

Advanced Track, Epoch 5

Chemical Evolution

This Advanced Track provides a technical supplement to the introductory web site on cosmic evolution, produced by Eric Chaisson and based on courses taught mainly at Harvard University for the past few decades:

http://www.cfa.harvard.edu/~ejchaisson/cosmic_evolution/docs/splash.html

Currently, this Advanced Track is abbreviated while addressing mainly the concept of energy rate density—a numerical quantity proposed as a useful complexity metric for an underlying, unifying process that guides the origin, evolution, and destiny of all organized systems across the arrow of time, from big bang to humankind. In the summer of 2014, this supplement will grow dramatically, providing much more pertinent technical material at an advanced, quantitative level (suitable for colleague scientists and graduate students) well beyond that presented in the above-linked introductory web site (which is meant for non-scientists and beginning students).

A summary of this Advanced Track is here:

http://www.cfa.harvard.edu/~ejchaisson/advanced_track_sitesum.pdf

Further material related to the subject of cosmic evolution is available at:

<http://www.cfa.harvard.edu/~ejchaisson>

including a collection of recent research papers easily accessed and downloadable at:

http://www.cfa.harvard.edu/~ejchaisson/current_research.pdf

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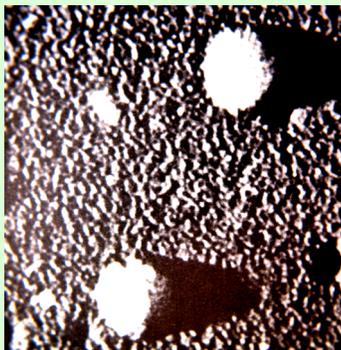


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Cosmic Evolution

Chemical evolution is a subset of the larger category of physical evolution, which is itself part of the grand scenario of cosmic evolution:

Cosmic evolution = **physical evolution** + biological evolution + cultural evolution.

During this fifth, chemical epoch, energy rate density, Φ_m , averaged between tens to hundreds of erg/s/g, as life began to emerge as animate structures on Earth.

Emphasizing Energy Flow

Energy is at the core of our study of cosmic evolution, but not just energy. Energy *flow* needs to be stressed, for without flow nothing much happens. Cosmic evolution is an active process that relies heavily on change; to be intentionally redundant, it is an *evolutionary* process. And there is probably no better example of the multifaceted dynamical flow of a system's energy than in our own biosphere, where the incoming Sun's rays (and its entropic tendencies) mix materials on Earth more thoroughly than might be imagined. Geologists have estimated that if a single thimbleful of H₂O were poured into a river, after only a few years the circulation on a global scale would be so complete that a similar thimbleful of H₂O taken from anywhere on Earth would contain some molecules from the original thimble. Others have expressed much the same idea regarding atmospheric circulation by estimating that every breath of air we inhale contains molecules that were once breathed by Galileo, Aristotle, and the dinosaurs.

That's mixing; that's entropy—the propensity to equalize, to achieve the lowest energy state, to spread things around evenly, in short to reestablish equilibrium at any and every opportunity. Water, air, and other climaspheric cycles can be very effective in redistributing energy and resources, some of the cycles impressively self-sustained when powered by

energy, all in accord with the 2nd law. Yet life itself defies the normal entropy degradation of the world around us; ironically, both Earth's life and Earth's pollution derive from the same principles of thermodynamics. The act of living is akin to an intermediate, improbable enterprise precariously balanced between the energy source (mainly) in the hot Sun and the energy sink in the cool Earth, and ultimately in cold, empty space beyond. Again, as for all open systems, it is not energy as such that makes life go, but the flow of energy through living systems.

