Imagine a penny carefully balanced atop the Washington Monument. Affixed to the cent is a postage stamp. Proportionately, the Monument represents the age of the Earth, the coin the entire age of the species of man, and the stamp the length of time since humans first learned to use tools.[2109]

Our minds are easily boggled. The whole history of the United States spans a mere two hundred years, a series of only eight generations of humankind. The differences between the late 18th century and the modern world seem immense. To contemplate our world as it may exist two hundred years hence sorely taxes our imagination (Figure 6.2).

Figure 6.2 Radical changes on the Earth due to 50 million years of continental drift are predicted by three University of Chicago paleoclimatologists[477]

A look ahead: 50,001,974 A.D.


WORLD AND WEATHER: A 50-MILLION-YEAR FORECAST

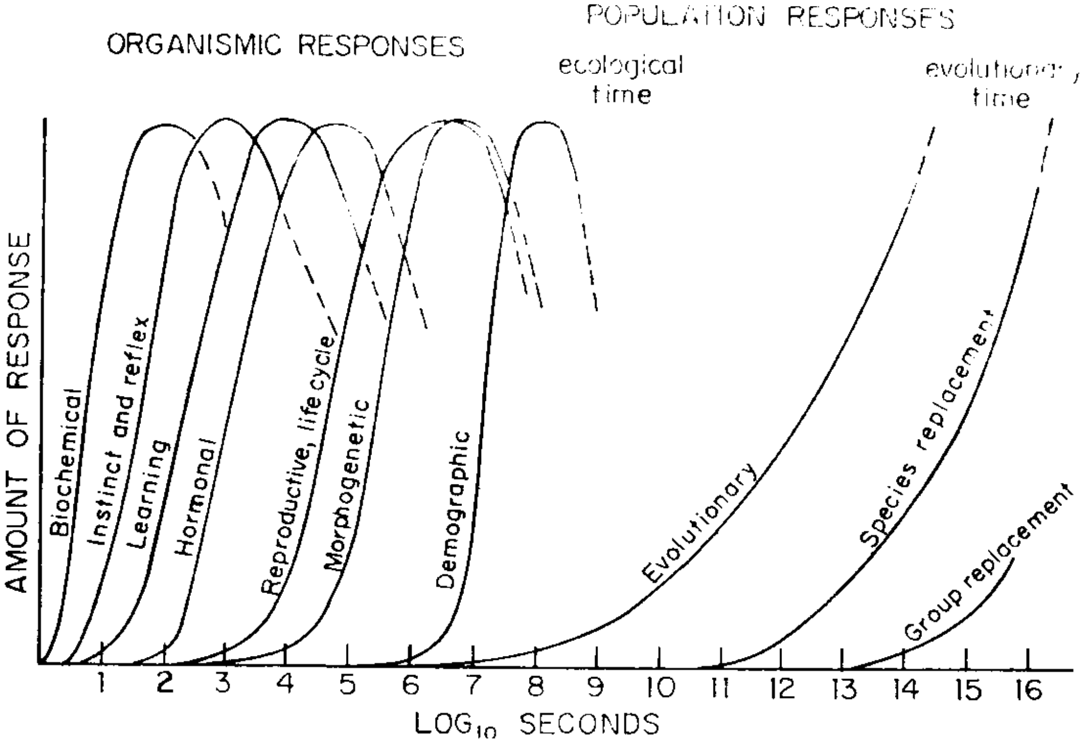
But hundreds or even thousands of years are nothing to the xenologist.143 As biochemist and Nobelist George Wald aptly observes, *"in geological time, even one million years is just a day."*867 It is inconceivable that all other lifeforms throughout the Galaxy began evolving at exactly the same time as we, and at the same rate. If ETs do exist, many of them undoubtedly possess civilizations millions of years our senior - if not hundreds of millions or even billions of years more advanced.

Before such numbing timescales, humanity pales into relative insignificance in view of the mission of intelligence in the cosmos. Even if mankind were to be virtually annihilated in some terrible natural catastrophe, over a span of millions of years other mammals might evolve to take up the niche vacated by ourselves. Considering the broad sweep of the evolution of sentience, there seems no reason to doubt that higher intelligence would reassert itself on this planet.

Barring such catastrophes, humanity and its progeny may have literally eons of life and development ahead of it.* The Age of Dinosaurs lasted only a hundred million years, roughly 0.2% the age of the Earth. Says Arthur C. Clarke : *"If we last a tenth as long as the great reptiles which we sometimes speak of disparagingly as one of nature's failures, we will have time enough to make our mark on countless worlds and suns."*81

Part of our problem in understanding time is due to the differing order of change in nature (Figure 6.3). Humans are accustomed to dealing with events that can best be classified as "organismic responses" - instincts and reflexes, learning, cycles of reproduction and so forth.565 We are only now, in the 20th century, becoming dimly aware of the concept of ecological time, the scale upon which demographic (population) and ecospheric changes take place. And the next highest levels - of evolutionary and geological times - still remain beyond our ken.

Figure 6.3 Timescales of Responses to Change (from Wilson565)



One interesting example of a long-term trend is the change in the length of day. Every million years, because of tidal friction caused by the Moon, Earth's day becomes about 3.3 minutes longer.2206 A couple hundred million years ago, during the Age of Dinosaurs, our planet revolved about one hour faster. In the steamy Carboniferous Period, when giant insects cruised forests of giant ferns, the day was only 22 hours long. One eon ago the components of Earth's air were stabilizing near their present values and marine organisms were reeling with the discovery of sex. But they had to accomplish in only 18 hours what we take 24 to do.

Projecting into the future, a day in 1.000.000.000 A.D. will last about 30 hours. The Earth is gently slowing, a giant top marking time in eons.

"I perceived that I was on a little round grain of rock and metal," wrote Olaf Stapledon in his 1937 science fiction classic Star Maker,

> filmed with water and with air, whirling in sunlight and darkness. And on the skin of that little grain all the swarms of men, generation by generation, had lived in labor and blindness, with intermittent joy and intermittent lucidity of spirit. And all their history, with its folk-wanderings, its empires, its philosophies, its proud sciences, its social revolutions, its increasing hunger for community, was but a flicker in one day of the lives of stars.1946

All of these considerations are of great significance to the origin of life on this planet. Until recently, scientists were of the opinion that the creation event itself might have taken place one or two eons after the formation of the Earth. But how much time was really required ? As late as the middle of this century, no one really knew the answer to this question. The skeletal fossil record extends back only to the beginning of the Cambrian Period, about 600 million years ago. The Precambrian, comprising the first 87% of our world's history, remained enshrouded in mystery and ambiguity.

In the last decade or two, improved techniques and several major finds have lifted the veil of ignorance. Scientists now hunt for molecular fossils, traces of the biochemical signatures left behind by the remains of microscopic organisms long dead.[1420] The evidence now seems fairly clear that single-celled life existed some 3.4-3.6 billion years ago. (But note Schopf.[2369]) It is plausible that extremely primitive replicative lifeforms existed for several hundred million years prior to these earliest finds.[41]

The implication is that life had half a billion years, perhaps even less, in which to assemble itself from nonliving chemical precursors. As two pioneers in abiogenesis research have noted : *"There is no way at present to estimate when, during this (first) billion or so years, life arose. Periods of a hundred million years are so removed from our experience that we can have no feeling or judgement as to what is likely or unlikely, probable or improbable, within them. If the formation of the first living organism took only one million years, we would not be very surprised. We cannot even prove that 10000 years is too short a period."*[521]

The process of biological evolution must have begun as soon as the first living system emerged from the primieval "soup" four eons ago. Early forms of anaerobic photosynthesis probably arose three eons ago, in response to what one scientist has called "the world's first energy crisis." Energy-laden molecules floating in the seas had become depleted. Photosynthesis allowed organisms to directly tap the power of the sun, which partially solved the crisis.

Unicellular life began to diversify about 2.3 billion years after the formation of the Earth, with the appearance of the first metazoans (multicellular animals).[939] Aerobic photosynthesis was invented a short while later, and the concentration of oxygen - a harmful, poisonous waste product detrimental to most lifeforms in existence at the time - rose dramatically. In response to this "smog crisis," nature invented organisms able to consume the harmful oxidant and return carbon dioxide, thus detoxifying the air. These efforts were not entirely successful, however: Burning oxygen proved more efficient and made possible the conquest of land.

