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Wondering about what it takes to make Earth a Habitable Planet

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Abstract
Life on Earth depends on many favorable factors that are related to cosmology, astrophysics, nuclear chemistry and physics, geochemistry, geology, chemistry, and biology. Most people take Life as we know it as a given, and do not think much about how it came about, and how precious Life on this planet Earth really is. This paper draws on the works by Wallace S. Broecker [1] and Langmuir and Broecker [2], as well as on other sources that provide a blueprint for addressing the question about how the raw materials and conditions came about to favor Life. It is meant to convey wonder and awe about how it all came together over billions of years that Life could get a foothold and flourish.

Key Word and Phrases
Space and Time, Big Bang, Cosmic Expansion, Nucleosynthesis, Neutron Capture, Formation of Galaxies, Suns, Planets, Supernovae, Water, Plate Tectonics, Planetary Fuel Cell, Volcanic Eruptions, Meteorite Impacts, nuclear Geyser, Organic Molecules, Self-assembly and Polymerization, RNA and DNA, Single Cell and Multi Cell Organisms, Evolution and Extinctions.

Quote
"The most beautiful thing we can experience is the mysterious. It is the source of all true art and all science. He to whom this emotion is a stranger, who can no longer pause to wonder and rapt in awe, is as good as dead: his eyes are closed."
― Albert Einstein.

1. Introduction

To better understand what it takes to build Life from scratch, one needs to view Life as a planetary process. Most importantly, one first needs to imagine the vastness of space and time, for both cosmic and nuclear scales. For example, the smallest building blocks of matter are 18 orders of magnitude smaller than human scales, while the oldest structures of the cosmos are 26 orders of magnitude larger. Distances in space are measured in Astronomical Units (distance to sun), parsec (1 pc = 3 light years), and light years, while the smallest scale is measured in attometer (10^{-18} m). Thus, to go from the smallest to the largest scale man studies covers 44 orders of magnitude. As an example of how confined mankind is to the solar system, the travel to the International Space Station (ISS) 400 km away, it takes about 1 day. The travel to Mars will take 7 months using current technology, and NASA's Parker Solar Probe to explore the sun's corona launched in 2018 arrived there in 2021. Thus, travel outside of our solar system would be immensely more challenging.

For this incredible journey from the big bang, the creation of atoms and molecules, galaxies, the Sun, planets, and primordial soup of simple organic molecules, their polymerization to biopolymers, and eventually to intelligent Life, took 13.8 billion light years. During this time, one can distinguish seven different stages in this evolution [3], whereby each state lasted millions and billions of years. Thus, for Life to have evolved, it needed lots of Time.

1. *Radiant Stage:* About 13.8 billion years ago, a Great Radiance (Big Bang) lit up our Universe [4], [5]. How do we know that the big bang happened? The evidence for this includes 1) the measured abundances of elements, 2) the observed expansion of space, and 3) the discovery of the cosmic microwave background radiation (C.M.B.), the radiation from a black body that currently has a temperature, T of 2.7 ^{o} K (3 x 10^{-4} eV, 7.35 cm wavelength). This temperature, T, of the background radiation can be obtained after adiabatic expansion of a boiling cloud for some 10^{10} years. When it was emitted after 380,000 of the big bang, T was 10^{13} ^{o} K or higher, calculated from

the equivalence of energy to mass times speed of light squared, mc^2, and thermal energy equal to Boltzmann constant, k, times absolute temperature, T, i.e., kT.

2. *Chemical Stage:* Within the first few minutes after the Great Radiance, protons, and neutrons, the building blocks for all chemicals, had formed, thanks to an imbalance or asymmetry of matter and antimatter particles. This has been explained by an initial asymmetry in quarks, the components of Baryons. Around 380,000 years after the Great Radiance, the Universe cooled enough to allow the first elements to form. This cooling allowed electrons to combine with nuclei to form the first hydrogen and helium atoms. As nuclei captured electrons, light was released.