Pre-Cellular Evolution

Primordial Earth was surely too hot for amino acids and nucleotide bases to survive; there were no hiding places then—no cool lithosphere, no dark hydrosphere, no protective atmosphere. Remarkably, however, as soon as our planet cooled enough for rocks to form, energy sources to diminish, and the atmosphere to thicken, life arose. Geological dating by radioactive means and paleontological observations of deposited strata reveal that the oldest rocks solidified ~4 Gya, primitive cellular life appeared probably ~3.8 Gya, and early life began to express its main metabolic function as long ago as ~3.5 Gya (Schopf, *Cradle of Life*, Princeton U Pr, 1999). If life did emerge indigenously on primitive Earth (as opposed to arriving intact from space)—and almost all working scientists agree that it likely did—then it must have done so as soon as it was chemically possible. The gap between the oldest fossils and the oldest rocks grows smaller with each new discovery, the implication being that the pre-cellular phase of chemical evolution must have been astoundingly rich in invention and innovation, much as biological evolution has subsequently produced a cornucopia in number and diversity of species in more recent times. The difference is that biological evolution leaves a record preserved in the rocks, whereas chemical evolution does not.

The Advanced Track for the PARTICLE EPOCH encapsulates how physical phenomena and environmental conditions can tease order from chaos, and not merely regarding inanimate objects. Impressive amounts of order emerge in laboratory experiments that simulate primeval Earth and the production of life's building blocks, often with the aid of agents that constrain chance. Catalysts, for example, play prime roles in governing the rates at which molecules react, thereby removing some of the randomness, either in the test-tube simulations of life's origin or among today's evolving life forms. Fine-grained mineral clays, with

their crystalline structures and "lock-and-key" surface geometries, could well have acted catalytically on early Earth, collecting certain small molecules and not others, thereby guiding them to interact and combine into larger ones. Clays are remarkable substances made of microscopically thin plates with H₂O-seeking chemicals on each side. The clays' ions preferentially attract matter around them to react in specific, non-random ways; clays can also act as desiccators, removing H₂O to allow larger molecules to assemble from smaller fragments. Such catalytic agents would have then likely operated selectively during chemical (*ie*, pre-biological) evolution long ago, an integral part of the more inclusive cosmic-evolutionary scenario.

Chicken or Egg?: In that hazy interface between life and non-life, a kind of natural selection—to distinguish it, let's call it chemical selection—was likely as important then, at the dawn of life, as in biological evolution now. Chemical selection doubtlessly rewarded reaction pathways and cycles that remake moderately sized molecules needed in the further synthesis of increasingly complex organic products, thus speeding reactions that would otherwise proceed sluggishly in the dilute, pre-life environment. Such so-called autocatalytic cycles, acting like positive feedback loops, and especially integrated sets of these cycles, termed "hypercycles," can increase catalytic efficiency and specificity in the production of key polynucleotide and polypeptide sequences. In this way, chemical selection could have regulated reaction pathways, choosing some while rejecting others, thus making molecules capable of cyclical replication even before a primitive metabolism arose. (Eigen, *Steps Toward Life*, Oxford U Pr, 1992).

Today, we would surmise that if one product among a mixture of possible products displays autocatalysis, then the chemical reaction producing it is favored over other possible courses of reaction. Pre-Darwinian selection would have provided a dose of determinism, which, when working alongside chance, might well have created molecules resembling (or equal to) the guanine, cytosine, adenine, and uracil bases comprising RNA—molecules capable to replication thanks to base pairing, whereas molecules with other bases unable to engage in base pairing were non-randomly eliminated. Not far behind would have been the replicating DNA ancestors of all living things, again the result of Darwinism among the molecules. If so, then the roots of life indeed penetrated the realm of non-living matter. These speculations are based mostly on mathematical models

of feasible chemical routes available to primitive molecules on early Earth, and are favored by theorists like Eigen (above reference) who argue that "selection does not work blindly . . . [rather] it is highly active, driven by an internal feedback mechanism that searches in a very discriminating manner for the best route to optimal performance"

By contrast, many empiricists, informed more by laboratory experiments, argue that the emergence of metabolism more likely preceded replication. And in modern organisms, metabolism (comprising cell structure, boundary membrane, and enzymic activity) is strictly dependent upon the existence of proteins. Actually, it is not only experimentalists who generally favor metabolism first. At least one noted physicist (Dyson, *Origins of Life*, Cambridge U Pr, 1985) has proposed a theoretical model for 2 origins of life, once with cells and later with genes, stressing diversity and error-tolerance as life's salient characteristics. Yet it is the experimentalists, mostly, who maintain that semi-permeable membranes—the border between cells themselves and their immediate tissue environment governing the 2-way transport of small molecules—must have been an essential prerequisite for any early replicating molecules, lest they have no stable locale, or discrete unity, for the concentration of cells' chemical components.