Perhaps the vastness of time and our place in it can best be illustrated by the chronology in Table 6.1. Earth's biography is plotted as a series of slow, painstaking steps from the formation of our planet 4600 million years ago up through the present. Truly, man is a mere footnote to history.

Sir James Jeans gracefully surmounts the barriers of temporal chauvinism : *"We are living at the very beginning of time. We have come into being in the fresh glory of the dawn, and a day of almost unthinkable length stretches before us with unimaginable opportunities for accomplishment. Our descendants of far-off ages, looking down this long vista of time from the other end, will see our present age as the misty morning of human history. Our contemporaries of today will appear as dim, heroic figures who fought their way through jungles of ignorance, error and superstition to discover truth."*[2109]

* Ultimately, we are limited only by the lifetime of our sun. Another 8-10 billion years remain before it flickers and dies, although Earth will probably become uninhabitably hot in 4-5 eons.[20,2056] Perhaps by then, humanity will have discovered a new homeland.

6.2 What is Life ?

Anthropologists jokingly tell of two cannibals watching an airplane fly overhead. Eyeing the craft wistfully, one says to the other, "It's very much like lobster. It's hard to get into, but very good once you get inside."

Kenneth Boulding, Director of the Institute of Behavioral Science at the University of Colorado, insists that the cars, planes and factories which surround us bear an analogous relation to the life inhabiting them as the lobster's shell does to the lobster. *"If a being from outer space were observing this planet," Boulding suggests, "he might well report that the process of evolution had produced a species of large four-wheeled bugs with soft, detachable brains."*[30]

How can we accurately differentiate the living from the nonliving ? For years, science fiction writers have been teasing our imaginations, giving us stories about plants that act like animals,[564,2115] animals that act like plants,[607,2168] and other organisms that almost defy classification.[1561,2163,2210,2221] Countless stories have been written around the theme of "machine life,"[983,1755,1836,1912] and a well-known Stanford radioastronomer has speculated that there may exist aliens which are simply spherical balls. Instead of handling objects as we do, Dr. Ronald Bracewell suggests that *"they might have to ingurgitate them and manipulate them as we can manipulate things with our tongues. Perhaps their tongues would be luminescent and there would be an eye in the roof of their mouth, or a microscope."*[1040]

Science fictioneers have devoted a great deal of time to an attempt to identify some of the problems we may encounter simply in recognizing that an object on another world is alive. False calls in either direction are possible. We may, for instance, mistakenly ascribe life to what is in reality a purely physical process. Conversely, there is the more frightening possibility that we might fail to identify a fascinating but unusual lifeform, which could cause irreparable harm before the error was discovered.

Such hypothetical organisms generally fall into five broad categories (although there are numerous exceptions). First we have the polymorph, a creature having a plural or changeable form. In Olaf Stapledon's First and Last Men, Earth is invaded by a host of microscopic organisms from Mars. On occasion, these microbes form themselves into a rational entity by solidifying as a kind of "intelligent cloud."[81] Such is not without precedent even on Earth : It has long been debated whether the sponge (Porifera) is a true organism or a colony of unicellular organisms.[443]

Ralph Milne Farley wrote "Liquid Life" back in 1936, in which a virus in a pond achieves group-collective consciousness.[581] This is similar to the "scum-intelligence" proposed by Bracewell[80] or the "mold-intelligence" proposed by Academician A. Kolmogorov, a Soviet writer.[1330] Perhaps easier to view as living but equally difficult to understand are Arthur Clarke's Palladorians, each of which is described as possessing *"no identity of its own, being merely a mobile but still dependent cell in the consciousness of its race."*[2207] Another class of exotic fictional lifeforms are the lithomorphs, organisms having the form of rock. Such creatures have actually been discussed in sober scientific circles.[1238] The two extremes of the problem of false calls are nicely illustrated by a pair of science fiction tales involving lithomorphs.

The Star Trek episode entitled "Devil in the Dark" deals with the discovery of a silicon-based organism that lives in the rocky mantle of a small planetoid. The human miners had been collecting and destroying apparently useless spherical silicon nodules - which turned out to be the Horta's eggs. In Clarke's novel Imperial Earth, exactly the opposite difficulty is encountered. Early settlers on Titan, the largest moon of Saturn, discover the "waxworms," entities snaking around on the surface at speeds up to fifty kilometers per hour and often pausing to climb over hills. *"To the bitter disappointment of the exobiologists,"* Clarke writes, *"they had turned out to be a purely natural phenomenon. . ."*[1947]

Macromorphs are beings having a large or elongated distribution. Typical of this class is the huge single-cell lifeform encountered in the Star Trek adventure "Immunity Syndrome," or the Gaia concept of the living planet sponsored by scientists Margulis and Lovecock.[1293]

Perhaps the most fascinating suggestion along these lines was made by the Swedish writer Gosta Ehrensvärd, who pointed out that organisms in the sense we understand may not even be a prerequisite for life.[257] As an example, he envisions a coordinated network of lakes and streams covering a planet, participating in a complementary carbon cycle together with a sun-activated circum-planetary flow of water. Such a system, Ehrensvärd claims, *"would undeniably constitute life, but it would hardly correspond to our idea of organism life. We could hardly recognize at first that we were dealing with something living, for we would not see any mass, body, or anything moving, but only a global activity in chemical serenity."*

The fourth class of unusual creatures are the amorphs, those entities which exist without form or shape. Perhaps the best-known amorph is from the 1958 Paramount Studios movie "The Blob," the story line of which will not be gone into here. Suffice it to say that such organisms are not wholly without precedent on Earth. Slime molds are acellular plants which, because their construction is not unlike a sheet of water, find it possible to slowly creep about on the ground.

Blobs could also arise by natural evolution from Euglena ancestors (a photosynthetic microbial animal), or by artificial evolution as a direct consequence of genetic experimentation with "plantimal" cells. Plantimals are created by fusing animal cells with plant cells to form viable interkingdom protoplasts. To date, human tissues have been mated with carrot and with tobacco cells, and rooster cells have been joined with tobacco as well. According to Dr. James X. Hartmann of Florida Atlantic University at Boca Raton, a living, meatlike amorph might eventually be grown as livestock which could build animal protein by converting the sun's energy directly into chemical energy - just as plants do.[1617]

There have been many variants on this theme in science fiction,[1389] including petroleum-blobs such as in Brenda Pierce's "Crazy Oil" on Venus.[2071] In a familiar plot line, the human miners discover too late that the sticky black goo they've been extracting is part of a living organism. Still more fascinating is the possibility of superfluid amorphs, such as those described by Larry Niven in his "The Coldest Place" :

Even this close it looked like a shadow. It also looked like a very flat, monstrously large amoeba, or like a pool of oil running across the ice. Uphill it ran, flowing slowly and painfully up the side of a nitrogen mountain, trying desperately to escape the searing light of my lamp. ...Helium II, the superfluid that flows uphill.[548]

Finally, we have the electromorphs - beings having the form of electronic energy, fields or plasmas. These ethereal creatures, first described by the Russian space pioneer K. E. Tsiolkovsky[445] and later given a more public airing in the Kubrick-Clarke masterpiece 2001 : A Space Odyssey,[1912] are among the most beloved of science fiction writers. Hal Clement notes that *"one must admit that very complex electric and magnetic field structures other than those supplied ready-formed by atoms and molecules are conceivable."*[878] One of the first science fiction novels the author ever read, decades ago, was about a form of intelligent ball lightning inhabiting the planet Mercury.*

Arthur Clarke has warned that we might not even be able to detect the presence of an alien species on a planet, save by the use of sophisticated electronic gadgetry. The lifeform could be gaseous, electronic, or could operate on timescales far faster or slower than our own.[81] Hal Clement has fictionally created creatures constructed of densely packed electrons possessing quasi-solid properties and which live inside suns,[2139] and still others that inhabit neutron stars, existing in a kind of superoptic quantum space and feeding directly on patterns and structures of information.[2183]

The classic electromorph of all time remains, however, astronomer Fred Hoyle's Black Cloud - a kind of intelligent comet.[62] (Being a lifeform of the dimensions of a solar system, it is also a macromorph.) In the novel, a great patch of ionized gas, which enters our solar system and engulfs Sol, is found to be alive when efforts to predict its movements using the simple laws of mechanics fail. Says the astronomer-protagonist in The Black Cloud : *"All our mistakes have a certain hallmark about them. They're just the sort of mistake that it'd be natural to make if instead of the Cloud being inanimate, it were alive."*

It turns out that the biochemistry of this amazing organism is plasma physics instead of molecular chemistry. Memory and intelligence are stored on a conductive substrate of various solid materials, and are controlled, operated and manipulated purely by means of electromagnetic forces. Ionized gases carry substances to wherever they are needed, like a bloodstream. The Cloud must therefore be recognized as alive, at least in the sense of possessing intricate structures, a capacity for regeneration and energy utilization, and a complex behavior.