3. *Celestial Stage:* Soon after the first gaseous elements formed, these gases began swirling into clumps of matter that would form a hundred million years after the Great Radiance, becoming stars, galaxies, supernovae, neutron stars and black holes. Finally, within galaxies, planets, and their moons formed, including Earth 4.5 billion of years ago.

4. *Biological Evolution:* About four billion years ago, Life began on Earth. How the first organisms emerged on Earth is still a great mystery. These first organisms were simple-celled organisms lacking a nucleus. Initiation of this process required RNA and DNA.

5. *Cooperative Evolution:* Over Time, simple life forms cooperated with other simple-celled organisms to become more organized, more complex, and more able to inhabit new environments. Cooperation occurs at the subcellular, cellular, organismal, and societal levels was important.

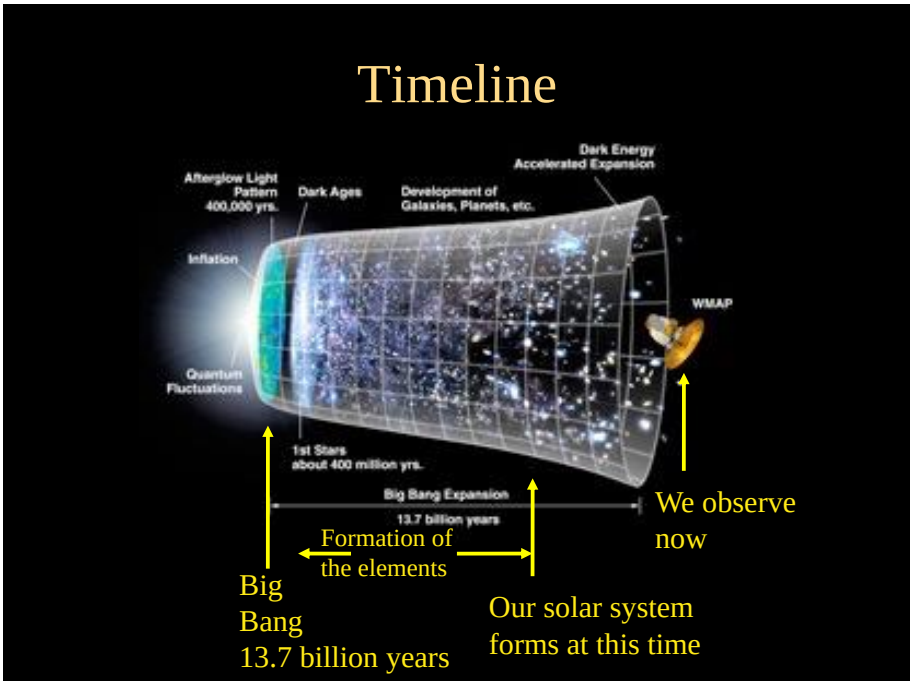


Fig. 1 Hot Big Bang [2]

6. *Cultural Evolution:* With the emergence of the prefrontal cortex a few millions of years ago, humans gained the power of words and language and the power to imagine the future before it happens.

7. *Enlightened Evolution:* While some people fear humans are near the end of evolution, others are more optimistic.

2. Formation of Atoms

Life forms contain most of the 92 naturally formed chemical elements we know about. The elements following uranium on the periodic table are only produced artificially. Thus, one first needs atoms to allow the formation of chemical compounds. While a few of these atoms originated in the Hot Big Bang 13.8 billion years ago (Fig. 1), the currently accepted hypothesis that describes the events forming the early Universe, all the others required other mechanisms. During cooling

and expansion of this early Universe, neutrons, protons, and electrons coalescence into hydrogen, H, and helium, He, the most abundant elements in the Universe. Nuclear reactions within stars and supernovas completed the periodic system of chemical elements that occur in the Universe. Nucleosynthesis involved three different modes: 1) primordial nucleosynthesis (e.g., H, He); 2) energetic particle (cosmic ray) interactions, i.e., spallation reactions (e.g., Li, Be, B), and 3) stellar nucleosynthesis (C and heavier elements). Specifically, the Hot Big Bang Fusion provided mainly H, He. The merging of Neutron Stars created up to U; the dying Low Mass Stars created Li, C, N, and Actinides; Cosmic Ray Fission created Li, Be, B; and Exploding Massive Stars: up to Rb.