Lab simulations of life's origin that go beyond the simple Miller-Urey-type syntheses demonstrate that, with energy easily accessible on primitive Earth, amino acids concentrate further into ~2- μ m-diameter "proteinoid microspheres," which are essentially organized, organic condensates displaying a remarkable kind of cell-like metabolism—and at least a mechanical form of simple replication (Fox, *The Emergence of Life*, Basic Books, 1988). One of the recurrent criticisms of these advanced experiments, however, is that such polymerization requires the initial amino-acid mixture to be heated to $T > 373$ K; yet now that geothermal vents (*cf*, Advanced Track of PLANETARY EPOCH) have become leading environmental contenders for the onset of life, this liability might be an asset. Although these microscopic condensates are not true proteins in the sense of having biological activity, it would seem that Nature is playing a malicious joke on us if they are not at least examples of organic clusters somewhere on the chemical-evolutionary road to life. The question remains: Which came first, naked genes or protobionts?

Considered by some a procedural compromise yet by others an experimental breakthrough, an "RNA world" on early Earth seemingly solves this chicken-or-egg

dilemma by asserting that primitive ribonucleic acid acted as both replicator *and* catalyst; such a "ribozyme" would have performed double duty by storing genetic information and catalyzing its own replication. RNA molecules that can catalyze biochemical reactions are known to exist (Cech, *Ann Rev Biochemistry*, v59, p543, 1990), and the chemical evolution of these ribozyme molecules could have been subject to selective pressure, including an ability to hydrolyze compounds faster, given variations among early RNA sequences on Earth billions of years ago (Gesteland, *et al*, *The RNA World*, Cold Spring Harbor Laboratory Pr, 1999). Eventually, if correct, that RNA world somehow collapsed or evolved into one obeying the central dogma of modern molecular biology: DNA \leftrightarrow RNA \rightarrow protein (the arrows signifying transfer of biological [genetic] information, not chemical reactions), the last of which often act as catalysts in today's living systems. Whether ribozymes self-polymerized the first long nucleotides and eventually life itself, or enzymic proteins emerged alone (perhaps in hydrothermal sites), or even whether clays or other environmental catalysts acted as templates for life, remains unknown (Shapiro, *Origins*, Summit Books, 1986).

The origin of life, along with the origin of galaxies, represents the two chief missing links in all of cosmic evolution.

Thermodynamics of Pre-Life

We return now to consider thermodynamics again, as we almost always do in complexity analyses. Energy flow was an inevitable result of the non-equilibrium conditions needed for either route toward life, the central role of which has been clear to biophysicists for decades (Morowitz, *Energy Flow in Biology*, Academic Pr, 1968). The source of that energy supplied to any pre-life system could have taken the form of solar radiation, atmospheric lightning, shock waves, energy-rich chemicals, geothermal heat, or any combination of these or other suitable sources undoubtedly available on early Earth ~4 Gya. Most likely, gradients and flows would have pooled resources to organize both replicating and membrane molecules among effusing protocells, after which chemical selection presumably favored autocatalytic cycles capable of making products that can capture and store information in macromolecules. Here, then, is also the beginning of ecology, which seeks to place life into the general context of environmental energetics.

The chemical evolutionary steps that led to the origin of cells follow, in the main and in principle, a straightforward sequence: acids and bases → proteinoids and polynucleotides → protocells and life. In practice, this sequence does indeed seem to occur, and straightforwardly and rapidly at that, each of the open systems along the way consuming more energy (per unit mass) and thus growing in complexity. Provided the energy is nurturing (*ie*, within optimal ranges), the ingredients appropriate, and the environment protective, organic molecules increasingly self-assemble, or self-organize, into cell-like blobs, much as hypothesized for the origin of the first cell by biologist George Wald (*Scientific American*, v191, p44, 1954) in a classic paper of nearly a half-century ago. All of which brings to mind another pioneer, Louis Pasteur, who posed his famous, lingering question during a theatrical lecture in 1864 at the Sorbonne, where he disproved the popular 19th-century doctrine of spontaneous generation as viable for life's origin: "Can matter organize itself?" As for galaxies, stars, and planets, the answer for life forms is apparently in the affirmative—self-assembly, yes, but not without energy flowing.