* I have since forgotten the title, which annoys me greatly.

6.2.1 The Traditional Answer

The possibility of discovering an exotic lifeform such as the above has spurred biologists to carefully reconsider their assessment of the nature of life. Scores of situations can easily be conjured up in which our tried-and true common sense rules break down horribly. The need for a more rigorous definition is clear.

If so many different kinds of life are possible, though, can we hope to reach them all with a single definition ? Perhaps. For instance, one comprehensive characterization of life, at once exact and unsatisfying, might be : "Life is a highly improbable state of matter."[1171] The difficulty arises when we try to be a bit more specific than this.

Some of the most generalized functional definitions have been rather ingenious. One author presents an ecological specification: A rock has small influence on another rock, but an organism profoundly affects all other living things around it. Living creatures alone can form ecological systems.[64] Dr. Daniel Mazia has suggested that survival is the key to understanding what life is. As he correctly points out, "the living world thwarts time by survival, all the rest combats time by endurance."[313]

Another writer, Dr. V.A. Firsoff, has proposed that "mind" underlies all life, but is a quality denied to the nonliving.[352] Others would claim that "the exclusive property of life is consciousness"[171] or "self-direction."[444] Still another definition hinges on the similar concept of "free will." As the late John Campbell, former editor of Analog, once put it : "Inorganic matter displays the characteristic that what it can do, it must. Any nonliving system always does everything it can do. Living systems don't display that characteristic; if a living organism can do something, it - may."[200]

The traditional biologist points out that all living things possess certain unique properties. One way to define life rigorously is in terms of specific, enumerated traits : Growth, feeding and metabolism, motility (physical movement), responsiveness to environmental stimuli, and reproduction with adaptation.

Let's look at each of these in turn.

During the process of growth, a living organism takes in raw materials and integrates them into itself. Molecules of various substances are added, redistributed, or removed as the body changes shape and develops new structures. Growth also allows for replacement of old worn-out parts.

Unfortunately, many non-living systems also display growth. Crystals of table salt, for instance, or hailstones can be said to grow.

"Chemical gardens," made from heavy metal salts immersed in a bath of sodium silicate solution, also exhibit growth. It is true that most of these counterexamples involve only simple accretion from the outside, and the structure remains basically unchanged. But the flame of a candle appears to grow, and in a fire there is an actual throughput of new atoms. Hence, the candle flame is a valid exception to growth as a defining characteristic of life.

How about the criteria of feeding and metabolism ? We know that living organisms eat primarily for two reasons. First, food is ingested and metabolized to provide an energy exchange with the surrounding medium. This gives a lifeform the ability to carry out any other functions it may wish to perform - reproduction, movement, thinking, more eating, etc.

Second, food must be accumulated to secure the raw materials necessary to effect repairs and to maintain growth. As has been pointed out, the kind of food consumed is really irrelevant. While humans and worms may prefer apples, some bacteria thrive on the most putrefactious sewage (and abhor oxygen), and plants "eat" carbon dioxide and sunlight.

But here again we note that the candle flame has a kind of metabolism. Fires may be said to digest their fuel and to leave wastes behind as chemical energy is converted to heat. Crystals too may eat, if we are willing to consider the saturated chemical solution in which they grow to be their food. Even machines metabolize their fuel, whether to manufacture spare parts or to build near-duplicates of themselves.

Motility is another oft-touted characteristic of life : Animals, and plants to a lesser extent, are capable of bodily movement. Yet there are many analogues in the world of the nonliving. Rocks and snow move in avalanches, cars travel highways, rivers flow, and under the proper thermal conditions metals will expand and contract. Granted, most of these are the result of the imposition of strictly external forces.[444] Nevertheless, the fact that forest fires may spread under their own power constitutes an exception to the motility rule.

What about irritability ? It has been said that if organisms are to profit from their association with the environment, they must be responsive to it at all times. Sensors and effectors thus become more and more highly developed as we climb the evolutionary ladder.

However, some non-motile bacteria show little evidence of reaction to stimuli,[64] and plants are notorious laggard in their responses. Also, irritability is a property demonstrated by many nonliving systems. Crystals react quite sharply to changes in the solute concentration or temperature of their environment. The candle flame recoils when an open door admits a draft. A flask of nitroglycerine is highly responsive to certain environmental stimuli, particularly heat and shock.[881]

Reproduction is probably the most frequently cited "essential" defining characteristic of living systems.[20,521] Although a few scientists would demand the presence of DNA or RNA molecules, proteins, lipids, polysaccharides and the like as requirements for life, most stick to the basics: Replication plus adaptation.

According to these so-called "genetic" definitions of life, living things are entities capable of reproducing themselves, mutating, and subsequently re-reproducing the new mutated form. Organisms are required to multiply geometrically as well. Simple arithmetic reproduction, as in a printing press, is insufficient. The copies themselves must also be able to make more copies. When mutations arise, they are faithfully duplicated - variation is preserved in subsequent replications.

The central idea behind this attempt to define life by reproduction is that living organisms must be the subjects of natural selection, capable of adaptation and evolution. Any system that can replicate, mutate, and replicate mutations will be susceptible to normal evolutionary processes. Favored organisms with the highest potential for survival go on to multiply; others who fare more poorly in the struggle for existence eventually become extinct. Fundamental to the genetic definition of life, then, is the built-in and perhaps unwarranted assumption that a certain level of complexity cannot be achieved save by natural selection operating via adaptive replication.[2358]

It is entirely possible that some lifeforms may have no need to reproduce themselves. Such nonreproducers, if they exist, must be either immortal or very recent arrivals. One class of such beings would be self-creating but nonreplicating organisms, such as robots capable of making continual repairs and of upgrading their own mechanisms periodically, or such as astronomer Hoyle’s Black Cloud mentioned earlier.

There could even exist beings who evolve by means of acquired characteristics.[2216] Such lifeforms could neither die nor reproduce, but would instead modify their parts in response to the changing environment. As Dr. P.H.A. Sneath of Leicester University puts it : *"Evolution and selection would then operate internally on their constitution, rather than on a succession of descendent organisms."*[64] Dr. Sneath suggests that the closest analogy to this might be soils, which don’t reproduce in the usual sense but are complexly organized systems nevertheless. Soils respond to environmental changes, arise wherever there is rock and wind to erode it, and are virtually immortal. Organisms such as these would be unable to "compete" with their neighbors without blending together with a total loss of individuality.

There are other objections to the use of adaptive reproduction as the fundamental criterion for life. Mules, the offspring of a mare and a male donkey, are sterile and so technically are not "alive"- under the genetic definition. Most bees, ants, wasps and termites don’t reproduce either. Selection acts on the whole nest, rather than on individual units, so evolution proceeds through the queen and drones alone. Many varieties of hybrid flowering plants are similarly sterile.

The inorganic world too is rife with exceptions. Flames, driven by wind or with sparks, can reproduce and "mutate." Crystals placed in solutions doped with foreign ions are perfectly capable of reproduction, mutation, and of propagating the mutation (i.e., lattice imperfections).

We see that traditional concepts of life are unduly restrictive for our purposes. As Dr. Mazia laments : *"The problem is not that our conception of a living thing is vague; on the contrary, our concern is that it is too definite because it is too provincial."*[313] We must seek more generalized means to identify and to define life.

6.2.2 Organization

Life is a process by which relatively unorganized environmental components are made more organized. That is to say, life is a building up-process, although to organize also means to cut down the possibilities. But certainly a basic characteristic of all lifeforms is that they are highly organized.[2214]

What do we mean by "organization" ? The concept may be viewed in terms of what Sneath has called "complex interrelatedness."[64]

Interrelatedness means simply that all parts of the pattern are related to and somehow affect all other parts. Each component reacts to changes in its surroundings so as to preserve internal integrity and minimize the effects of any disturbances. This damping action is the principle of homeostasis, common among biological systems. Of course, biochemical homeostasis can be preserved only within certain critical tolerance limits. Death will rapidly overtake any system which is subject to stresses it cannot tolerate.