These elements then coalesced into clouds, then stars and galaxies composed of stars; large stars evolved into supernovas, and from supernova debris, planet Earth thus formed 4.5 billion years ago. If we look at the element abundance in the Universe (Fig. 2), we find that H and He are dominating (>99%).

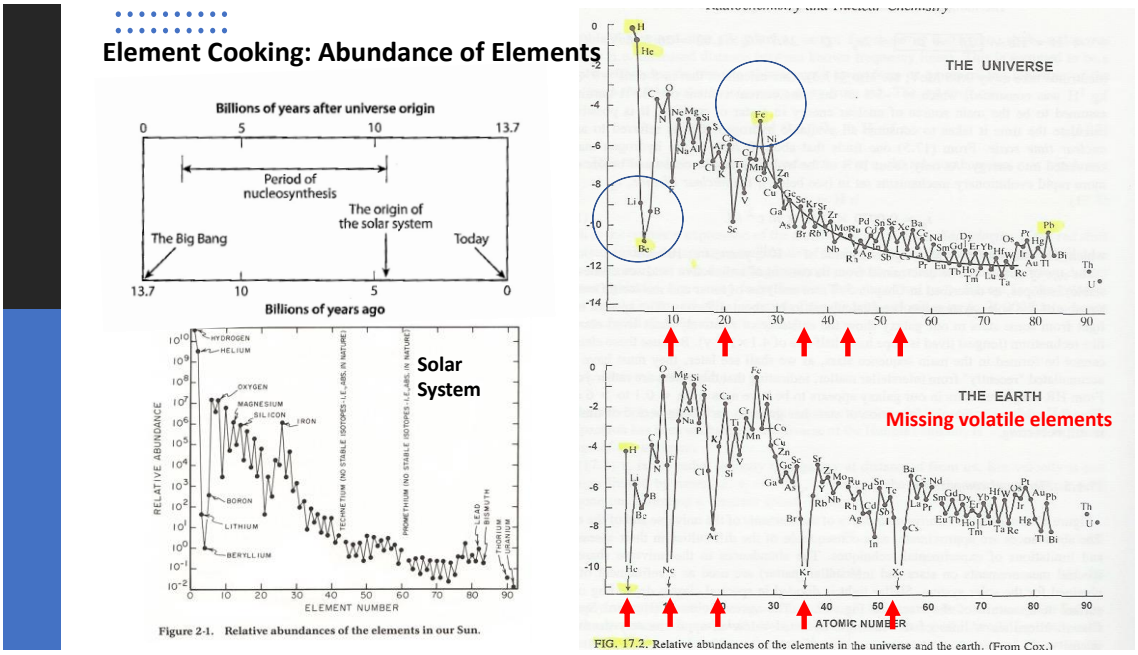


Fig. 2 Elemental abundances in Cosmos, Solar System, and Planet Earth

Nuclear Physics and Chemistry can explain the relative abundance of elements that decreases rapidly with increasing atomic number, Z; a pronounced abundance peak is at Z=26 (Fe), and minor peaks at Z=6,8 (C, O). Elements with even Z are more abundant than those with uneven Z. Isotopes with masses (A=Z+N) of multiples of 4 have the highest abundance indicating the fusion of 4 He-atoms. For isobars lighter than A of 70 or greater than A of 70, there are opposite patterns of stability concerning proton to neutron, Z/N, ratio indicating two different modes of elemental synthesis. Elements with N or Z values close to magic numbers (e.g., 2, 8, 20, 28, 50, 82, and 126) are more abundant than their neighbors.

Surprisingly, atoms in the known Universe only make up a small fraction, i.e., about 4%, of the known Universe, with 25% composed of Dark Matter. Energetically, the remainder, i.e., 73 %, is composed of dark energy. Our understanding of dark matter (deduced from extra gravitational pulls in galaxies) and dark energy (deduced from the accelerating expansion of the Universe) is, however, still evolving.