The energy of synthesis for a few representative biomolecular building blocks will further our case, each of them members of the group of 20 amino acids comprising the protein machinery that executes essentially all the functions involved in life as we know it—storing and transferring matter, energy, and charge, performing catalysis, controlling reactions, and acting as the DNA-determined and covalently linked substances of all organisms. Glycine (CH₂NH₂COOH), with a molecular weight of 75 amu (1.2×10⁻²² g) and the simplest side chain of a single H atom, requires ~370 kJ/mole; lysine, a somewhat more complex amino acid with a weight of 146 amu and a linear side chain of one N and four C atoms, requires 1530 kJ/mole. Not surprisingly, the energy needed to fashion even these simple molecules is proportional to the complexity of their being.

Controversial though they may be, the proteinoid microspheres noted above would have been among the most elementary life-like systems. These alleged protocells contain no recognizable proteins as such, but they do harbor collections of myriad protein-like polypeptides, and evidently utilize energy flows in accord with their degree of complexity. For example, a rough estimate of Φ_m for a 2 μm -diameter (*E. coli*-sized) microsphere harboring typically 10⁻¹¹ g of synthesized organic polymers yields ~200 erg/s/g. This

value assumes an energy flux of 400 erg/s/cm², which is typical of that for undersea geothermal vents, although high for a single atmospheric electrical discharge or for solar UV radiation reaching Earth's surface (shortward of the 2500 Å^o) wavelength needed to break and reform, for example, O-H, C-H, or C=C bonds of ~10⁻¹¹ erg, or ~5 eV, each, and suitably corrected for 1/3 less solar luminosity reaching early Earth in primordial times (*cf*, Advanced Track for STELLAR EPOCH). Admittedly, the energy input is not well known as we are still uncertain what event really did trigger the origin of life. It is unlikely that any single source of energy could account for all the organic compounds on primitive Earth, but this broadly representative value of Φ_m does put it in a reasonable range midway between the complexity of embryonic Earth ($\Phi_m \sim 10$ erg/s/g—*cf*, Advanced Track for PLANETARY EPOCH.) and that of photosynthesizing plants (~900 erg/s/g—*cf*, Advanced Track for BIOLOGICAL EPOCH.).

We are crossing the interface between chemistry and biology, indeed between astronomy and biology, and our proposed synthesis, broadly construed across all complex systems and predicated on energy flows, seems to be holding up.

Cellular Metabolism

Energy-flow diagnostics show a disconcertingly wide range of Φ_m values when analyzing contemporary unicells, the smallest and simplest entities (save viruses) that everyone would agree are definitely alive. We seek to characterize how energy is used for synthesis and transport of molecules, for performance of functional work, and for reserve of storage in energy-rich molecules, among other tasks—energy acquired, energy expressed, and energy stored. Surprisingly, a hugely diverse array of single-cell types and actions confront us, making even back-of-the-envelope calculations tricky; sizes and shapes of single cells vary greatly, as do their metabolic and reproductive rates, for there is no idealized, textbook cell. Some bacterial cells (such as *pneumococcus*) are as small as 0.2 μm in diameter and 10⁻¹⁵ g in mass, compared to typical liver cells that measure a hundred times as large and nearly a million times as massive; nerve cells can be longer than a meter and appropriately more massive still.

Metabolic rates for cells can also span many orders of magnitude, making consequent values of Φ_m cover a spectrum so wide as to make it difficult to find a typical, modern cell, let alone a primitive one that might

have eked out a living on early Earth. For example, a single, 5- μm -diameter cell of a plant algae takes in $\sim 10^{-15}$ mol/s of CO_2 while photosynthesizing a mass of $\rho V \approx 10^{-15}$ g, and it typically requires 10^{-9} W of solar energy to do it, yet it converts solar to chemical energy with a low efficiency of $\sim 0.1\%$ (cf, Advanced Track for BIOLOGICAL EPOCH); thus $\Phi_m \approx 10^3$ erg/s/g characterizes the simplest system undergoing photosynthesis.