Complexity is the other facet of organization.[64,1643] "Complex" is used here in its normal sense, as opposed to "simple." Candle flames have a great deal of interrelatedness, yet they lack complexity and hence "organization" as well. Conversely, a lump of granite is highly complex, but because it lacks interrelatedness it cannot be considered "organized" in the sense of having life.

Dr. Sneath cites a most useful example of the role of complexity. If complexity is defined as the amount of information needed to completely characterize a system, the perplexing case of the growing crystal is greatly simplified. We might describe a small cube of rock salt as follows : "A simple-cubic Bravais crystal lattice structure with spacing of 2.82×10^{-8} cm, consisting of alternating sodium and chlorine atoms, containing a total of 10^{20} atoms of each kind." This requires only a few lines of print, and is complete.

On the other hand, living things are typically characterized by enormously more complicated descriptions. Life systems possess order on a scale far smaller than the macroscopic. Unlike the monotonous repetitiveness of the salt crystal, even the simplest bacterium needs some

10^3-10^4 different enzymes, each with a unique sequence of perhaps a hundred or so amino acids.[64,630] This is real complexity. On the microscopic level, life might best be characterized as a highly "aperiodic crystal."[2213,2364]

The key to life may well be information itself. The living world is built from the stuff of the nonliving world, different only in its complexity and organization. Organisms find it possible to actually store and replicate the information that specifies their organization.

Yet it is purely capricious to set some arbitrary level of complexity as the threshold of life.[1717] A frozen amoeba, for example, has an amazingly detailed and intricate structure without being alive - it has only the potential for life. Organization, as we shall see presently, is a most useful parameter for assessing the intensity or efficiency of life. However, it is more reasonable to base our definition on the fundamental processes and functions displayed uniquely by living systems.

6.2.3 Towards a Definition of Life

Thermodynamic and statistical principles are among the most fruitful tools of scientific inquiry. They are equally applicable to simple and to complex systems, living or nonliving, terrestrial or extraterrestrial. As Dr. James P. Wesley, Associate Professor of Physics at the University of Missouri in Rolla, tells us : *"The relationship of life to the environment is, above all, a thermodynamic relationship. Wherever man may go and whatever alien lifeforms he may encounter, the thermodynamic behavior of life will always be basically predictable."*[1717] The idea of entropy is often involved in modern discussions of the definition of life.

What is entropy ? There are really two relatively straightforward aspects of this concept. The first ties in to the thermodynamic aspects of matter, having to do with heat and energy; the second pertains to statistics and order in any system.

Entropy in the thermodynamic sense is a distinct, physically measurable quantity, much like length, temperature, or weight. At a temperature of absolute zero, to take one example, the entropy in a lump of matter is exactly zero. If the temperature is slowly increased in tiny, reversible little steps, the increase in entropy is mathematically equal to the amount of energy (in joules) divided by the temperature at which it was supplied. This holds even if a change of state occurs, as from solid to liquid.

Suppose that we melt a cube of solid ice at 0 °C. If the mass is 1 kg, the increase in entropy can be calculated as exactly 1223 joules/degree. Entropy in the thermodynamic sense is thus a very real, physical quantity.

In the statistical sense, entropy is a measure of the disorderliness of a system. It seems rather clear that when we melt our 1 kg block of ice, the neat orderly arrangement of water molecules in the cube is destroyed. The rigid crystal lattice is converted into a less ordered system - the continually changing, sloshing, randomized distribution of molecules in a liquid.

When the orderliness of a system decreases, the entropy correspondingly increases. The situation is analogous to the state of the public library when the shelvers are out on strike. Books are removed from their proper places but are not returned. Disorder and randomness - entropy - increase.

The greater the structural complexity of a system, the more information is required to describe it. The more organization a system has, the more information and the less entropy it possesses. But information and orderliness, on the one hand, and entropy, on the other hand, are irreconcilable.

The Second Law of Thermodynamics states that entropy and disorder shall always increase and that information will naturally tend to be degraded and lost in any isolated physical system. (Such isolated systems drift from less probable states to more probable ones.) It is the business of the universe to destroy complexity and to become progressively more randomized.

How does this relate to life ? Organisms appear to present a rather curious thermodynamic anomaly. Living systems "violate" the Second Law, by developing well-ordered systems (themselves) out of relatively chaotic systems (their food).[85] At first blush, lifeforms seemingly oppose the "universal drive to disorder" mandated by thermodynamic principles. They organize their surroundings and produce order where there was little or none before. Entropy is actually reduced.

This apparent conflict has only been resolved in the last decade or so. Classical treatments dealt with idealized, isolated systems which transfer no energy or matter between themselves and the external environment.[2213] In sharp contrast, most systems in nature are nonisolated "open" systems, exchanging matter and energy with the surroundings.

Energy by itself is not enough - there must be a useful flow of it. This means that to support life, an environment must possess both a "source" and a "sink." Energy emerges from the source, flows to the sink, and is there absorbed.

Living systems customarily establish themselves as intermediate systems, interposed between some source and some sink in the environment. Then, they utilize the energy flow from source to sink to power their own internal functions.

The total entropy of the entire system, which we shall label E, is the sum of the entropies generated in two separate places. First, there is the entropy caused by the source-to-sink energy flow which we shall call S. Then there is the entropy generated by the intermediate system (the living organism) due to exchanges of matter and energy with the surroundings. If we call this L, then we know that the change in total entropy $DE = DS + DL$.

The second Law of Thermodynamics demands that the total entropy E of any isolated system always increase. Hence, the amount of change must always be positive, so $DE > 0$. The flow of energy from source to sink (S) consists of irreversible processes, so it too must always cause entropy to increase : $DS > 0$. Consequently, $-DL < DS$ is our only constraint.

What does this mean in plain English ? The last equation above simply says that while the entropy of a living system is always permitted to increase by the Second Law (e.g., upon death), a short range of decrease is allowed as well. That is, it is thermodynamically permissible to have local pockets of negative entropy change - "negentropy."

Dr. Erwin Schroedinger was really the first to point out that the essence of life is that it feeds on negentropy.[1678] An organism able to transfer disorder from itself to its environment can reach a plateau for which the steady-state entropy within the living system is less than the formal entropy entering it.[85] Life involves a continuing struggle against increasing entropy.

Living systems thus increase local order at the expense of a larger decrease in order within the environment.