3. Creation of the Sun and its Planets

Life would not be possible without our Sun and its planets. Our solar system formed about 4.5 billion years ago from a dense cloud of interstellar gas and dust. The cloud eventually collapsed, possibly due to the shockwave of a nearby exploding star called a supernova. When this dust cloud

collapsed, it formed a solar nebula, i.e., a spinning, swirling disk of material. Our sun is a small star, powered by nuclear fusion of H into He in its core, emitting intense radiation to its planets. While the Sun heats Earth from the outside, radioactive decay of U, Th, and K isotopes in Earth's interior heat the it from the inside, allowing plate tectonics and an interior magnetic geodynamo that shields us from damaging cosmic radiation. Solar radiation also drives weather, ocean currents, seasons, and climate on Earth, and makes plant life possible through photosynthesis.

4. Importance of Natural Systems

Life is embedded into various nested natural systems, such as the Cosmos, Earth, Ecosystems, Mankind, Human Physiology, etc. As Natural Systems, they are:

- In movement: e.g., the plates, mantle, core, atmosphere, ocean.
- Sustained by external energy source and energy flow through system, e.g., external heating by the Sun and internal heating by radioactive decay of U, Th, K isotopes.
- Matter cycles through the system, providing sustainability through recycling that redistribute chemical elements on the surface of the Earth.
- System maintained over a narrow range of states that are usually at "steady state disequilibrium": e.g., temperature.
- Feedbacks operate to sustain these steady-state conditions: e.g., temperature.
- Almost all systems are nested with a larger and smaller scale systems: e.g., solar, climate, eco-systems
- There is change with time – creation, long-term evolution, and eventual death.

5. Importance of Water

Complex life forms would not have evolved without just the right amounts of water, not too much nor too little. Without that, Earth would not be habitable. Water likely came from asteroids falling on Earth (deduced from stable isotopes) as water from early Earth would have evaporated as it was too hot. The current amount (mean depth of 4km) of water and ocean area (70% of Earth) is just right for Life to develop because it also drives mantle convection, as water lubricates tectonic plates and influences rock viscosities and melting processes and slows down seismic waves. Importantly, water is highly abundant in the cosmos, and has exceptional properties among the hydrides of O, S, Se, and Po, in that due to its polarity; water is an excellent solvent for all sorts of constituents, has a high freezing and boiling point due to high heat of fusion and vaporization, has a density that is lower in its solid than in its liquid form, and is liquid in much of the range of biologically significant temperatures. Again, without these unique properties, Life as we know it would not have been possible.

6. Importance of an Atmosphere

Life would also not exist without Earth having an atmosphere. Earth's early atmosphere was composed of gaseous carbon dioxide, CO_2, nitrogen, N_2, and water vapor, providing a comfortable temperature of 286 K (14 ^oC), because of the greenhouse effect by CO_2, and H_2O. Without an atmosphere, Earth's temperature would be only 255 K (-18 ^oC); thus, all water would be frozen.

7. Kickstarting Early Life Forms

But how exactly was Life started? Simple organic molecules are abundant in the Universe, and asteroids could have seeded Earth early on. Organic molecules (amino acids (L-alanine), carboxylic acids (propionic acid), hydroxyacids (lactic acid), sugar-related compounds (dihydroxyacetone), amines (propylamine), amides (pyroglutamic acid), nitrogen heterocycles (uracil), sulphur heterocycles (benzothiophene), aromatic hydrocarbons (2-methylnapthalene), and most importantly, all RNA/DNA building block molecules are found in comets derived from the interstellar clouds from which the solar system was formed. However, the concentrations of these organic monomers was likely not high enough to allow self-assembly and polymerization. For that, one would need suitable conditions on Earth. As reviewed by Maruyama et al. [6], early Life forms could have originated a number of different ways, with likely only one place that fulfills all the