Likewise, the common bacterium, *E. coli*, a 2- μm -diameter microorganism about which perhaps more is known than any other unicell, can replicate as quickly as 3 times per hour under maximally robust (37.5°C, or 310.5 K) conditions, such as a delicious nutrient broth in a warm Petri dish or the cozy gut of a healthy human; its metabolic rate can be approximated knowing that laboratory studies show 0.015 erg of heat associated with the biosynthesis of each microorganism (2×10^{-12} g) of *E. coli*, so that when normalized to its peak 22-minute reproductive cycle we find $\Phi_m \approx 10^6$ erg/s/g. This prodigious value of Φ_m (probably a survival-related feature since bacterial cells live in environments over which they have little control and from which they cannot escape) is, however, tempered by the knowledge that *E. coli* could not indefinitely, or even regularly, metabolize at this extraordinary pace. A single microbe of *E. coli* with a doubling time of 22 minutes during exponential growth would, if unconstrained, produce a progeny of $\sim 10^{28}$ g, or roughly the mass of the entire Earth, within a single day!

Most individual cells do not operate under such peak conditions nor do they have such robust reproductive rates, and for these their metabolic rate is less; for instance, O_2 -consumption measures show *Paramecium* to have $\Phi_m \approx 10^4$ erg/s/g, heat transfer during simulation shows nerve cells to have $\Phi_m \approx 40$ erg/s/g, and a whole suite of bacteria, algae, and fungi that sluggishly metabolize in pore spaces within barren rocks in the otherwise lifeless, extremely dry valleys of Antarctica have values of Φ_m close to unity (Lehninger, *Bioenergetics*, 2nd ed, Benjamin, 1971).

By comparison, here's a calculation for cells in the human body today, although of course these eukaryotic cells are highly evolved and not necessarily representative of those prokaryotic systems present at the dawn of life. The $\sim 10^{14}$ cells in a human being share ~ 2800 kcal of energy daily, thus each cell, very much on average, consumes energy at a rate of 10^{-12} W. And since a typical human of 70 kg has individual cell masses, again very much on average, of 10^{-9} g, that makes $\Phi_m \approx 10^4$ erg/s/g. In fairness, this is just the

value of Φ_m for humans *en masse* (cf, Advanced Track for BIOLOGICAL EPOCH) and probably pertains little to the earliest cells extant after the origin of life on Earth.

Despite the extreme diversity of cell types, the average value of cellular Φ_m (hundreds to thousands of erg/s/g) agrees reasonably well with that expected at the interface of non-life and life—namely, Φ_m values for chemical and biological evolution that are typically greater those for inanimate systems experiencing physical evolution yet less than those engaged in cultural evolution (cf, Advanced Track for CULTURAL EPOCH).

Microbe Caveats: Simple microbes found on Earth today might be typical of the complexity of life at the time of its origin ≥ 3.5 Gya. Surprisingly, some well-known respiring bacteria have Φ_m values often reaching millions of times that of the Sun, or an astonishing 10^7 erg/s/g. For example, the common soil species, *Azotobacter*, is (along with *E. coli* just noted a few paragraphs previous) among the most voracious heterotrophs in Nature, producing 7 kg of ATP for each gram of its dry mass. Perhaps this is why some species of prokaryotic bacteria are the most abundant—some would say, the most successful, even dominant (Margulis and Sagan, *Microcosmos*, Simon&Schuster, 1986)—organisms in the biosphere.

Aside from complexity measures, microbes might indeed be best "fit" for their environments, for they invest a great deal of their stunning metabolism into reproduction. Yet the eubacteria (including life's most common prokaryotic bacterial groups) and their cousin archaeobacteria (the most recently discovered, separate domain of life) are unicellular, un-nucleated organisms only a few microns across, and that puts them in a class by themselves; creatures much smaller than the smallest mammals are not subject to gravitational considerations (that do affect bigger species—cf, Advanced Track for BIOLOGICAL EPOCH), since (surface tensional) forces other than those due to gravity and inertia are important for microscopic beings. Furthermore, being unicellular, bacterial cells are not specialized; each one must be general enough to accomplish the job needed to survive and replicate in a world of high surface-to-volume ratio. What's more, tiny cells are subject to life-or-death disordering effects that can harm them more readily, requiring more frequent repair; small structures like 1-celled bacteria have more skin to maintain per pound than larger structures like huge

elephants, for the same reason that single-family homes have higher maintenance costs per pound than high-rise skyscrapers. All of which demands that the microbes have relatively high energy flows per unit mass when respiring.