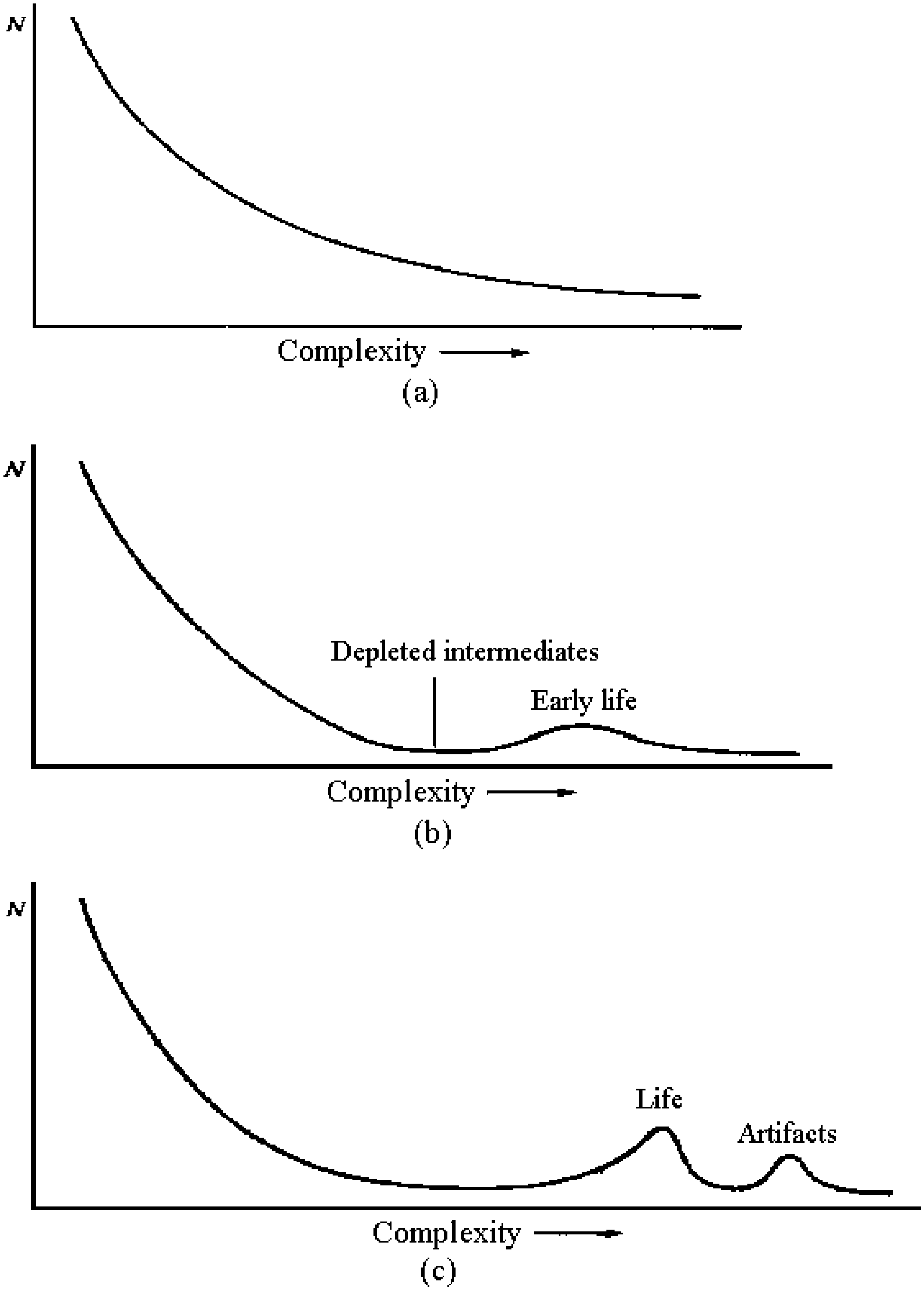
Does life really violate the Second Law of Thermodynamics ? We’ve seen that organisms can effect a local decrease in entropy by maintaining an energy flow.* This leads to an ordering of the intermediate (living) system. So the Second Law does not hold for nonisolated systems (L), but only for isolated ones (E). It is invalid for lifeforms alone, but does hold if that same living system is considered in conjunction with the medium in which it is immersed.

Life by itself is a nonisolated system capable of achieving negentropic conditions locally. Life plus environment is an isolated system, for which the total amount of entropy must always increase.

As one writer puts it : *"Living systems convert order in their surroundings into disorder, and* *thereby increase their own internal order. To say that living systems feed on negentropy is equivalent to saying that their existence depends upon increasing the entropy of the rest of the Universe."*[2213]

At the most fundamental level, negentropic ordering processes are achieved by living organisms. Life drives its environment to physical or chemical disequilibrium, establishing an entropy gradient between itself and its surroundings.[1144] All living systems possess this feature, and it is contended that any system engaging in such negentropic operations must be considered "living" to a certain extent (Figure 6.4).

Figure 6.4 Life, Entropy, and Organizational Structure (after Morrison[1279])



A schematic presentation of the origins of living things. The first graph shows the population of structures - molecules, for instance - against some measure of size or complexity for a case where a free-energy flow has spread the composition to include species of high free energy. The second graph shows what happens when some autocatalytic process begins to increase the population beyond some level of complexity by further degrading the less elaborate, material present. The last graph suggests how artifacts might be looked at in this process, a second and rarer, but more costly, bump.

The question is, of course, to what extent ?

Rather than viewing the question of life in absolutist terms, it seems more fruitful to establish the intensity of negentropic processes as a measure of the extent of the life-quality. One of the more fundamental distinctions between "life" and "nonlife" is the degree of organization and internal structure possessed by living systems. Order and structure are virtually synonymous with information content.[1012]

That is, living systems do more than merely establish a thermodynamic entropy gradient - they establish an organizational/informational gradient as well. As organisms feed on negentropy, they in effect remove information from the surrounding medium and store it within themselves. It is the business of life to accumulate information and complexity.

In a physical sense, these data bits which permeate all lifeforms may be thought of as being stored in an "aperiodic crystal" - a biological lattice with highly irregular small-scale nonuniformities.[2213] The more effective the negentropic processes, the greater the organization which will arise and hence the more aperiodic the physical structure will become. Organization is maintained by the extraction of order from the environment.

If we consider every "autonegentropic" system to be alive, then its character or richness of expression may be defined along a spectrum from lesser to greater levels of organization. At one extreme are the viruses, which are not negentropic systems by themselves and thus cannot be considered alive in the absence of living hosts. At the other extreme are mules and bees, earlier rejected by the genetic definition of life because of their individual inability to reproduce. These animals are quite clearly auto negentropic systems possessing a vast degree of organization both in the macroscopic and microscopic realms. Thus they are not only "alive" (because they feed on negentropy to build internal complexity) but also "very alive" (because they are so internally complex).**

The refrigerator in my house technically should be considered a "live" system in the very broadest sense, as it is a well-defined intermediate system which uses an energy flow to decrease entropy within (the icebox gets colder, and well-ordered ice crystals collect on the freezer walls) at the expense of increasing the entropy in the external environment (the kitchen air gets warmer). Yet its organizational structure is minimal. Little information is stored, and there is only trivial interrelatedness even on the macroscopic scale. There is scant evidence of aperiodic crystal, no complexity at all on the microscopic stage. So the intensity of life in my refrigerator is negligibly small.

Note that "machine life" or "solid state life" per se is not ruled out. As machines become more and more sophisticated, complexity follows. Large-scale integrated circuits available today pack millions of components onto a tiny silicon wafer the size of a postage stamp. Under the microscope, significant aperiodicities have begun to appear in the latest generation of electronic devices. It is entirely possible that, in time, machines will evolve beyond the point of negligible life-quality. This is true, despite the fact that modern digital computers (which merely process data without adding any of it to their internal structure) are not yet alive at all.

In conclusion, xenologists suspect that there are two fundamental properties any system must possess before it can be considered alive. First, it must be thermodynamically negentropic, establishing an entropy gradient between itself and the environment. Second, it must utilize the entropy gradient to create or to maintain structural order internally - that is, it must be autonegentropic or self-organizing. Then there is the quality of organization, known as complex interrelatedness or aperiodic crystal, which reflects the intensity of the life process displayed by a given entity.

For those who prefer succinct and pithy definitions, the author would life to offer the following as a starting point for further discussion : Life is negentropic and self-organizing aperiodic crystal.

* A probable corollary is the necessity for "phase separation." In some sense, the sources and sinks should be physically separated with the living system inserted between them. So we expect barriers to exist between an organism's sources and its sinks. This prevents dissipation of the system, protects it from adverse changes in the environment, and insures the lifeform's ability to exert and maintain control over its interior.[2213] The exact nature of these barriers -- whether gravitational, electromagnetic, or utilizing some hitherto unsuspected principle -- has not been widely discussed.64

** While evolution and the capacity to reproduce are of immense biological importance, a system need not be capable of reproduction for it to be classified as living.[2213,62]

Chapter 7. The Origin of Life

"Who knows for certain ? Who shall declare it ?
Whence was it born, whence came creation ?
The gods are later than this world's formation;
Who then can know the origins of the world ?

None knows whence creation arose;
And whether he has or has not made it;
He who surveys it from the lofty skies,
Only he knows - or perhaps he knows not."
- Rig Veda, ca. 1000 B.C.

"If a dirty undergarment is squeezed into the mouth of a vessel containing wheat within a few days (say 21) a ferment drained from the garments and transformed by the smell of the grain, encrusts the wheat itself with its skin and turns it into mice. And what is more remarkable, the mice from corn and undergarments are neither weanlings nor sucklings nor premature, but they jump out fully formed."

- Jan Baptista van Helmont (1577-1644)[2481]

"It is often said that all the conditions for the first production of a living organism are now present, which could have been present. But if (and oh! what a big if!) we could conceive in some warm little pond, with all sorts of ammonia and phosphoric salts, light, heat, electricity, etc., present, that a proteine compound was chemically formed ready to undergo still more complex changes, at the present day such matter would be instantly devoured or absorbed, which would not have been the case before living creatures were formed."

- Charles Robert Darwin (1809-1882)[1017]

"Ultimately, such a scientist is saying that man's mind was created by a batch of dancing chemicals. He is saying that Shakespeare and St. Francis of Assisi were manufactured by something like Alka-Seltzer fizzing in a glass."