necessary pre-conditions. Proposed sites for the birthplace of Life on Earth include (Fig. 3): (1) Classic concepts, including Darwin's warm little pond [7] with a primordial soup or a shallow marine tidal flat [8], (2) Panspermia [9] or Neo-Panspermia [10], (3) Mars [11], (4) a mid-oceanic ridge hydrothermal system [12] or in an alkaline hydrothermal vent [13], (5) a hydrothermal environment with island arc volcanoes [14], and (6) a nuclear geyser system on the Hadean primordial continent [15]. A primordial soup containing organic molecules, while originating several different ways, required several different factors for efficient self-assembly and polymerization to occur. According to [6], the 9 requirements for early life forms to originate include:

1. Energy source (ionizing radiation and thermal energy). One of the most critical conditions is energy density to promote prebiotic chemical reaction between thermodynamically stable substances such as N_2, H_2O, and CO_2.; early Earth contained high concentrations of Uranium., with equal amounts of non-fissionable ^{238}U and fissionable ^{235}U. Natural reactors existed on earth (e.g., Oklo Reactor, ~ 2 billion years ago). One may assume that when ^{238}U ($t_{1/2}$= $4.5x10^9$ y, 99.27%)) was formed during the genesis an equal amount of ^{235}U ($t_{1/2}$ = $7.04x10^8$ y, 0.72%) was formed. Ionizing radiation by U ores ore have a high enough energy density to promote polymerization reactions (through radicals production). Even though the decay of ^{235}U has been regarded to be deadly for life, there are many radiation resistant bacteria even on modern Earth.

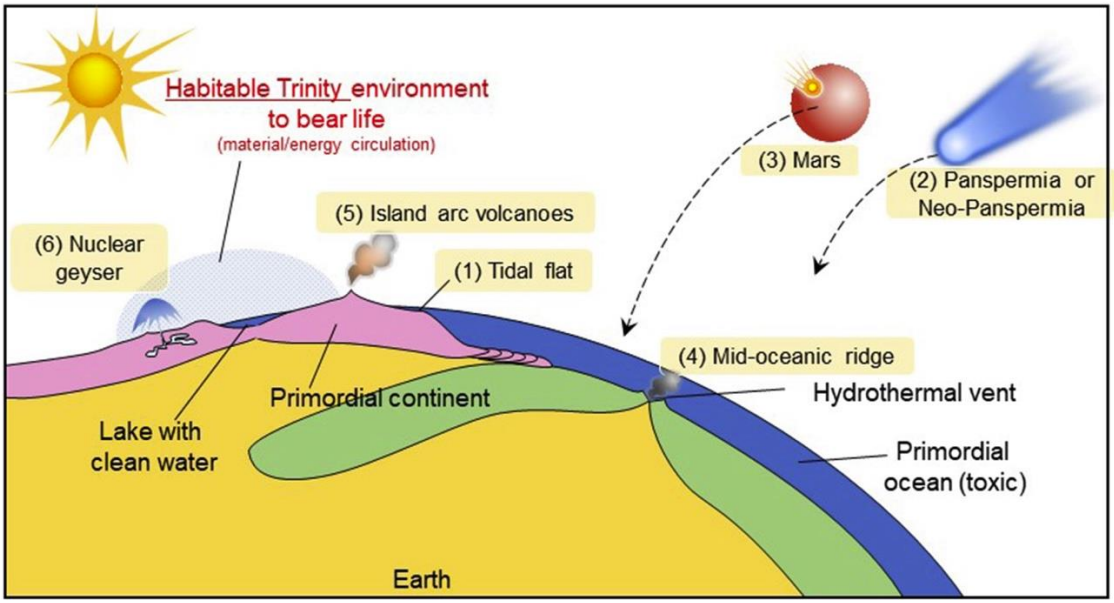


Fig. 3 Sites for the birthplace of Life on Earth [6]

2. Supply of nutrients (P,K, KREEP {KREEP is an acronym built from the letters potassium, K, REE (rare-earth elements)} and P (for phosphorus), geochemical components of some lunar impact breccia and basaltic rocks. etc.);

3. Supply of Life constituent elements (C, H, O, N), mobilized from leaching of rocks;

4. Concentration of reducing gases, e.g., H_2;

5. Dry/wet cycle to allow protein folding reactions;

6. Na-poor water (modern cell cytoplasm is extremely poor in Na, while conversely, it is enriched in K, and also enriched in phosphate). This indicates that the first cells originated from highly reduced conditions that were highly depleted in Na^+ ions and conversely enriched in K^+, Zn^{2+} and Mn^{2+}.