That said, microbes, like all else in this energy-flow analysis, need to be placed into a larger perspective, including a larger temporal perspective, for not all of them respire continuously; in fact few, if any, of them do. Many bacteria have marked resistance to starvation and exceedingly long survival capability in the near absence of any nutrients (Fletcher and Floodgate, eds, *Bacteria and Their Natural Environments*, Academic Pr, 1985). The aforementioned *Azotobacter* bacteria are indeed exceptional, having extremely high respiratory rates far greater than for other aerobic bacteria. By contrast, more than three-quarters of all soil bacteria are virtually dormant, and thus have negligible Φ_m values, while eking out a living in nutrient-poor environments. Most of them enjoy a physiological ability to switch their metabolisms on and off, which is probably another survival-related trait. Extremophilic microbes living in the deep biosphere have reproductive rates in the centuries, with some of the deepest sub-surface organisms reproducing only once every millennium. Accordingly, the metabolic scope, or range of Φ_m values above the basal rate, for microorganisms spans some 10 orders of magnitude, a vast range nonetheless narrowed by environmental restraint; that such constraint is indeed operative among microbial life is exemplified by the presence of similar, yet different, microbes at Earth's poles, almost surely the result of convergent evolution along quite independent paths (Morris, *Crucible of Creation*, Oxford U Pr, 1998). Exhaustion of available resources as well as the accumulation of toxic products of metabolism are among the principal reasons that *E. coli* bacteria do not consume the whole Earth, however ridiculous that proposition may sound; their nutrients are severely limited even on the surface of our planet.

Although much of the microbial world remains the least explored part of biology, we hypothesize as before that, when the peak metabolic rates operating for short periods are time-weighted by the nearly negligible rates during much longer dormant periods, their average values of Φ_m range from 100s to 1000s of erg/s/g, as expected for systems of intermediate complexity.

Regarding the prodigious, yet sporadic, metabolic processes among microbes, an analogy might be made to some larger life forms, such as the world's biggest

lizard. Komodo Dragons of the Indonesian archipelago can consume up to 80% of their body weight at one meal, such as a 30-kg boar in 15 minutes, yet not need another meal for a month. Their time-averaged metabolic rate is much less than their instantaneous rate while eating, thus their Φ_m values vary greatly depending upon the activity. Among many other examples of large mammals encountered in the Advanced Track for the BIOLOGICAL EPOCH, black bears can eat about half of its *annual* energy needs in a month of foraging on moths and berries, making its Φ_m value then anomalously high; by contrast, during hibernation its metabolic rate is ~25% of normal and Φ_m equally below normal (Toien, *Science*, v331, p906, 2011). Likewise, ~25-kg sled dogs can consume up to 12,000 (dietician's) Calories each day of a race (for an impressive $\Phi_m \approx 2 \times 10^5$ erg/s/g) *but only during the race*.

For many life forms—small or large, microbes or mammals—energy acquired and expressed is sometimes irregular and intense during brief periods of high performance yet much less so when closer to normal activity or resting, thus their metabolic metrics must be appropriately averaged over long durations.

Faint-Sun Paradox

As noted earlier in the Advanced Track for the STELLAR EPOCH, stars like the Sun increase their L with time as their cores grow while converting H into He; more heat and light are released from larger fusion zones within them. Stellar-evolutionary models imply an early Sun that was a good deal dimmer than now. Satellite measurements of the solar constant (α energy reaching Earth) concur, implying that the Sun is currently brightening by ~1% every 100 My. Extrapolation back 3-4 Gya suggests that the early faint Sun was probably $\sim 1/3$ less luminous than today (*ie*, $\sim 0.7 L_\odot$)—an estimate that also agrees with recent geophysical evidence of early Earth conditions (Sagan and Chyba, *Science*, v276, p1217, 1997). Hence, the "faint Sun paradox" whereby H_2O on early Earth should have likely been frozen, thus making highly improbable the origin of life. However, the fossil record clearly shows that life emerged at least 3 Gya, and much geological data imply that Earth's oceans remained largely liquefied throughout the first half of our planet's existence, as it has mostly ever since.