- in The Sign, a Catholic monthly (1956)[114]

"The molecules that could not copy themselves did not. Those that could, did. The number of copying molecules greatly increased..."

- Carl Sagan, in The Cosmic Connection (1973)[15]

Scientists today will still admit that they really don't know how life began on our planet. Laboratory work is tricky, and nobody was present to witness events at first hand on the primitive Earth. Researchers in abiogenesis can only invent some reasonable story about how life arose, and then maximize its plausibility by theoretical and experimental investigations.[20]

There are two central themes that run as undercurrents throughout the whole of xenobiology. First, what is the probability that life of our kind will evolve on other worlds ? By illuminating the abiogenic processes of this planet in ancient times, scientists hope to get a handle on the exact combination of conditions and events necessary for the origin of carbon-based Earthlike life anywhere in the Galaxy.

The second central theme of xenobiology, to which we shall return in later chapters, is the likelihood that life, once having emerged in a planetary environment, will constitute a form of biota more or less similar to that found on Earth. The laws of biochemistry demand that molecules combine only in certain specific ways, and usually only in a very few most probable ways. In other words, what are the physical and biochemical limits of the possible ?

7.1 Historical Views on the Origin of Life

Speculations on the source of life have been abundant throughout recorded history. The Rig Veda mentions that biology began from the primary elements, and the Atharva Veda suggests that the oceans were the cradle of life. The Bible, with its contradictory accounts of the Creation in Genesis (did man arrive before or after the beasts ?), is strictly adhered to by many fundamentalists. Philip Henry Gosse, an eminent 19th century zoologist and Christian, found it a simple task to reconcile the growing mass of paleontological evidence with the Scriptures. God, he declared, created the Earth entirely in accordance with scientific findings. The Lord fabricated geological strata, embedded fossils and the like for the sole purpose of fooling geologists. The apparently extreme age of Earth is only an illusion.

Peculiar ideas abound. Hylozoism, for instance, is the belief that matter and life are one and inseparable. From this viewpoint, life either has no origin and has always existed, or else the question may be deferred to the origin of all matter.

The theory of pyrozoa, to cite another example, was advanced by William Preyer in the last century. Preyer believed that life has existed at all times, even when our planet was still in the molten state. These first fiery living things, the pyrozoa, slowly modified and adapted themselves as the environment cooled and changed, eventually assuming the form in which life presents itself to us today.[2218]

Most theories on the origin of life have fallen into one of four distinct categories :

1. Life has no origin - both life and matter have existed forever;
2. Life is the consequence of a supernatural event, intractable and in explicable by the methods of science;
3. Life originated via ordinary chemical evolution in a deterministic fashion -- under similar circumstances, the same general evolutionary patterns would repeat themselves on any world; and
4. Life originated elsewhere by means unknown, and was subsequently transported to Earth (panspermia).

The first two are self-explanatory, and the third closely approximates the leading modern theories. The last deserves a word of explanation.

The Greek philosopher Anaxagoras of Clazomenae (ca. 500-428 B.C.) was possibly the first to suggest that the seeds of life permeated the universe. With the downfall of spontaneous generation millennia later, panspermia enjoyed a brief revival. The theory was sponsored by many 19th-century notables, including Richter, Kelvin, Helmholtz, Arrhenius, and the great Italian chemist Avogadro.

The doctrine of lithopanspermia held that meteorites were the means by which life wandered from planet to planet throughout the cosmos. Lord Kelvin, a central proponent of this view, considered it probable that countless life-bearing "stones" existed in space, perhaps as the result of collisions between inhabited worlds. Hermann von Helmholtz, a German philosopher and a pioneer in physics, believed that the interior of a meteorite would be a safe retreat for interplanetary microbes during the long incandescent journey through thick planetary atmospheres. The presence of hydrocarbons in the carbonaceous chondrites was cited as evidence of the biological activities of the tiny organisms from space.

Modern analyses suggest that microscopic lifeforms embedded in interstellar comets are possible, but unlikely. The accumulated radiation dose from cosmic rays and natural internal radioactivity is "embarrassingly high" over the large transit times involved between worlds.[22] Furthermore, it is now known that meteorites are of roughly the same age as the rest of the solar system, and that the organic molecules found in chondrites are reproducible by strictly chemical means.[208,2030,2219]

The famous Swedish physical chemist and Nobelist Svante Arrhenius was the loudest advocate for the theory of radiopanspermia.[2304,2305,2306] He suggested that minute spores might be carried upward through planetary atmospheres by convection, where electrical forces could provide sufficient energy to expel them from the body. The pressure of sunlight would then be enough to propel these cosmozoa to other solar systems. Tramping through space, or riding piggyback on small grains of dust, these legions of microscopic interstellar emissaries thus brought the good news of life to the rest of the Galaxy.

Carl Sagan has done a careful analysis of the problem,[20] the details of which will not be repeated here. His conclusion is that radiopanspermia is not a viable theory of the origin of life on Earth. Those microbes ejected from a stellar system by radiation pressure accumulate a dose of x-rays and UV three or four orders of magnitude higher than the maximum lethal irradiation sustain able by even the hardiest terrestrial organisms. Shielding won’t help: Life-forms large enough not to be killed aren’t ejected by radiation pressure because they are too heavy.[22]

The theory that life arose in the ancient swirling gas and dust clouds of interstellar space and then traversed the cosmos, seeding the Galaxy with life, may be called cosmospermia. Dr. J. Mayo Greenberg at New York State University set up a laboratory experiment a few years ago, using tiny grains of matter the size of space dust and appropriate gases. He found that many compounds of relatively high molecular weight could be formed under the influence of ultraviolet radiation. Greenberg evidently believes that a similar mechanism could lead to the production of grains of a size and composition similar to that of viruses.

Dr. Sagan has disputed such theories, noting that any hypothetical extraterrestrial organism of 10^{-5} cm - the size of a rabies virus or the PPLO (the smallest lifeform known) - would have a replication time on the order of two hundred million years. There could only have been fifty or so generations since the Galaxy first formed, insufficient time for natural selection and evolution to operate.[141] It is hard to imagine a smaller yet viable organism; the replication time for a larger microbe would be even longer, permitting still fewer generations.

Accidental panspermia is a class of theory typified by the "Gold Garbage Theory," popularized by Dr. Thomas Gold, a leading astrophysicist at the Center for Radiophysics and Space Research at Cornell University. The Garbage Theory was first announced in a paper read before a Los Angeles meeting of space scientists in late 1958,[139] and proposes that Earth may have been visited by an expedition of advanced ETs who carelessly allowed some of their native microbiota (picnic basket litter ?) to escape. *"While this garbage theory of the origin of life understandably lacks appeal,"* one xenologist notes wryly, *"we should not exclude it altogether."*[20]

A similar idea is the concept of directed panspermia, which suggests that organisms were deliberately transmitted to Earth by intelligent beings on another planet.[1283] Advanced civilizations might intentionally seed sterile worlds, either as a prelude to colonization or perhaps simply to perpetuate the heritage of life on the home planet as insurance against catastrophe.

Panspermia does not address the phenomenon of abiogenesis but merely displaces the problem in space and time.* Consequently, panspermia hypotheses aren’t strictly relevant to the ultimate origin of life in the universe but simply explain how any particular world might have come to be inhabited.

* One science fiction story suggests that life on Earth may have arisen from biota left behind by a careless time traveler from our planet's future.[636] If any theory begs the question it is this one !

7.2 Cosmochemical Evolution

The building blocks for life are lying around everywhere.

Great clouds of organic molecules have been discovered drifting between the stars, presumably formed by various natural processes.[1002,2219,2220,2221] Radioastronomers have seen relatively complex compounds hiding deep in inter stellar space, including methyl alcohol, ethyl alcohol, cyanogen, formaldehyde, formic acid and ether,[1002,2217] and the search is on for amino acids.