7. Non-toxic water environment, as the early ocean had low pH and high metal concentrations;

8. Diversified environments with changing conditions (Ocean: pH, salinity, heavy metals, atmosphere: temperature & pressure, continent: varied geology);

9. Cyclic change. According to Maruyama et al. [6], only the hydrothermal geyser system

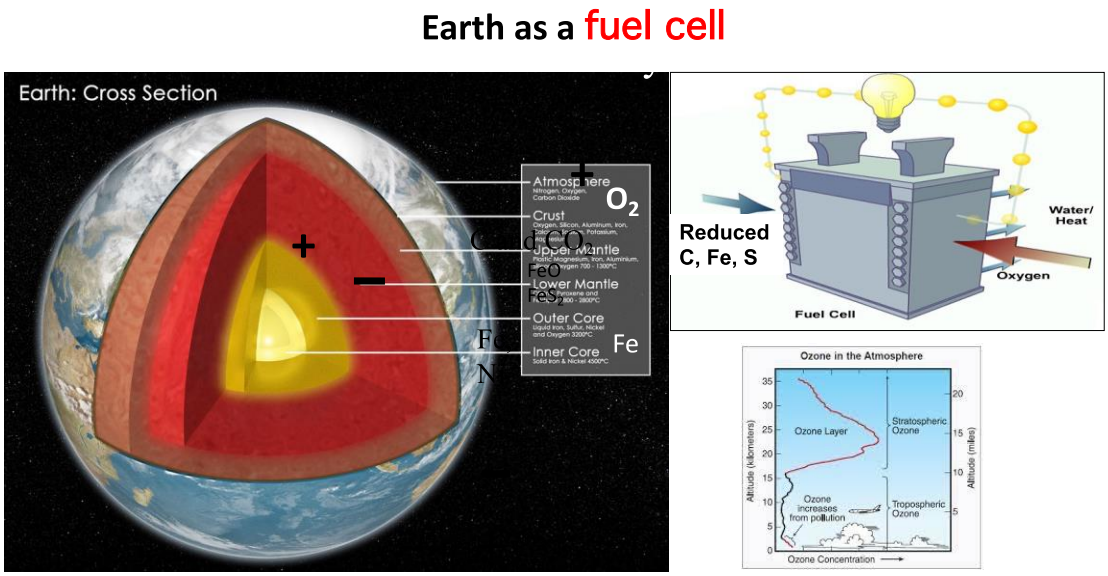
fulfills all these requirements.

The creation of more complex molecules from simple monomers is challenging. While Earth was in a "reduced" state for many millions of years, there was no oxygen, and little energy potential for creating early life forms. The earliest evidence of microfossils dates back to about 3.5-4 billion years ago. Thus, it took many millions of years for simple cells, i.e., protocells, to form from micelles containing lipids, proteides, and carbohydrates. As will become evident, biological evolution was completely coupled with planetary evolution. Over time, Earth became energized by photosynthesis and formed a "planetary fuel cell" (Fig. 4) with a reduced core and oxidized crust and atmosphere.

This then permitted advanced life forms to develop. Up to the present day, all human civilization depended on exploiting this fuel cell that has developed over billions of years of planetary evolution.