Possible solutions to the paradox include changes in either the Sun or the Earth, and maybe both:

- Early Earth might have been substantially warmed by greater greenhouse heating than

present today, caused perhaps by CO_2 levels hundreds of times those today, or perhaps by the release of even minute amounts of CH_4 from undersea hydrothermal vents, since CH_4 is a more efficient greenhouse gas than CO_2 . However, the presence of magnetite in banded-Fe formations in Greenland constrains CO_2 atmospheric levels to at most 3X those of today, and larger amounts of CH_4 would have chemically reacted to form a cooling haze, implying that neither gas would have likely prevented our planet from freezing early on. Small amounts of NH_3 , which is also a more potent greenhouse gas than CO_2 , might have also warmed early Earth, but even this idea is controversial since some researchers argue that all NH_3 would have been quickly converted into greenhouse-irrelevant N_2 upon interaction with solar UV radiation, which would have been plentiful at the time, even at Earth's surface (Chyba, *Science*, v328, p1238, 2010).

- The young Sun rotated more rapidly and was thus more chromospherically active, which might have then emitted slightly more energy than it does now.
- A substantially darker Earth surface and a near-absence of light-scattering clouds would have then naturally warmed our planet. Early on, the continents, which are lighter, were also much smaller; oceans, which are darker, would have absorbed more solar energy. Some 3.8 Gya, it is estimated that only ~3% of Earth's surface was covered with land; ~2.4 Gya that fraction was ~17%, and now it's ~29%. Furthermore, without life and the biologically produced particles around which water vapor coalesces to form clouds and then rain, clouds were probably fewer long ago (even with more oceanic surface area), thus more sunlight might have reached Earth's surface. However, these analyses did not consider the effects albedo arising from any high-latitude ice that might have been present (Rosing *et al*, *Nature*, v464, p744, 2010).

Each of these solutions to the faint-Sun paradox has its pros and cons, and a scientific consensus for any one of them is not yet embraced by all researchers. Unfortunately, it is not even clear if some of the proposed solutions either solve or exacerbate the faint-Sun paradox. More research is clearly needed to

understand how the Archean Eon on Earth gave rise to life and thereafter remained habitable.

Early Archaean Life

However they originated, the earliest life forms were much the same biochemically as life today—C-based life operating in a H_2O -based medium. Early microbes' genes were still made of DNA, their proteins comprised the same set of 20 amino acids, and their energy needs likely met by the molecule ATP.

In contrast to traditional Darwinism and the Modern Synthesis that focuses on origin of species of plants and animals, microbial evolutionary biology probes the earliest origins of life itself. To address microbial evolution, we need to reconsider much of classical biology's understanding of the processes of evolution. This assumes that gradual, incremental change characterizing neo-Darwinism does not pertain to how the cell and its parts originated and evolved early on; furthermore, symbiosis and horizontal gene transfer are fundamental to microbial evolution.

Microbes have always been problematic for evolutionary biologists. Darwin largely left them out of his study, as did the authors of the Modern Synthesis. Here, we strive to include them in our grand cosmic-evolutionary synthesis.