Compounds of carbon and hydrogen, particularly cyanogen, methane and hydrocarbon radicals, are detected on the surfaces of stars.[1973,2297] To find the limits of such processes, Dr. John Oró performed an experiment which simulated a hot stellar plasma. Using a graphite resistance apparatus and a plasma torch device temperatures from 1500-4000°C were obtained. Methane, ammonia and water were introduced continuously. The products were condensed at room temperature and allowed to interact for a few hours before analysis. Three amino acids appeared - alanine, glycine, and aspartic acid - along with hydrogen cyanide and a host of other organics.[1072]

There is no doubt that the carbon compounds essential for the development of Earthly life are ubiquitous. Organics have been detected on the Moon,[2443] other planets,[2037,2046] asteroids,[2037] and in comets.[1973,2222]

The carbon chemistry of meteorites is also well-documented.[702,2219]

The Murcheson rock which fell in Australia on September 28, 1969 contains 2×10^{-7} moles of amino acids per gram of meteorite, which is more than many desert sands on Earth.[521] These amino acids correspond rather closely to those produced in prebiotic synthesis experiments performed in the laboratory.[225]

The Orgueil meteorite contains approximately 7% organic matter, including hydrocarbons, fatty acids, aromatics, porphyrins, nucleic acid bases, optically active lipids, and a variety of polymeric material.[1075] On the basis of the amounts of carbon compounds detected in various meteorites, researchers have concluded that these interplanetary wanderers could have brought as much as 5 × 1010 kg of formaldehyde and 3 × 1011 kg of amino acids to Earth during the first eon of its existence.[134]

Taken together, these studies of meteorites, comets, planets and interstellar matter strongly suggest that chemical evolution is a continuing and commonplace occurrence in all parts of the cosmos. The basic constituents necessary for the emergence of life are universal. This implies that life should be widely distributed throughout the Galaxy, wherever conditions are clement, since the required ingredients of abiogenic processes are abundantly available everywhere.

7.3 Early Chemical Evolution on Earth

Chemical evolution refers to the period in Earth's history during which the chemical components on the surface changed from simple forms into complex substances from which the first living organisms - protobionts - could develop. The primary investigative tool in abiogenesis research has been the prebiotic synthesis experiment. Plausible primitive Earth conditions are arranged in a closed laboratory apparatus, and the changes that take place are carefully monitored.

The argument has long been made that since no geological record of the origin of life exists, the course of events leading up to the creative event is fundamentally unknowable. While most biochemists today would dispute this supposition, how close to reality are the simulated prebiotic experiments ?

It is unnecessary for scientists to heat together water, methane, ammonia and hydrogen (components of the primitive atmosphere), irradiate the mess with various forms of energy, and then sit back to wait for a recognizable lifeform to reach its slimy paw over the edge of the beaker and crawl out onto the lab desktop. We won't ever achieve this kind of completeness, because that takes evolution and the secret to evolution is time.[225] (But it has been seriously suggested that a complete artificial seashore be set up to test some of the proposed mechanisms in the origin of life.[1630])

From chemical equilibria we know the kinds of substances that had to be floating around in the primitive atmosphere and seas. Protein molecules ultimately consist of different combinations of only twenty different amino acids. Nucleic acids are composed of one of five bases, one of two sugars, and a single type of phosphate group. As Cyril Ponnamperuma of the NASA/Ames Exobiology Division once remarked : *"The alphabet of life is extremely simple; the wide variety of life observed today may be traced to a mere handful of chemicals."*[85]

Abiogenesis research differs markedly from most other scientific work, in that an unverifiable historical process is being reconstructed. It probably is not practical to run through an entire origin of life "from scratch," so different criteria must be used to evaluate hypotheses. For instance, postulates must at least be consistent with known astronomical, geophysical, and biochemical principles insofar as this is possible. And stepwise experiments, in which only one step of abiogenesis at a time is simulated, are reasonable if plausible and appropriate prebiotic conditions are maintained.

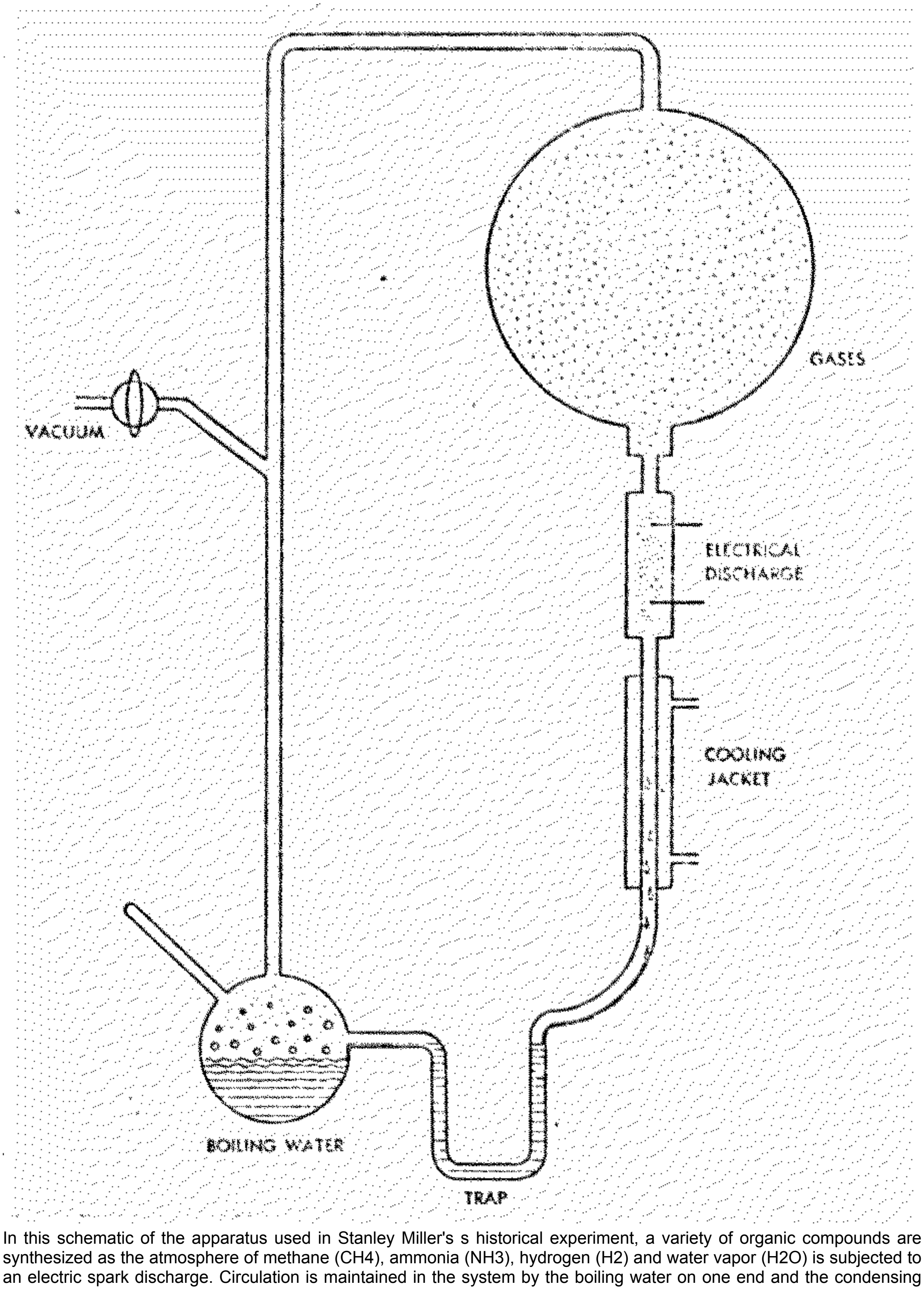
It is believed that the origin of life may have happened very fast, certainly less than a billion years[521] and possibly less than a hundred million years.[225,305,2160] Most estimates today place the creative event in the primitive seas, roughly 4.2 to 3.6 eons ago.

7.3.1 Prebiotic Synthesis

For many years it was known that mixtures of carbon dioxide, ammonia and water vapor would produce small amounts of simple organic chemicals if energy was supplied. But the results of these experiments were generally very discouraging and the yields miniscule under these oxidizing conditions. To originate life in such a poor, thin broth would be well-nigh impossible.

In 1953 a graduate student named Stanley Miller, working under Nobelist Harold C. Urey at the University of Chicago, constructed an apparatus to imitate the conditions of the primitive Earth (Figure 7.1). Previous investigators had always assumed the atmosphere to be oxidizing or neutral. Miller and Urey, following the suggestions of A. I. Oparin in the Soviet Union and J. B. S. Haldane in Britain during the 1920's, took the unprecedented step of devising a reducing environment instead.[2258]

Figure 7.1 Miller Apparatus for Prebiotic Synthesis[2315]



In this schematic of the apparatus used in Stanley Miller's s historical experiment, a variety of organic compounds are synthesized as the atmosphere of methane (CH_4), ammonia (NH_3), hydrogen (H_2) and water vapor (H_2O) is subjected to an electric spark discharge. Circulation is maintained in the system by the boiling water on one end and the condensing jacket on the ether.