8. Importance of Earth as a Fuel Cell

Life is an electric current that makes organic carbon and an oxidized complement; this charges the fuel cell. Once we have the building blocks of polysaccharides, proteins, enzymes, and RNA, self-assembly and polymerization becomes possible. Self-Assembly followed by polymerization of building blocks that form lipids, proteins, enzymes, and subsequently, RNA and DNA to create single cell organisms required mineral surfaces such as clays. In addition, the invention of DNA required the appearance of enzymatic activities for both syntheses of DNA precursors, retro-transcription of RNA templates, and replication of single and double-stranded DNA molecules, mutations, and horizontal gene transfers, cooperation, as well as competition among species. Evolution, as a self-sustaining process, followed this blueprint over billions of years.



→ **Permits far greater energy flow than earlier in Earth history**

Fig. 4 Planetary Fuel Cell (modified from [2]).

9. Series of Energy Revolutions

From thereon, Lifes's transformation of the surface is marked by a series of "energy revolutions ."1) Eat what the planet makes available from 3.5 to 4 billion years ago; 2) Make your food using sunlight (started ~ 3.4 billion years ago); 3) Photosynthesis (started ~2.6 billion years ago, Fig. 5), but this makes the poisonous pollutant oxygen, O_2; 4) Use the O_2 for "aerobic" respiration since then.

These three energy revolutions include:

1. *Chemoautotrophs:* $CO_2 + 4H_2 = CH_4 + 2H_2O$

2. A) *Photoautotrophs*: $12\ H_2 + 6\ CO_2 + hv = C_6H_{12}O_6 + 6\ H_2O$ (hv = solar energy)

   B) *Oxygenic Photosynthesis*: $6\ CO_2 + 12\ H_2O + hv = C_6H_{12}O_6 + 6O_2 + 6\ H_2O$

3. A) *Anaerobic respiration*: Glucose = CO_2 + Ethanol + 2 ATP (energy-rich molecule)
B) *Aerobic respiration*: Glucose + O_2 = CO_2 + H_2O + 36 ATP
Aerobic respiration was thus able to provide a much higher amount of ATP, an energy rich molecule, allowing more efficient cellular processing.

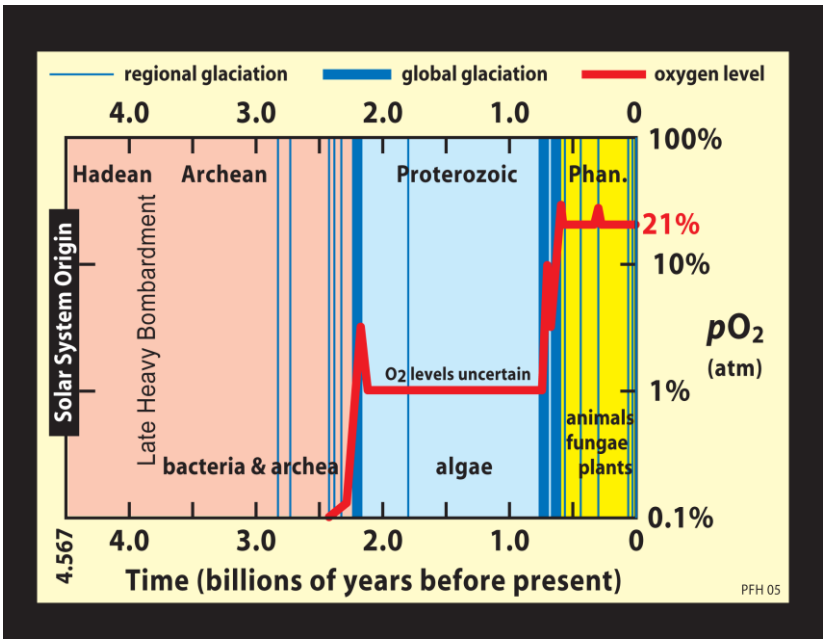


Fig. 5 Postulated rise in atmospheric oxygen over geologic Time and its relationship to ice ages (blue bars) and biospheric evolution [16]. Third Energy Revolution: Respiration using oxygen, allowing the full potential of aerobic respiration requiring high O_2, allowing a planetary transformation to a fully activated fuel cell. O_2 in the atmosphere also allowed the Ozone layer to form, drastically reducing UV radiation harmful to Life.