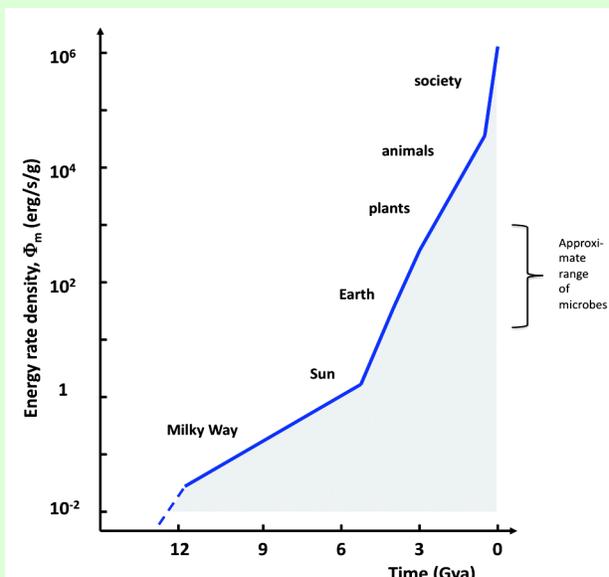
That said, some of the earliest creatures displayed similarities to some of the most advanced, heterotrophic life forms, such as animals (including humans) that gather energy by eating locally available chemicals. Archaean microbes ~3 Gya likely absorbed energy from the soupy sea of otherwise inorganic materials—this we know because such life forms still exist today. Microbial communities are now found living deep in Earth's crust, this novel type of life reducing CO_2 with H to form CH_4 , which is why some such microbes are called "methanogens". (Thus, methane detection on alien planets, notably Mars, might be a signature of simple extraterrestrial life.) Other Archaean life forms get their energy by reducing S in hot springs, yet none of them truly photosynthesize (by fixing C, as do the morphologically similar yet genetically different bacteria). All together, this "deep biosphere" of ancient microbes that is theorized to exist today might outweigh all the surface biota combined. Even so, archaean microbes seem to have surprisingly little effect on the general biosphere of our planet; they reproduce at very slowly, impacting the environment hardly at all. Their energy supply is limited by the rate at which Earth provides them with chemical nutrients, thus their total metabolic activity

is small compared to life at the surface where organics and light are plentiful.

Φ_m for Cellular Life

This work is not the first to stress the role of energy in constructive matters, although most others have been either qualitative in approach or restrictive in application. In particular and as an example of the latter, Morowitz (*Energy Flow in Biology*, Academic Pr, 1968) has pioneered the study of energy flow in biological systems, not only showing how such non-equilibrium (or as he calls them "steady") states can acquire properties very different from those that might be expected in equilibrium, but also asserting that biological evolution, function, and increased organization can be studied as a physical process. He furthermore goes on to say that "from the study of energy flow in a number of simple model systems, . . . the evolution of molecular order follows from known principles of present-day physics and does not require the introduction of new laws"—a sentiment roundly embraced here, for systems both alive and abiotic.

The figure below presents for a variety of microbes a similar graph to those plotted earlier for other physical systems. Here, we are crossing from the chemical origins of life, which still occurs among physical systems, to primitive life forms themselves, which are clearly biological systems. In the main, the rising trend of Φ_m is much the same as in previous epochs, though the spread and uncertainty among these simplest forms of life are greater for microbes and lower-order cellular life than for the higher-order plants and animals throughout the major evolutionary stages of life (*cf*, Advanced Track for BIOLOGICAL EPOCH).



This graph repeats the essence of an earlier one (cf, end of Advanced Track for PARTICLE EPOCH), suggesting Φ_m as a measure of rising complexity over all historical time. The bracketed range at right outlines some of the increasingly ordered structures for a variety of living systems—in this case, for numerous microbes in the late-chemical and early biological-evolutionary phases of cosmic evolution.

In Sum

Onward across the bush of life—cells, tissues, organs, and organisms—we find much the same story unfolding. Studies of life's precursor molecules, as with life itself, show the same *general* trend found earlier for galaxies, stars, and planets: The greater the perceived complexity of the system, the greater the flow of free energy density through that system—either to build it, or to maintain it, or both.

Energy is essential to every aspect of life. But not just total energy incident on living systems; a more detailed study of life would distinguish the inputs containing more concentrated energy from the dispersed wastes, for it is this energy difference that is used by organisms to order and maneuver the atoms in their bodies. Origin, differentiation, growth, and evolution all involve energy-requiring syntheses of vital substances, such as nucleic acids and proteins. Mechanical work done by muscles and limbs, electrical impulses in nerves and brains, active transport of substances against osmotic concentration gradients, and thermal maintenance of warm-blooded animals, to name but a few examples of key biodynamics, all reduce to flows of energy through open systems. That energy is generated by the oxidation of foods consumed by the body and subsequently supplied to the tissues in the form of chemical energy released by metabolic reactions of specific "energy-rich" compounds (ATP). All accords with the 2nd law of thermodynamics, and all underscores the mechanical, chemical, electrical, and thermal work upon which all life depends.