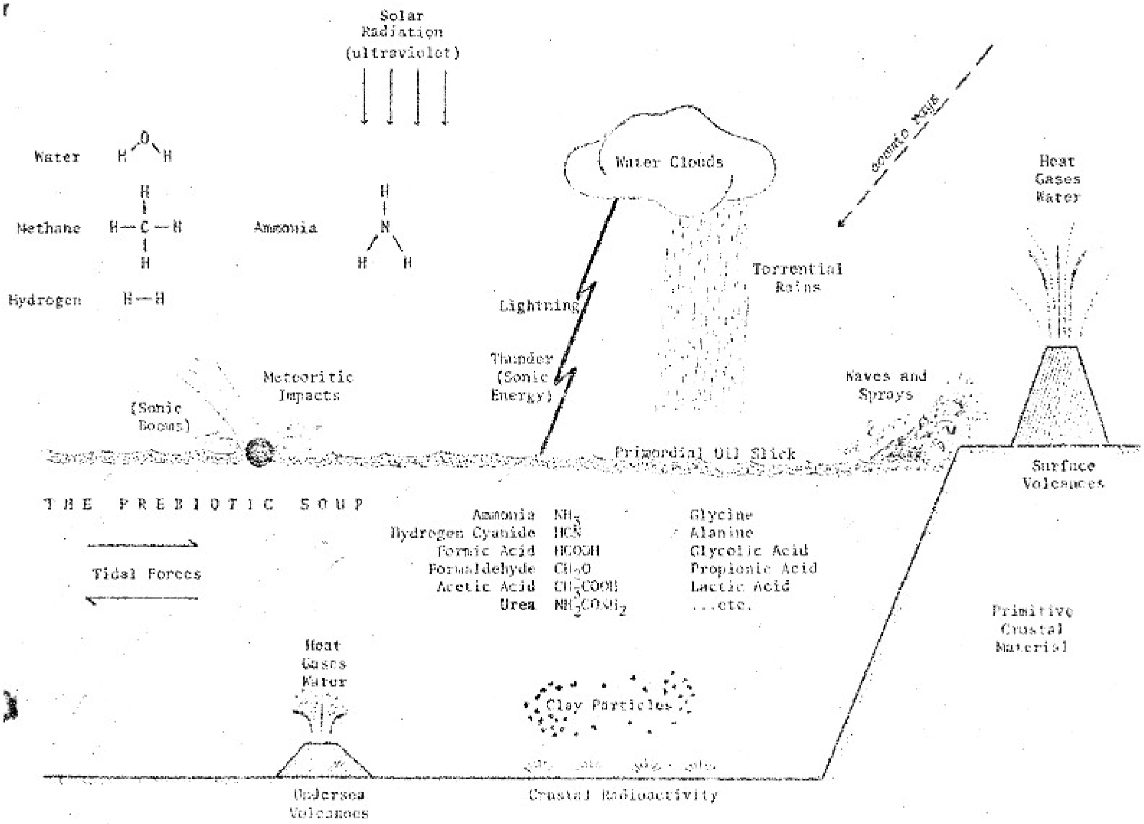
After one week of continuous operation, the water was removed and tested by paper chromatography. A great abundance of amino acids and other organics was detected.

Miller mixed together methane, hydrogen, ammonia and water, and carefully eliminated all oxygen from the system. This gaseous concoction was then circulated past an electric spark discharge, followed by a water bath to simulate the primitive sea. After about one week of continuous operation, the "ocean" had turned a deep reddish-brown.

The experiment was halted and the contaminated water removed for analysis. Miller discovered to his amazement and delight that many amino acids had been produced in surprisingly high yields. Two percent of the total amount of carbon in the system was converted into glycine alone. Sugars, urea, and long tarlike polymers too complex to identify were also present in unusually high concentrations.

Of course, electrical energy was only one of the many sources of energy available on the primitive Earth (Figure 7.2). In fact, ultraviolet radiation was probably the principle source: UV would have been able to penetrate to the surface be cause the protective ozone layer in the upper atmosphere did not yet exist. A Miller-type experiment using ultraviolet rays and a reducing atmosphere was performed in 1957 by the German biochemists W. Groth and H. von Weyssenhoff at the University of Bonn.[2307] Their results closely paralleled those obtained at the University of Chicago half a decade earlier.

Figure 7.2 Prebiotic Chemical Evolution on the Primitive Earth



Countless prebiotic simulations have since been achieved which confirm Miller's original conclusions. One bibliography, current through 1974, lists more than three thousand papers on the subject.[1679] An exhaustive treatment of all of them is clearly beyond the scope of this book, but the interested reader in encouraged to dive into the literature (Table 7.1).

Table 7.1 Summary of Prebiotic Synthesis Experiments through 1975

Table 7.2 lists the sources of energy believed to be present during the first eon or so of Earth's history. Ultraviolet radiation leads the pack. Carl Sagan and others have completed experiments with UV which seem to indicate rather high yields for prebiotic amino acids, the building blocks of proteins. Over the first billion years of chemical evolution on this world something like a hundred kilograms of amino acids per square centimeter may have been produced, resulting in a "soup" of about 1% concentration. This is the approximate consistency of chicken bouillon.

Table 7.2 Energy Available for Synthesis of Organic Compounds on the Primitive Earth

Source of Energy		Energy Available (joules/meter^2/year)
Solar radiation, all wavelengths		1.1×10^{10}
Ultraviolet,	1 < 3000 Ang	1.4×10^{8}
	1 < 2500 Ang	2.4×10^{7}
	1 < 2000 Ang	3.6×10^{6}
	1 < 1500 Ang	1.5×10^{5}
Electrical discharges		1.7×10^{5}
Decay of crustal K-40, 4 eons ago		1.2×10^{5}
(Decay of crustal K-40, today)		(3.4×10^{4})
Shock waves		4.6×10^{4}
Heat from volcanoes		5.4×10^{3}
Meteoritic impact		4.2×10^{3}
Cosmic rays		6.3×10^{1}

But ultraviolet radiation is a two-edged sword. While it may be the most abundant form of energy for molecule building, it is also the most destructive. Early researchers were concerned that organics would be destroyed as fast as they were created. Fortunately, the primitive oceans probably turned opaque like the brownish glop in Miller's apparatus rather quickly. Vital chemicals newly synthesized and carried a short distance beneath the surface of the soup by convection undoubtedly escaped decomposition.

Of the remaining energy sources, electrical discharge was the most potent. As much as 5-15% of the carbon in a mixture of methane, ammonia and water may be converted to amino acids and other organics by the energy of the discharge. Various forms of ionizing radiation give high yields as well. a particles, b particles, and g rays were common on the surface of the primitive Earth because of the presence of intense natural radioactive sources in the crust - such as potassium-40, thorium-232, and isotopes of uranium.

Volcanic heat was another prebiotic power supply.[2368,2380] It has been shown that lava-heated seawater and underwater volcanoes may be effective in producing biologically important compounds. Heat and sonic energy would have been released by infalling meteorites -- certainly a significant factor in the environment of the primitive solar system.[1417,2375] In fact, experiments performed recently by Bar-Nun and others have conclusively demonstrated that as much as 30% of the nitrogen in an ammonia atmosphere can be converted into amino acids in this manner.[315,1664,2375] Torrential rains have even been suggested as a possible source of energy for prebiotic synthesis, and experiments have shown that a flask of formaldehyde, allowed to stand for a few days at room temperature, will produce some simple sugars.

The great lesson appears to be that the exact nature of the power supply is relatively unimportant. Amino acids, sugars, and other chemical precursors to life probably arise on any planet possessing an initially reducing atmosphere and quantities of hydrogen, carbon, nitrogen and oxygen in gaseous reduced form - regardless of the particular source, or sources, of energy available.*

* Other factors may also be important. For instance, early-type stars (F) are more likely to emit ultraviolet radiation in copious quantities than are late-type stars (K, M). The speed of chemical evolution in primitive planetary environments may actually slow as we move from class F through classes G to K stars among habitable solar systems.