10. Importance of Catastrophic Events

Importantly, the appearance of new species is only one half of the evolution story. "Catastrophic" events have modified the evolution of Life (Fig. 6).

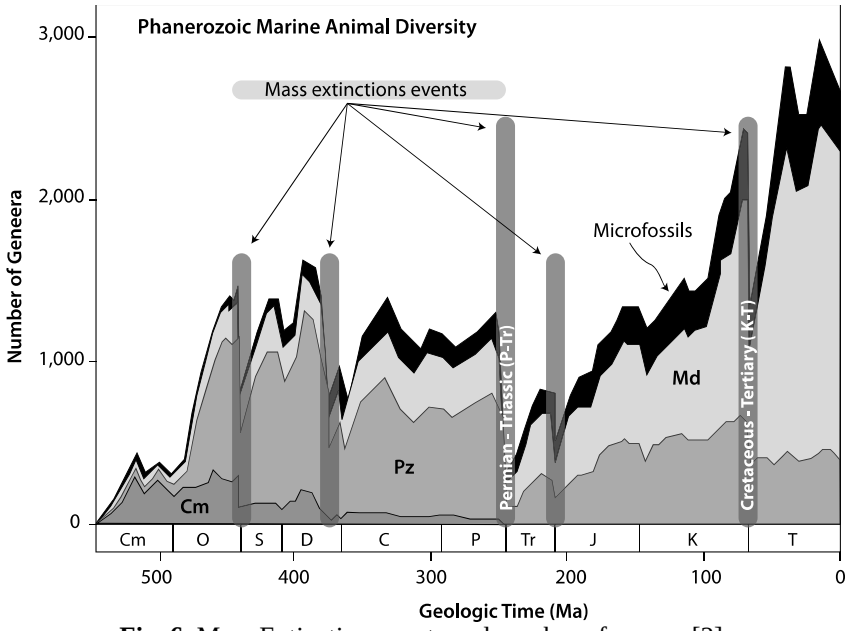


Fig. 6 Mass Extinction events and number of genera [2].

The origination of species was very gradual, occurring with small changes over long time scales leading to separate species, interrupted by abrupt extinctions that eventually led to homo sapiens on Earth. Apart from mass extinctions, the mean Life of species is about 10 million years, with 99% of species turnover every 43 million years. Over several mass extinctions, up to 75% of species became extinct, and new life forms proliferated and became dominant.

11. Summary and Outlook

As was documented by [2], and discussed here, the origin of Life is a Planetary Process. Multiple environments over long periods of time and changing conditions are likely to have been important. Many of these environments of the ancient Earth might not have modern analogs. Many of the processes may have occurred before the existence of a rock record, leaving significant uncertainties and potential speculation. It may be that the energetic imperatives and characteristics of molecules permit a few avenues to Life.

C, H, O, and N, are four of the most abundant elements in the Universe that can form organic molecules. Organic molecules are everywhere in the interstellar clouds from which solar systems are formed, e.g., in comets and asteroids. One successful replication in millions of years "wins" and made Life possible. Time is certainly on the side of Life. Life increases the overall entropy production (even though for an organism, entropy decreases), therefore, is energetically preferred. The discovery of any one avenue to Life shows that the origin of Life is a natural and, possibly, a typical planetary process. However, Life on our planet took billions of years to evolve, until it became a self-sustaining process. There is no plan B and no planet B. Our future is here, and humanity is at a crossroads with the event of the climate crisis, acidification of the ocean, and global change that is now evident everywhere we look.

And it's not just global warming. The scarcity of water and food resources have become a major problem, apart from biodiversity, that will only become worse with time. Migration of species, including man, is a consequence of that. Wars are another consequence of that, e.g., in Syria and elsewhere. We already live on the edge of extinction of multiple species. One might ask if this will make room for more intelligent Life on Earth? The relationship between humans and the planet is now a central question of our Time. Recalling our unique place in this Universe can only inspire wondering, awe, and appreciation of where we came from and how we are related. This should be a major factor in guiding our lives.

12. Acknowledgements

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